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ASSESSING EARTHQUAKE HAZARDS AND REDUCING RISK IN THE PACIFIC NORTHWEST

Volume 2

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1560

U.S. Department of the Interior
U.S. Geological Survey

Cover. *Insert*, ground-shaking damage from the 1949 Puget Sound earthquake to unreinforced masonry in Seattle, Wash. Photograph by George Cankonen, Seattle Times. *Background*, landslide damage to the railbed between Olympia and Tumwater, Wash., in the 1965 Puget Sound earthquake. Photograph by Greg Gilbert, Daily Olympian.

Cover design by Carol A. Quesenberry.

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Albert M. Rogers, Timothy J. Walsh, William J. Kockelman, *and*
George R. Priest, *Editors*

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An investigation of the earthquake potential in the Pacific Northwest and examination of the measures necessary to reduce seismic hazards

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1998

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Assessing earthquake hazards and reducing risk in the Pacific Northwest / Albert M. Rogers...[et al.], editors.
p. cm.—(U.S. Geological Survey professional paper ; 1560)
Includes bibliographical references.
Supt. of Docs. no.: I 19.16:1560
1. Earthquake hazard analysis—Northwest, Pacific. 2. Earthquakes—Northwest, Pacific. I. Rogers, A.M. II. Series.
QE535.2.U6A825 1997
363.3′495—dc20
ISBN 0-607-89262-5 95–37559
CIP

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VOLUME 2

TABLE OF CONVERSION FACTORS

Multiply	By	To obtain
Area		
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Density		
gram per cubic centimeter (g/cm^3)	62.43	pound per cubic foot (lb/ft^3)
Length		
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
Volume		
cubic centimeter (cm^3)	0.06102	cubic inch ($in.^3$)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

Abbreviations: ka, thousand years ago; Ma, million years ago

EARTHQUAKE HAZARDS

Preceding page. *Insert,* debris left by the April 29, 1965, Seattle, Wash., earthquake. Photograph courtesy of NOAA/EDIS. *Background,* destruction caused by the fall of an unbraced masonry parapet in downtown Klamath Falls, Oreg., during the Sept. 20, 1993, *M* 5.9 and *M* 6.0 earthquakes. Photograph by Lou Sennick of the Herald and News, Klamath Falls, Oreg. (from Dewey, J.W., 1993, Damages from the 20 September earthquakes near Klamath Falls, Oregon: Earthquakes & Volcanoes, v. 24, no. 3, p. 121–128).

AN INTRODUCTION TO PREDICTING EARTHQUAKE HAZARDS AND LOSSES IN THE PACIFIC NORTHWEST

By Albert M. Rogers[1] *and* George R. Priest[2]

INTRODUCTION

The articles in the Earthquake Hazards section of the professional paper discuss ground-shaking and ground-failure hazards and the estimation of losses associated with these hazards. Ground shaking and ground failure are the major factors in loss of life and property during earthquakes. The delineation of these hazards by mapping and site-specific prediction techniques is an important step in the process of reducing the effects of earthquakes. Ground-shaking and ground-failure maps, for example, can be valuable in land-use-policy development, siting or relocation of local government emergency facilities, and urban-renewal decisions. Furthermore, hazard maps can aid in the design and siting of lifelines (see volume 1, Glossary) and ordinary structures and in emergency planning and response, each requiring advance information about the likelihood of earthquake damage to infrastructure. Estimates of the magnitude of economic losses and mortality during future earthquakes are also partly based on hazard maps. Loss estimates are not only useful in planning for earthquakes but also serve decision makers in establishing preventive actions and determining the rate at which resources should be expended to reduce earthquake effects.

Preparation of hazard maps requires extensive regional development of databases, a process that is far from complete in the Pacific Northwest. Useful hazard maps, for example, are based on detailed mapping of geologic deposits and measurement of their physical properties and on topography, sediment thickness, basin geometry, water-table depth, attenuation of ground motion, and the seismic and geologic mapping of young faults capable of producing damaging earthquakes. A new earth-science field called paleoseismology has emerged that provides information about recurrence rates on faults and the time since the last earthquake, data that can be incorporated into probabilistic ground-motion maps or used to forecast the probability of the next earthquake during a chosen time interval. Database development will also be of great value in continued research to improve hazards-prediction methodology.

Site-specific hazard estimates are most useful in the design of critical facilities and high-occupancy buildings such as bridges, power plants, hospitals, and high-rise structures. The information used for site-specific estimates is generally more detailed than that required to produce hazard maps. Such estimates are commonly based on borehole measurements at the site and modeling of local ground motions based on these measurements and also on data such as regional ground-motion attenuation and fault locations.

Estimating ground-shaking and ground-failure hazards in this region is complicated by three factors. First, several types of earthquakes are likely (see Rogers and others, volume 1, for a discussion of earthquake types), and each type is expected to produce damage that differs in geographic distribution and level of intensity. Second, very few strong-motion records exist that would permit calibration of models or generalization about the characteristics of ground shaking for the region. Furthermore, no records exist for the types of Pacific Northwest earthquakes having the greatest potential for destruction, that is, the great Cascadia thrust-fault earthquake and the shallow continental-crust earthquake. Third, the types of data needed to produce microzonation maps for strong motion, ground failure, and losses are not yet available except in limited areas.

Nevertheless, some estimates of these factors are possible. This volume presents work to develop several types of databases, research to predict site-specific estimates of ground shaking for several earthquake types, research to map limited areas that depict some types of ground failure, and the estimation of one type of economic loss. In the following, we review the reports that contribute to the

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understanding of these problems. A review of earlier work on this topic is presented in the introduction to this professional paper (Rogers and others, volume 1).

GROUND FAILURE

One of the first steps in the development of a ground-failure prediction capability is the assessment of past ground failures. This assessment is important in two respects. First, we know from experience elsewhere that ground failure is likely to recur in many of the same locations during successive earthquakes, given the same conditions. Second, past ground failures tell us about the local conditions, earthquake magnitudes, and epicenter distances likely to produce ground failures in the future. Chleborad and Schuster (this volume) present a study of ground failures associated with the 1949 and 1965 Puget Sound earthquakes. Failures from these events were spread across a large part of the Puget Sound region and northwestern Oregon and included landslides, ground settlement, ground cracks, and liquefaction effects such as sand boils and lateral spreading. Other miscellaneous effects that may have been related to ground failure, such as broken and bent underground pipes, are also mapped. These maps demonstrate the widespread susceptibility of this region to earthquake-induced ground failure and the concentration of these effects near bodies of water, along bluffs, and in lowland areas with a high water table. For larger earthquakes or earthquakes with shallower focal depths than the 1949 and 1965 events, the effects are expected to be more widespread and intense.

Grant and others (this volume) present a map showing the estimated liquefaction hazard for Seattle based on standard penetrometer measurements in more than 300 borings, depth to the water table, geologic maps of surficial units, and unit thickness. They develop two sets of criteria for liquefaction that in combination permit the delineation of areas of high, moderate, low, and very low liquefaction potential. This map shows that the zones of high and moderate liquefaction are concentrated along shoreline areas, in areas of fill, and along the Duwamish River tide flats and Interbay (Smith's Cove) areas. The map should help in development of land-use policies, estimation of future losses, recognition of the need for site-specific studies for some types of structures, disaster planning, and other decision making by local governments and citizens.

GROUND-MOTION ESTIMATION

DATABASE DEVELOPMENT

That near-surface geologic conditions can influence the level of strong ground shaking is well known (for example, see Kanai, 1952; Gutenberg, 1957; Borcherdt and others, 1975; and Rogers and others, 1985). The effects can be large at some places; consequently, any attempt to estimate future ground motions must account for the influence of site conditions in some manner. Several methods are available to predict these effects. In one method, detailed geologic maps are prepared that discriminate between the youngest geologic units that are most likely to influence shaking levels. From such information, hazard maps can be prepared that depict relative changes in expected shaking levels that can be expressed in terms such as low, medium, and high. Other methods might express these changes in terms of maps of Modified Mercalli intensity increments (or any other earthquake-intensity measure) associated with specific surficial sediments or Modified Mercalli intensity for hypothetical earthquakes on specific faults. Linear or nonlinear models of sediment responses can be used to calculate ground-shaking levels relative to rock if data for these calculations are available. Measurement of the actual response of each geologic unit using strong-motion recordings or recordings of local earthquakes and blasts can also provide a measure of spectral levels relative to rock. If calculations or measurements of this kind are available for enough sites that can be correlated with surficial geologic conditions, maps can be constructed depicting the relative changes.

King and others (1990) and Carver and others (this volume) have collected data that partly establish the influence of near-surface sediments on the level of ground shaking in Olympia and Seattle, Wash. In these studies, local earthquakes and blasts were recorded on a variety of geologic units and at sites for which the intensity of shaking in the 1949 and 1965 Puget Sound earthquakes could be established. The studies establish a correlation between shaking intensity in damaging earthquakes and relative spectral levels for typical sediment types. Amplification of shaking by as much as 800 percent has been observed in the Pacific Northwest on some alluvium types for some spectral bands. Because soils respond nonlinearly when subjected to very strong motion, such large amplifications are not commonly experienced in large earthquakes. However, these levels can be used to determine a qualitative measure of the relative geographic variation in shaking. For some alluvium types and for low to moderate shaking levels, relative factors determined from small regional earthquakes and blasts may accurately predict variations in strong-motion levels (for example, see Borcherdt and others, 1975; Borcherdt and Glassmoyer, 1992; and Rogers and others, 1985).

Madin (this volume) compiles maps of faulting and thickness of surficial sediments in the Portland, Oreg., region that depict alluvial units likely to affect ground-shaking levels. These maps have as a basis compilations of earlier geologic mapping combined with existing borehole logs. Such maps are the first step in studies to evaluate the ground-shaking, ground-failure, and faulting potential in this region. Based on this work, maps depicting these hazards are, in fact, in progress for the Portland area (George R. Priest, Oregon Department of Geology and Mineral Industries, written commun., 1992).

SITE-SPECIFIC GROUND-SHAKING ESTIMATES

Cohee and others (this volume) compute strong-motion time histories and spectra at sites underlain by both rock and soil for a moment magnitude (M_W) 8 subduction-zone rupture on the Cascadia thrust fault using a theoretical earthquake source model. The calculations were made on a geographic grid that includes the Portland and Seattle regions for two independent hypothetical M_W 8 earthquakes, one west of Seattle and the other west of Portland. These postulated earthquakes would produce damaging ground motions over large areas of western Oregon and Washington. Although the highest values, equaling about 0.6*g* (see **Acceleration** in the glossary) at soil sites, are computed near the outer coast of Oregon and the Olympic Peninsula, significant damaging ground motions of about 0.1*g* near Portland to 0.3*g* near Seattle are indicated at sites underlain by alluvium. These calculations show that strong motions at this level can be expected to last 10 seconds or more. Unfortunately, the calculations do not model the part of the ground-motion spectrum that would affect structures taller than about 10 stories. These long-period ground motions are dependent on sediment geometry and near-surface sediment properties, which are only partly modeled in the calculations. Considerable research is needed to evaluate the long-period shaking levels in the major urban areas in a manner that realistically accounts for the effects of geologic deposits and basin geometry.

Silva and others (this volume) model both Benioff-zone and Cascadia thrust-fault ruptures using a band-limited white-noise earthquake source. The model is tested by comparing model predictions against the strong-motion records available from the 1949 and 1965 Puget Sound earthquakes. In modeling the thrust-fault earthquake, Silva and others (this volume) assume a M_W 8.5 event. This simulation yields peak acceleration values of about 0.15*g* at Seattle, considerably smaller than that determined by Cohee and others (this volume). This discrepancy is due to assumptions about the extent of downdip rupture. Silva and others (this volume) assume downdip rupture is limited to a point near the outer coast, whereas Cohee and others (this volume) assume rupture occurs farther downdip, to points well within the Olympic Peninsula. This result demonstrates the importance of improving our understanding of thrust-fault properties and slip mechanisms. At present, these issues are unresolved.

These studies provide a valuable first step toward our goal to evaluate the degree of hazard and risk due to earthquakes in the Pacific Northwest. Nevertheless, it is clear that much additional work is needed. With respect to ground-failure and site effects, more detailed geologic maps of young deposits are needed in urban areas by measuring the properties of such geologic units using standard penetrometer measurements or borehole shear velocities. The estimation of site effects in records of regional earthquakes recorded at different basin locations and on different geologic units should also be continued to fully understand the effects of geology on shaking levels. These records would also serve as a database for modeling such effects in order to estimate ground motions at other locations. Probabilistic ground-shaking estimates for this region need revision to incorporate the potential Cascadia thrust-fault earthquake, newly discovered continental-crust earthquake sources, and new information on paleoseismicity recurrence rates.

LOSS ESTIMATES

In a demonstration of Geographic Information System (GIS) techniques for loss estimation, Wang and others (1991) calculated earthquake-induced losses to water and sewer systems in Portland. Their study includes development of methods for inventory of facilities and formulation of an empirical loss-estimation algorithm that depends on earthquake shaking and liquefaction effects. They modeled two possible earthquakes, a surface-wave magnitude (M_S) 8.4 subduction-zone event and a M_S 6.5 local event, for their demonstration project. Dollar losses were tabulated by sewer- and water-pipe size, type of construction, materials, shaking intensity, and soil conditions. The subduction-zone earthquake was predicted to cause more than $4 million damage to both water and sewer pipelines in one drainage basin. Just as important, however, is that this type of study and methodology can quickly show the location of probable damage in map form, which can be important for emergency planning and eventual system redesign.

Much additional work is needed to extend the study of potential earthquake damage to water and sewer systems in other urban areas and to begin studies of damage to other infrastructure elements such as roads, power-distribution systems, bridges, pipelines, and other facilities. In addition, updated regional loss studies are needed in light of much new data concerning the earthquake hazards in the Pacific Northwest (for example, see Rogers and others, volume 1).

CONCLUSION

The studies reported in this volume, though only partial, show some of the types of research that can increase our understanding of earthquake effects and expected losses in the Pacific Northwest. It is clear from such studies that economic loss, life loss, and disruption of urban infrastructure is expected to be high for most earthquake-occurrence hypotheses. It is important to continue such studies in order to understand the hazards and to make realistic plans that minimize the effects and facilitate responses to future earthquakes. The long-term effect of mitigation based on these plans will be to reduce the economic burden of damaging earthquakes and to save lives.

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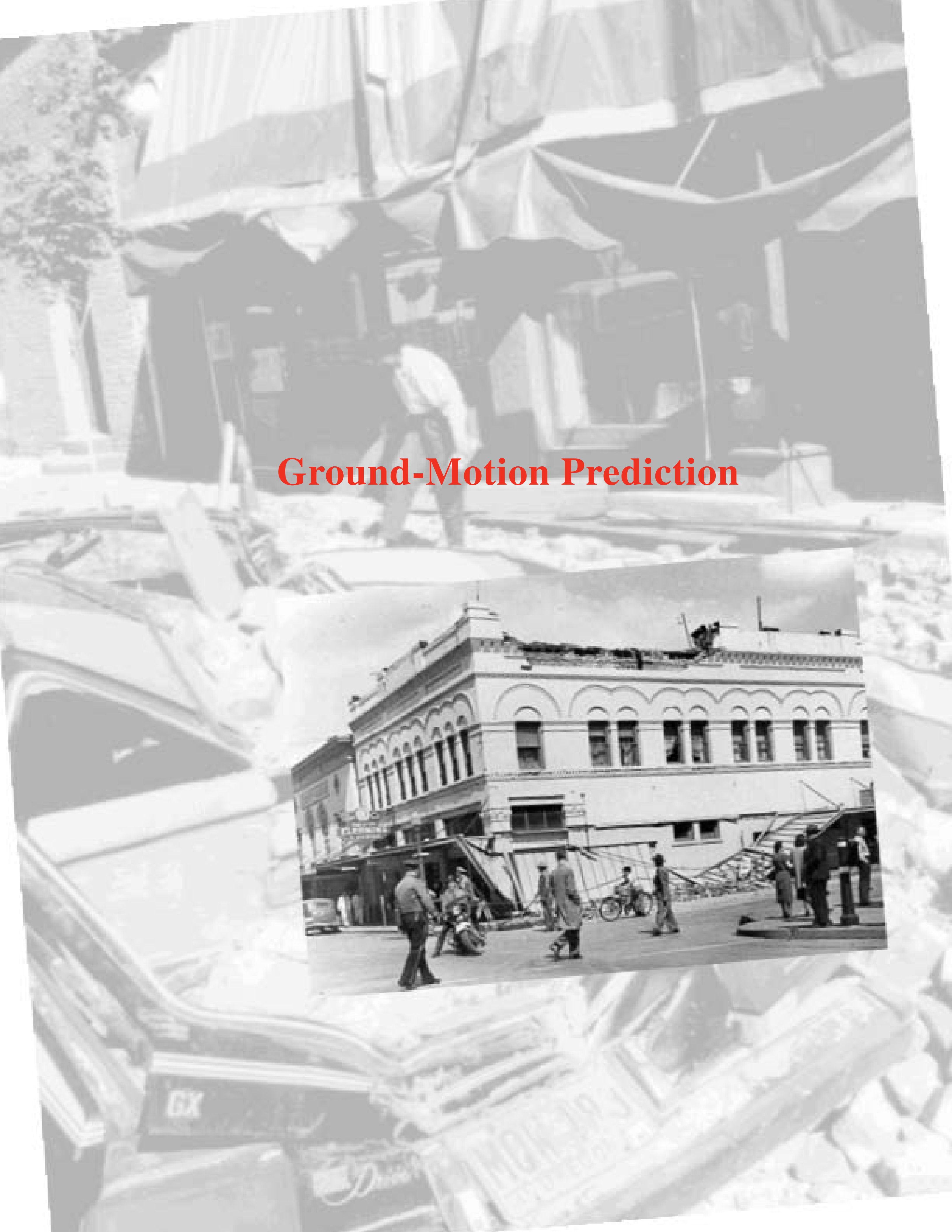

Ground-Motion Prediction

Preceding page. *Insert,* damage from the 1949 Puget Sound earthquake. Photograph by William P. Conser, by permission of the Olympia Heritage Commission. *Background,* destruction caused by the fall of an unbraced masonry parapet in downtown Klamath Falls, Oreg., during the Sept. 20, 1993, *M* 5.9 and *M* 6.0 earthquakes. Photograph by Lou Sennick of the Herald and News, Klamath Falls, Oreg. (from Dewey, J.W., 1993, Damages from the 20 September earthquakes near Klamath Falls, Oregon: Earthquakes & Volcanoes, v. 24, no. 3, p. 121–128).

ENGINEERING CHARACTERIZATION OF EARTHQUAKE STRONG GROUND MOTIONS IN THE PACIFIC NORTHWEST

By Walter J. Silva,[1] Ivan G. Wong,[2] *and* Robert B. Darragh[3]

ABSTRACT

Strong-motion recordings of earthquakes in the Pacific Northwest are few in number and nonexistent for events along the megathrust fault of the Cascadia subduction zone. The prediction of strong ground shaking from future large earthquakes in the region based on an empirical approach is hampered by this lack of data. In this study, strong ground motions for the 1949 surface-wave magnitude (M_s) 7.1 Olympia and 1965 M_s 6.5 Seattle-Tacoma earthquakes in Washington have been computed in terms of acceleration response spectra based on a numerical modeling technique that incorporates the band-limited-white-noise earthquake source model and random-vibration theory. The estimates compare favorably with the actual records of these earthquakes, as recorded at two soil sites in Seattle and Olympia, although the model underpredicts the motions for the latter. Based on this calibration of the technique, acceleration response spectra for a hypothetical moment magnitude (M_w) 8.5 Cascadia subduction-zone earthquake have also been predicted for the same two soil sites. At source-to-site distances of 101 km and 146 km for Olympia and Seattle, respectively, the estimated peak horizontal ground accelerations are 0.15*g* and 0.14*g* (where *g* is 980 cm/s^2). Because these values strongly depend upon the assumed crustal damping beneath western Washington and the location of the eastern extent of rupture of a potential Cascadia subduction-zone earthquake, they should be viewed as approximations. Based on our analysis, the effects of near-surface soils and the properties of the underlying rock will likely be significant factors controlling strong ground motions in the Puget Sound region and other geologically similar regions in the Pacific Northwest such as the Willamette Valley.

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INTRODUCTION

An essential element in the seismic design of engineered structures is a quantitative estimate of the characteristics of strong ground motion. Of particular importance is a specification of the peak levels of ground motion as well as spectral content as typically characterized by response spectra. The spectral content is reasonably well defined for crustal earthquakes of approximate moment magnitude (M_w) 6–7 occurring in western North America (Mohraz, 1976; Seed and others, 1976; Joyner and Boore, 1988). However, recent observations of strong ground motions in other tectonic regimes have revealed significant differences in the spectral content of earthquakes recorded at rock sites. Ground motions recorded in stable tectonic regimes typical of eastern North America may have significantly higher frequency content and larger peak values than corresponding motions typical of active regimes like western North America (Boore and Atkinson, 1987; Toro and McGuire, 1987; Silva and others, 1989; Silva and Darragh, 1995). In the seismotectonic setting of the Pacific Northwest, which includes the Cascadia subduction zone, ground motions may also be unique. However, few strong-motion records exist and the prediction of strong ground shaking must rely on data from other regions, including other subduction zones, if traditional empirical techniques are to be used.

In the past decade, numerical modeling techniques have been developed in an effort to provide alternative approaches to ground-motion prediction. Such techniques have been used in evaluating strong ground motions in the Pacific Northwest including the Puget Sound region (Langston, 1981; Langston and Lee, 1983; Ihnen and Hadley, 1986; Cohee and others, 1991; Wong and Silva, 1994) and the Portland, Oreg., area (Wong and others, 1990, 1993). One such technique incorporates the use of a stochastic earthquake source model called the band-limited-white-noise (BLWN) model and random-vibration theory (RVT). This approach has been remarkably successful in predicting peak ground motion values as well as spectral ordinates in different tectonic regimes (Hanks and McGuire, 1981; Boore, 1983; Boore and Atkinson, 1987; Silva and others, 1989; Schneider and others, 1993; Wong and Silva, 1993).

In this study, we have applied the BLWN-RVT methodology to compute 5-percent-damped acceleration response spectra to compare with the 1949 surface-wave magnitude (M_S) 7.1 Olympia and 1965 M_S 6.5 Seattle-Tacoma earthquakes in Washington as recorded by the strong-motion instruments in the Highway Test Office in Olympia and the Federal Office Building in Seattle (1965 earthquake only). Both earthquakes occurred within the subducting Juan de Fuca plate. Site-specific shear-wave velocity and density data for these two sites and the source parameters of the two earthquakes were used in the analysis.

Of particular importance to seismic hazards in the Pacific Northwest is the possibility of a great earthquake (M_W greater than 8) occurring along the megathrust of the Cascadia subduction zone beneath western Washington and Oregon. Based on the calibration of the BLWN-RVT approach using the 1949 and 1965 events, 5-percent-damped acceleration response spectra for a postulated M_W 8.5 megathrust earthquake have also been estimated for the Olympia Highway Test Office and Seattle Federal Office Building sites.

The focus of this study is to incorporate the effects of appropriate source, region-specific path, and site-specific parameters in the evaluation of ground motions. Such effects influence ground motions at periods of greatest engineering significance, between 0.1 and 1.0 s. Large-scale two- and three-dimensional effects on ground motions such as those due to basin geometry, however, have not been incorporated into our analysis. Basin effects, as suggested by Langston (1981) and Ihnen and Hadley (1986), can be significant for long-period ground motions in the Puget Sound.

ACKNOWLEDGMENTS

This study was supported by the Professional Development Programs of Woodward-Clyde Federal Services and Pacific Engineering & Analysis. Sue Penn, Anita Quintana, and Sylvia Li assisted in the preparation of this paper. Our thanks to Bill Joyner and Kenneth Campbell for their thoughtful reviews of an early version of this paper and Al Rogers for his review of the final version.

APPROACH USED IN THE STUDY

The BLWN-RVT ground-motion methodology has been applied to a worldwide data set of earthquakes in the range of M_W 1.5–8.1 in an analysis of rock motions recorded at distances generally less than 50 km (Silva and Darragh, 1995). This included four earthquakes, among them the September 19, 1985, M_S 8.1 Michoacan mainshock, that occurred in the subduction zone along the coast of western Mexico and were recorded by the Guerrero strong-motion network. The spectral content of these events has been modeled quite well for periods of 0.03–4 s at distances to the rupture surface as close as 16 km (Silva and Darragh, 1995). The technique has also shown that the controlling factors in the specification of strong ground motion at rock sites for engineering design are moment magnitude, source-to-site distance, and the rock properties directly beneath the site. Specifically, the near-surface attenuation modeled through the approximate parameter κ exerts a predominant effect upon spectral composition for frequencies greater than about 3 Hz. Below this frequency, M_W or seismic moment through corner frequency (see equation 3) controls spectral shapes in the BLWN-RVT ground-motion methodology.

An additional advantage of the BLWN-RVT methodology is the ability to easily incorporate site-specific nonlinear soil response directly into the ground-motion analyses using RVT in an equivalent-linear formulation. This is an important consideration in seismic-hazard evaluations in the Pacific Northwest because of widespread alluvial deposits beneath most of the major urban areas in the Puget Sound region and the Willamette Valley of Oregon.

The BLWN ground-motion model first developed by Hanks and McGuire (1981) assumes a point source with energy distributed randomly over the duration of the source. The model assumes an ω^{-2} source model (Brune, 1970, 1971) with a single corner frequency and a constant stress drop (Boore, 1983). The acceleration spectral density, $a(f)$, is given by

$$a(f) = C \frac{f^2}{1+\left(\frac{f}{f_c}\right)^2} \frac{M_o}{R} P(f)\, A(f)\, e^{-\frac{\pi f R}{\beta_o Q(f)}} \qquad (1)$$

where f is frequency;
M_o is seismic moment;
R is distance to the equivalent point source;
β_o is shear-wave velocity at the source;
$Q(f)$ is the frequency-dependent quality factor;
$A(f)$ are near-surface amplification factors;
$P(f)$ is the high-frequency truncation filter;
f_c is source corner frequency; and

$$C = \left(\frac{1}{\rho_o \beta_o^3}\right)(2)\,(0.55)\left(\frac{1}{\sqrt{2}}\right)\pi \qquad (2)$$

where ρ_o is the density at the source (fig. 147). C is a constant that accounts for the free-surface effect (factor of 2), the S-wave source radiation pattern averaged over a sphere (0.55) (Boore, 1986), and the partition of energy into two horizontal components $\left(1/\sqrt{2}\right)$. In order to compute peak-time domain values, that is, peak acceleration and peak oscillator response, RVT is used to relate root-mean-square computations to peak value estimates (Boore, 1983; Boore and Joyner, 1984).

Source scaling is provided by specifying two independent parameters, M_o and the stress drop ($\Delta\sigma$) (fig. 147). The stress drop relates f_c to M_o through the relation

$$f_c = \beta_o \left(\frac{\Delta\sigma}{8.44\, M_o}\right)^{1/3} \qquad (3)$$

The spectral shape of the single-corner-frequency ω^{-2} source model is then described by the two free parameters M_o and $\Delta\sigma$ (Silva, 1991). The corner frequency increases with the shear-wave velocity and stress drop, both of which are region dependent.

The $P(f)$ filter models the observation that acceleration spectral density appears to fall off rapidly beyond some region-dependent maximum frequency. This observed phenomenon truncates the high-frequency part of the spectrum and is responsible for the band-limited nature of the model. In the Anderson and Hough (1984) attenuation model, the form of the $P(f)$ filter is

$$P(f) = e^{-\pi f \kappa(r)} \qquad (4)$$

The function $\kappa(r)$ is a site- and distance-dependent parameter that represents the effect of intrinsic attenuation on the seismic waves as they propagate through the crust from source to receiver. The parameter κ depends weakly on the epicentral distance (r) and on both the shear-wave velocity (V_S) and quality factor (Q_S) averaged over a depth of H beneath the receiver or site. At zero epicentral distance, κ is given by

$$\kappa(0) = \frac{H}{\bar{V}_S \bar{Q}_S} \qquad (5)$$

The value of $\kappa(0)$ (herein referred to as kappa) is attributed to attenuation in the very shallow crust directly beneath the site (Hough and Anderson, 1988). Silva and Darragh (1995) suggested that the predominant kappa effects extend from the surface down to several hundred meters and possibly as deep as 1–2 km. The intrinsic attenuation along this part of the path is thought to be frequency independent but site dependent (Hough and others, 1988). For a typical western North America rock site, kappa values are in the range of about 0.02–0.06 s (Boore, 1986; Silva and Darragh, 1995).

The acceleration spectral density, $a(f)$, models direct shear waves in a homogeneous half-space (with effects of a velocity gradient through the $A(f)$ filter). For vertically heterogeneous layered structures, the plane-wave propagators of Silva (1976) are used to propagate S_H or P–SV motion through the layered structure.

In a half-space model, the near-surface amplification factors, $A(f)$, account for the increase in amplitude as the seismic energy travels through lower velocity crustal

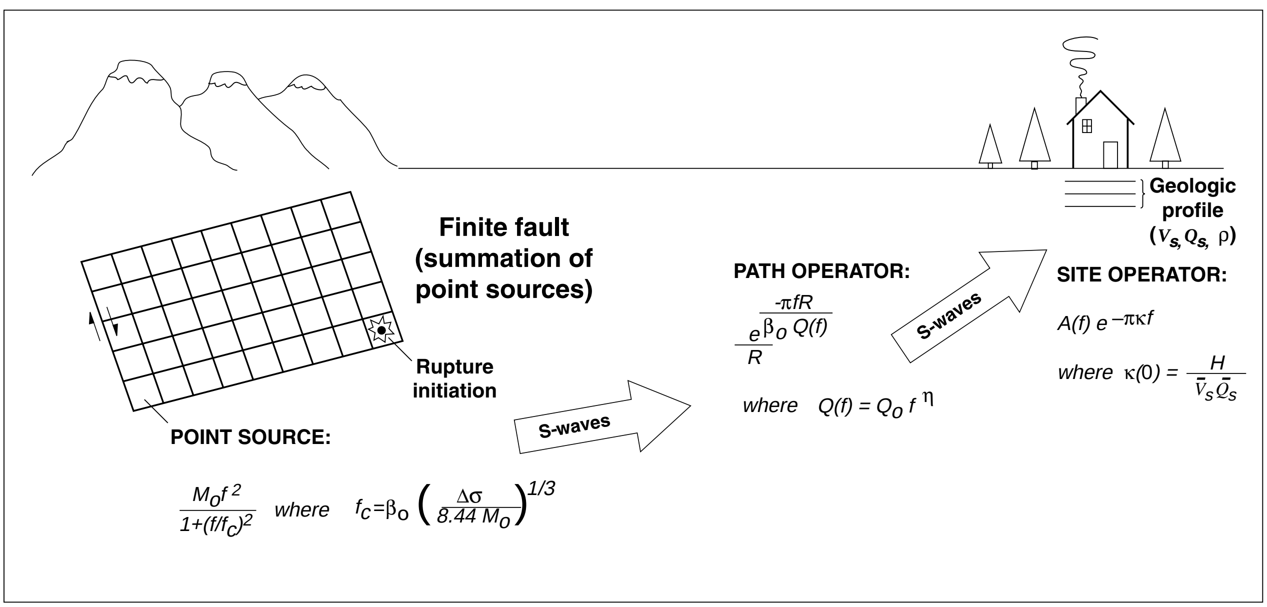

Figure 147. Schematic diagram of the band-limited-white-noise and random-vibration-theory approach used in this study to estimate ground motions due to earthquakes. Small arrows show relative motion across fault surface. M_o, seismic moment; f, frequency; f_c, source corner frequency; β_o, shear-wave velocity at the source; $\Delta\sigma$, stress parameter; R, distance to the equivalent point source; $Q(f)$, frequency-dependent quality factor where Q_o and η are model parameters; $A(f)$, near-surface amplification factors; κ, near-surface seismic-wave attenuation parameter where $\kappa(0)$ is the attenuation directly beneath the site; H, depth; V_s, shear-wave velocity; Q_s, shear-wave damping; and ρ, density in the site geologic profile.

materials near the surface. These factors depend on average crustal and near-surface shear-wave velocity and density. Western United States amplification factors developed by Boore (1986) have typically been used in the past to account for the amplification by near-surface velocity gradients. If detailed shear-wave velocity data are available for a site, it is more desirable to use such information instead of amplification factors.

The anelastic path attenuation from the source to just below the site is modeled with the frequency-dependent quality factor $Q(f)$ where $Q(f)=Q_o f^{\eta}$ and Q_o and η are model parameters. Geometric attenuation is taken as $1/R$ or $\left(1/\sqrt{R}\right)$ for distances greater than 100 km.

In order to accommodate the effects of site-specific soil response, the BLWN power spectrum of the rock outcrop motion is propagated through the one-dimensional soil profile using the plane-wave propagators of Silva (1976). In this formulation, only S_H waves are considered. Arbitrary angles of incidence may be specified, but normal incidence is used throughout the present analyses.

In order to deal with possible material nonlinearities, the equivalent-linear formulation is used. RVT is used to predict peak time-domain values of shear strain based upon the shear-strain power spectrum. In this sense, the procedure is analogous to the computer program SHAKE (Schnabel and others, 1972) except that peak shear strains in SHAKE are measured in the time domain. The purely frequency-domain RVT approach obviates a time-domain control motion and, perhaps just as significantly, eliminates the need for a suite of analyses based on different input motions.

FINITE-FAULT METHODOLOGY

A methodology that combines aspects of finite earthquake source modeling (Hartzell, 1978; Irikura, 1983) with the BLWN point-source model has also been developed to produce response spectra as well as time histories appropriate for engineering design (Silva and others, 1990). The approach is very similar to the empirical Green's-function summation methodology introduced by Hartzell (1978) and Irikura (1983). In this case, however, the BLWN point source is substituted for the empirical Green's function. Peak accelerations, peak velocities, and response spectra (when time histories are not produced) are estimated using RVT. The model can accommodate a region-specific $Q(f)$, Green's-function sources of arbitrary seismic moment or stress drop, and site-specific kappa values. A detailed description of the methodology is contained in Schneider and others (1993) and Wong and Silva (1993).

STRONG-MOTION DATA AND INPUT PARAMETERS

The strongest earthquakes to have shaken the Puget Sound region this century occurred in 1949 and 1965. Fortunately, both events were recorded by at least one strong-motion station (either the Olympia Highway Test Office or the Seattle Federal Office Building), and these records largely constitute the available empirical data for earthquakes in the region. As such, several investigators (for example, Langston, 1981) have used these records to evaluate strong ground motions in the Puget Sound region. It must be noted, however, that neither strong-motion station is in the desired free field. The Olympia instrument is located in a one-story wood-framed building. The Seattle accelerograph is located in the subbasement of an eight-story structure, 4.6 m below grade. Despite these possible complications, we have attempted to model these earthquakes with the intent of calibrating our approach.

INTRAPLATE EARTHQUAKES

The 1949 Olympia earthquake occurred at a depth of 54 km and at an epicentral distance of about 5 km from the Olympia Highway Test Office (Baker and Langston, 1987) (fig. 148). Peak horizontal ground accelerations of 0.16*g* and 0.28*g* were recorded at this site (table 22). The 1965 Seattle-Tacoma earthquake occurred at a depth of 60 km and at epicentral distances of 21 km and 61 km from the Seattle Federal Office Building and Olympia Highway Test Office, respectively (Langston and Blum, 1977) (fig. 148). Peak accelerations of 0.06*g* and 0.08*g* were recorded as horizontal components at the Federal Office Building, whereas horizontal values of 0.14*g* and 0.20*g* were recorded at the Highway Test Office. As also noted by others (for example, Langston, 1981), larger peak horizontal accelerations were recorded at the Highway Test Office than at the Federal Office Building although the earthquake was closer to the latter site.

Ground motions for the 1949 and 1965 earthquakes were calculated using the BLWN-RVT point source approach. Given the relatively long distances to Seattle or Olympia and the estimated source dimensions for either earthquake, a point source for both earthquakes was assumed valid. The input parameters required in the modeling are as follows: (1) earthquake source parameters including M_w and stress drop; (2) distance between the site and a point-source representation of the fault-rupture plane; (3) propagation-path parameters (assuming a half-space) including β_o, ρ_o, Q_o, and η; and (4) site parameters such as V_s and ρ specified as a function of depth, kappa, and appropriate shear-modulus reduction and damping curves for the soil and unconsolidated sediments overlying rock at each site.

Stress drops have not been estimated for either the 1949 or 1965 earthquakes. A stress drop of 100 bars, typical of western North America earthquakes (see Hanks and McGuire, 1981) was assumed in the modeling of the intraplate events.

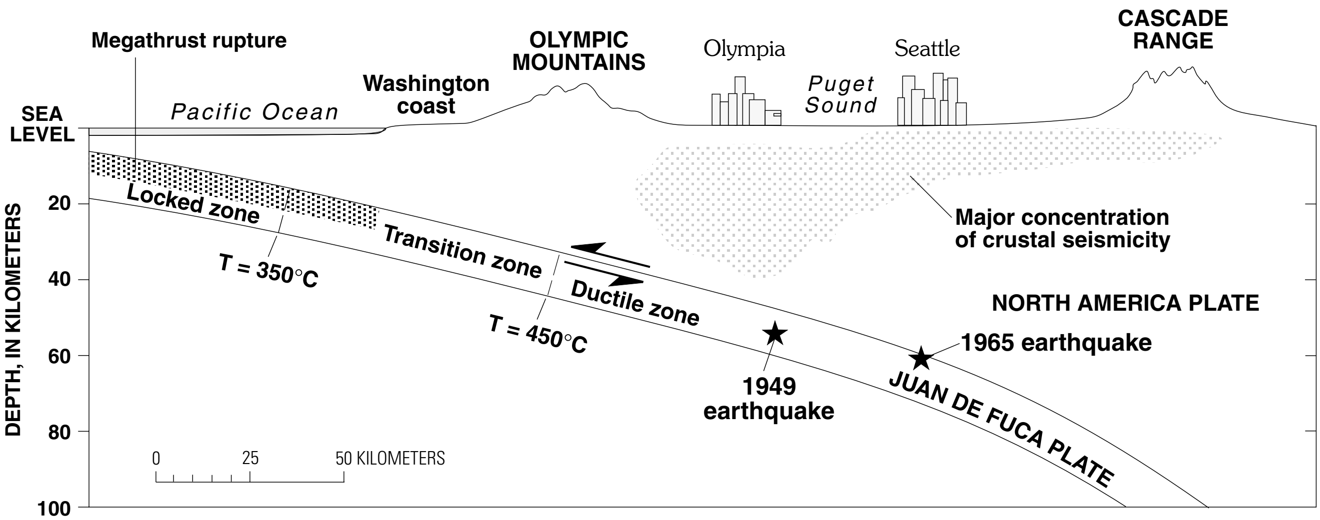

Figure 148. Cross section of the Cascadia subduction zone at latitude of southern Puget Sound in Washington. Divisions of subduction zone are adopted from Hyndman and Wang (1993). The rupture of a great megathrust earthquake is assumed to extend into one-third of the transition zone. Arrows show relative motions of plates. Temperatures (T) represent lower and upper bounds for transition zone in which stable sliding occurs. The zone separates the locked zone, where stick-slip sliding occurs and earthquakes may nucleate, from the ductile zone, where plastic deformation takes place due to high temperatures and where no earthquake rupture can occur.

Table 22. Observed and predicted median peak horizontal ground accelerations for earthquakes in the Puget Sound region.
[OHT, Olympia Highway Test Office; FED, Seattle Federal Office Building; (obs), observed; (pred), predicted; (--), not required]

Recording station	Earthquake	Depth (kilometers)	Horizontal[1] distance (kilometers)	Source-to-site[2] distance (kilometers)	Magnitude	Stress drop (bars)	Peak horizontal acceleration (*g*)
OHT	April 13, 1949	54	5	54	M_S 7.1	100	0.16, 0.28 (obs) 0.15 (pred)
OHT	April 29, 1965	60	61	85.6	M_S 6.5	100	0.20, 0.14 (obs) 0.07 (pred)
FED	April 29, 1965	60	21	63.6	M_S 6.5	100	0.06, 0.08 (obs) 0.10 (pred)
OHT	Cascadia subduction zone	25	98	101	M_W 8.5	--	0.15 (pred)
FED	Cascadia subduction zone	25	144	146	M_W 8.5	--	0.14 (pred)

[1]For the 1949 and 1965 earthquakes, this distance is equivalent to epicentral distance. For a Cascadia subduction-zone event, this is the shortest horizontal distance to the vertical projection of the rupture plane on the Earth's surface.

[2]For the 1949 and 1965 earthquakes, this distance is equivalent to hypocentral distance. For a Cascadia subduction-zone event, this is the shortest distance to the rupture plane.

The propagation path for the intraplate events was characterized by a β_o of 4.5 km/s and ρ_o of 3.05 g/cm^3 based on the *P*-wave crustal model for western Washington used in routine earthquake locations (Ludwin and others, 1991). A Poisson's ratio of 0.25 was used to determine *S*-wave velocities. A Q_o of 380 and η of 0.39 for the Cascadia subduction zone were assumed based on estimates by Atkinson (1995). The hypocentral distances from the 1949 and 1965 earthquakes to the Olympia Highway Test Office and the Seattle Federal Office Building were adopted as the point-source-to-site distances in the BLWN-RVT modeling (table 22).

Geologic profiles for the two recording sites were developed based on downhole data collected by Shannon & Wilson, Inc., and Agbabian Associates (1978) (fig. 149). At Olympia, a 156-m-deep borehole was almost entirely within glacial sediments. Low-strain shear-wave velocities ranged from 165 m/s at the surface to 1,000 m/s at a depth of nearly 152 m (fig. 149). At Seattle, fill material was found to a depth of 7 m. The natural deposits at the site have velocities ranging from 198 to 1,000 m/s to a depth of 122 m (fig. 149). Kappa values of 0.04 s and 0.06 s were assumed appropriate for the rock underlying the soils and unconsolidated sediments at the Olympia and Seattle sites, respectively, based on comparisons with similar rock types where site-specific kappa values have been estimated (Silva and Darragh, 1995). Rock in the geologic profiles was assumed to occur below the depths of 144 m at Olympia and 101 m at Seattle. Shear-modulus reduction and damping curves appropriate for soils comprising sands, gravels, and low-plasticity-index clays were used (Electric Power Research Institute, 1993). The degradation curves accommodate the effects of confining pressure on modulus reduction and damping and are implemented for profiles extending to 305 m (Electric Power Research Institute, 1993).

CASCADIA MEGATHRUST EARTHQUAKE

For the finite-fault modeling of the Cascadia subduction-zone earthquake, the rupture plane was defined as eastward-dipping (average of 7°), 280 km long, and 120 km wide. The rupture width was estimated based on the model of the megathrust proposed by Hyndman and Wang (1993) for offshore northern Washington. We assume the rupture will not only include the locked portion of the megathrust but will also extend downdip about one-third of the width of the transition zone (Wong and others, 1993) (fig. 148). The rupture length was constrained to a value where the rupture area (length times width) would be appropriate for a M_w 8.5

OLYMPIA HIGHWAY TEST OFFICE

DEPTH (m)	GEOLOGY	DESCRIPTION	V_S (m/s)	ρ (g/cm³)
3	Fill	Loose sand	165	1.5
12	Glacio-fluvial (?) deposits	Medium dense fine to medium sand	220	1.5
20	Glacio-lacustrine (?) deposits	Interbedded very stiff to hard fine sandy silt and very dense silty fine to medium sand	270	1.5
41	Glacio-lacustrine (?) deposits	Interbedded very stiff to hard fine sandy silt and very dense silty fine to medium sand	330	1.5
65	Glacio-fluvial (?) deposits	Very dense fine to medium sand	350	1.5
93	Glacio-fluvial (?) deposits	Very dense fine to medium sand	450	1.6
110	Glacio-fluvial (?) deposits	Very dense fine to medium sand	500	1.6
126	Glacio-fluvial (?) deposits	Very dense fine to medium sand	575	1.6
144	Glacio-fluvial (?) deposits	Very dense fine to medium sand	975	2.0
156	Glacio-lacustrine (?) deposits	Interbedded hard silty clay and very dense silty fine sand	1,000	2.0

SEATTLE FEDERAL OFFICE BUILDING

DEPTH (m)	GEOLOGY	DESCRIPTION	V_S (m/s)	ρ (g/cm³)
7	Fill	Loose to medium clayey, silty, fine sand	152	1.5
9	Quaternary glacial drift deposits	Very dense, silty, gravelly fine sand	198	1.5
16	Quaternary glacial drift deposits	Very dense, silty, gravelly fine sand	411	1.5
33	Quaternary glacial drift deposits	Very dense silty clay with gravel	427	1.6
47	Quaternary glacial drift deposits	Hard silty clay with some gravel	503	1.7
65	Quaternary glacial drift deposits	Very dense, silty, sandy, fine gravel and silty, gravelly, fine to coarse sand with some cobbles	610	1.8
101	Quaternary glacial drift deposits	Very dense, silty, sandy, fine gravel and silty, gravelly, fine to coarse sand with some cobbles	762	1.9
122	Quaternary glacial drift deposits	Very dense, silty, sandy, fine gravel and silty, gravelly, fine to coarse sand with some cobbles	1,000	2.0

Figure 149. Geologic profiles for the Olympia Highway Test Office and Seattle Federal Office Building strong-motion recording sites in Washington. V_s is shear-wave velocity, and ρ is density.

earthquake based on the empirical relationship between rupture area and magnitude by Wells and Coppersmith (1994). Both the Seattle Federal Office Building and Olympia Highway Test Office sites were assumed to be located approximately in the middle along the strike of the rupture plane model, given our lack of knowledge on the possible segmentation of the Cascadia subduction zone.

A total of 50 randomized slip models (fig. 150) were used to estimate ground motions, given the absence of information on the actual slip distribution of a future Cascadia megathrust earthquake. The randomized slip models were generated in the spatial domain using a process that preserves the area and number of asperities based on the slip models derived from a number of large earthquakes. Large slips near the edges of the rupture plane were suppressed by applying a cosine taper. Fifteen elements were taken along strike and eight elements along dip, giving a 280 km by 120 km rupture plane. Slip is initiated across the fault using a constant rupture velocity (circular rupture front) of 3.04 km/s. Because we do not know where rupture may nucleate in a future Cascadia megathrust earthquake, points of rupture initiation (foci) were also randomized along a 224-km-long zone (80 percent of the length of the rupture zone) centered in the deeper, east half of the rupture plane.

For the megathrust earthquake, a β_o of 3.9 km/s and ρ_o of 2.8 g/cm^3 were assumed appropriate for the source region based on the western Washington *P*-wave crustal model of Ludwin and others (1991). The Q_o and η values used in modeling the attenuation for the intraplate earthquakes were also assumed appropriate for the megathrust event. The source-to-site distances to Olympia and Seattle were 101 km and 146 km, respectively, although we estimate these values may be uncertain by as much as several tens of kilometers. These distances extend from the sites to the east edge of the megathrust rupture, which is located at a depth of about 25 km (fig. 148).

RESULTS AND DISCUSSION

Based on the above input parameters, acceleration response spectra were computed for (1) the 1949 earthquake at the Olympia Highway Test Office, (2) the 1965 earthquake at both the Olympia Highway Test Office and the Seattle Federal Office Building, and (3) a M_w 8.5 Cascadia megathrust earthquake at both sites. Figure 151 compares the recorded and predicted motions for the 1949 event at the Olympia Highway Test Office in terms of 5-percent-damped spectral acceleration (*Sa*) normalized by the peak horizontal acceleration (a_{max}). The use of this parameter, Sa/a_{max}, allows for a direct comparison of the spectral shapes. The 5-percent-damped recorded spectral shape is the average between the two horizontal components.

The match between the two spectral shapes is relatively good although there is an underprediction at short periods and an overprediction at periods longer than 0.6 s. Strong velocity contrasts in the geologic profiles (fig. 150) are responsible for the peaks in the computed motions. The large overprediction is likely a result of poorly known properties in the deeper part of the profile and points out the need to incorporate uncertainties by randomizing soil properties in modeling ground motions. The predicted peak horizontal acceleration for the 1949 event at the Olympia Highway Test Office is 0.15*g* compared to the average recorded value of 0.22*g* (table 22). A somewhat higher stress drop of about 130 bars, very much within the range of stress drops for western North America earthquakes, would result in matching the observed peak acceleration.

Comparisons between the 5-percent-damped spectral shapes of the recorded 1965 earthquake at both the Olympia Highway Test Office and the Seattle Federal Office Building and as predicted by the BLWN-RVT model are shown in figure 152. As with the 1949 event, the spectral shape of the predicted 1965 motions shows an underprediction at a period of about 0.1 s and an overprediction at periods beyond 0.2 s compared to the actual recorded motions at the Olympia site. The predicted peak horizontal acceleration is 0.07*g* compared to an average value of 0.17*g* for the recorded motions. The reason for this underprediction is unknown although this difference has been noted by other investigators (for example, Langston, 1981). Shakal and Toksoz (1979) suggested that higher values of Q_s are characteristic of the Olympia site as compared with the Seattle site. More detailed borehole and upper crustal information on v_s and Q_s is needed to resolve this inconsistency.

In contrast, the predicted peak horizontal acceleration 0.10*g* for the Seattle site is slightly higher than the actual, average value of 0.07*g* (table 22). In general, the spectral shapes of the recorded 1965 earthquake and the model prediction compare very favorably, with a slight model underprediction at long periods. Whereas these differences are likely due to site effects, the site-specific modeling captures quite well the large overall differences in spectral composition seen in the motions recorded at the two sites.

Based on this calibration of the BLWN-RVT model and path and site parameters, we have computed ground motions for a postulated M_w 8.5 Cascadia megathrust earthquake. Figure 153 shows the absolute 5-percent-damped acceleration response spectra for both the Olympia and Seattle sites. Although lacking the site resonant peaks exhibited by the 1965 earthquake, the differences in the spectral shapes of the Seattle and Olympia sites (fig. 153) again illustrate the significant site response effects of the near-surface geology. At a source-to-site distance of 101 km, the predicted median peak horizontal acceleration is 0.15*g* at Olympia (fig. 153, table 22). For Seattle, the model-predicted median peak horizontal acceleration is 0.14*g*. The Seattle site exhibits a greater high-frequency site amplification than the Olympia site, as exemplified by its peak horizontal acceleration, even though it is 45 km farther from the rupture

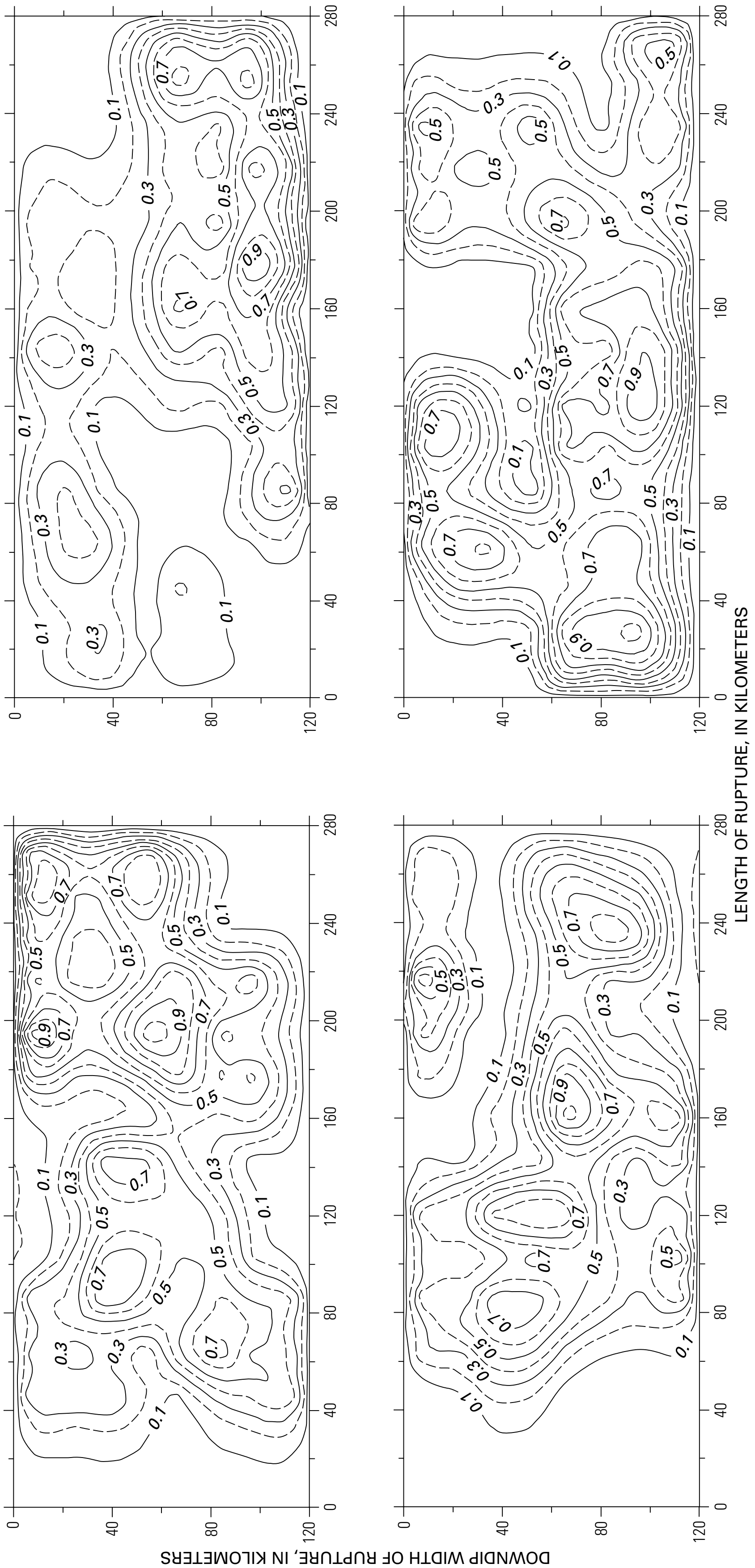

Figure 150. Four of the 50 randomized slip-distribution models used in the estimation of ground motions for the hypothesized M_W 8.5 Cascadia subduction-zone earthquake. Contours represent coseismic slip along the rupture planes, normalized to the maximum slip. Contour interval is 0.2. Areas of large slip are called asperities.

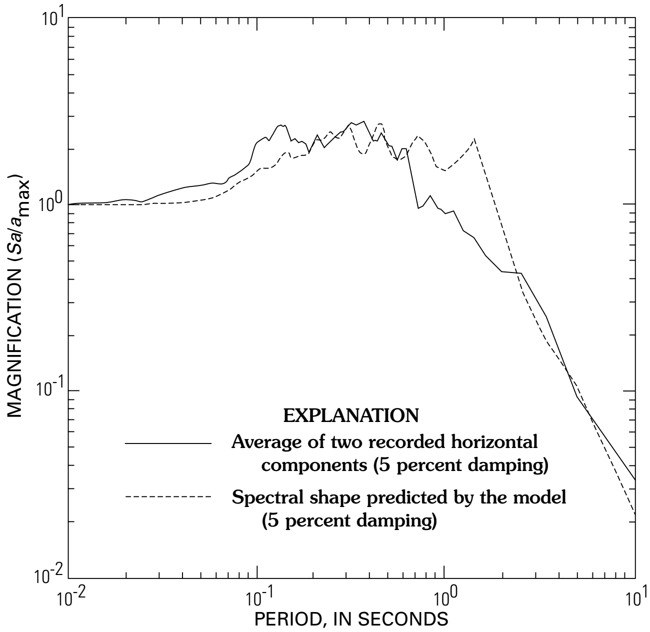

Figure 151. Observed and predicted 5-percent-damped acceleration response spectral shapes of the April 13, 1949, earthquake recorded at the Olympia Highway Test Office site. Spectral shape is defined by the parameter Sa/a_{max}, where Sa is spectral acceleration and a_{max} is peak horizontal acceleration.

zone of the megathrust earthquake. Based on an empirical attenuation relationship for subduction-zone earthquakes and rock-site conditions (Youngs and others, 1988), median peak horizontal accelerations for a M_w 8.5 megathrust event at distances of 101 km and 146 km are estimated to be 0.12g and 0.09g, respectively.

An important aspect of any numerical modeling approach is a proper statistical estimate of uncertainty. Total uncertainty is a combination of modeling and parametric uncertainties. A quantitative assessment of the modeling uncertainty associated with both the BLWN-RVT point source and finite-fault approach has been computed based on analyses of the 1989 M_w 7.0 Loma Prieta, Calif., earthquake (Schneider and others, 1993). The parametric uncertainties permit a rapid and cost-effective means of assessing which source, path, and site parameters are controlling the ground motions for a particular application.

The parametric uncertainties for the predictions of the megathrust earthquake are illustrated in figure 154 and listed in table 23. At all frequencies, the site profiles at both sites dominate the uncertainties in the ground motions, suggesting that a reduction in uncertainty is attainable with detailed site investigations. Source effects (focus and slip) are also large at low frequencies, with slip variation (asperity location) tending to remain constant with frequency (fig. 154). The path damping parameter Q_o is not a major contributor to the uncertainty in the ground-motion predictions because of the low attenuation in the Cascadia subduction zone, as suggested by Atkinson (1995). Because the motions are low, the effects of soil nonlinearity are insignificant, showing a near-zero uncertainty for modulus reduction and damping.

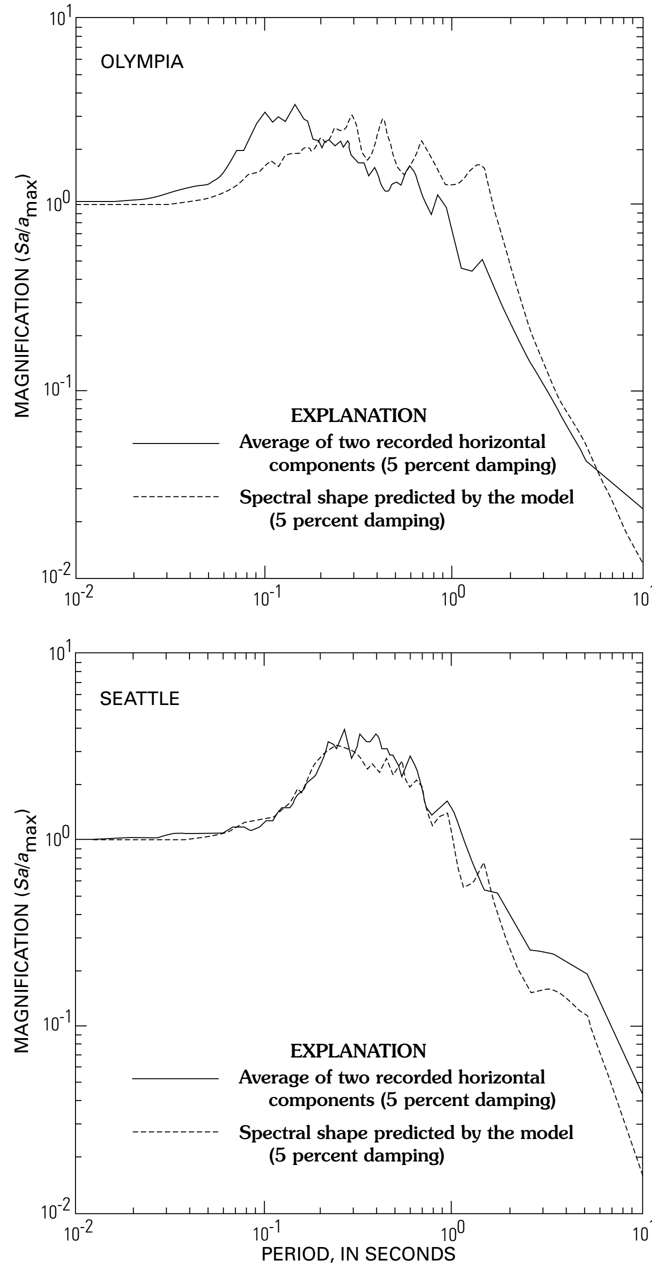

Figure 152. Observed and predicted 5-percent-damped acceleration response spectral shapes of the April 29, 1965, earthquake recorded at the Olympia Highway Test Office and Seattle Federal Office Building sites.

SUMMARY

Predicted peak accelerations and acceleration response spectra for the 1949 and 1965 Puget Sound earthquakes based on the BLWN-RVT ground-motion methodology

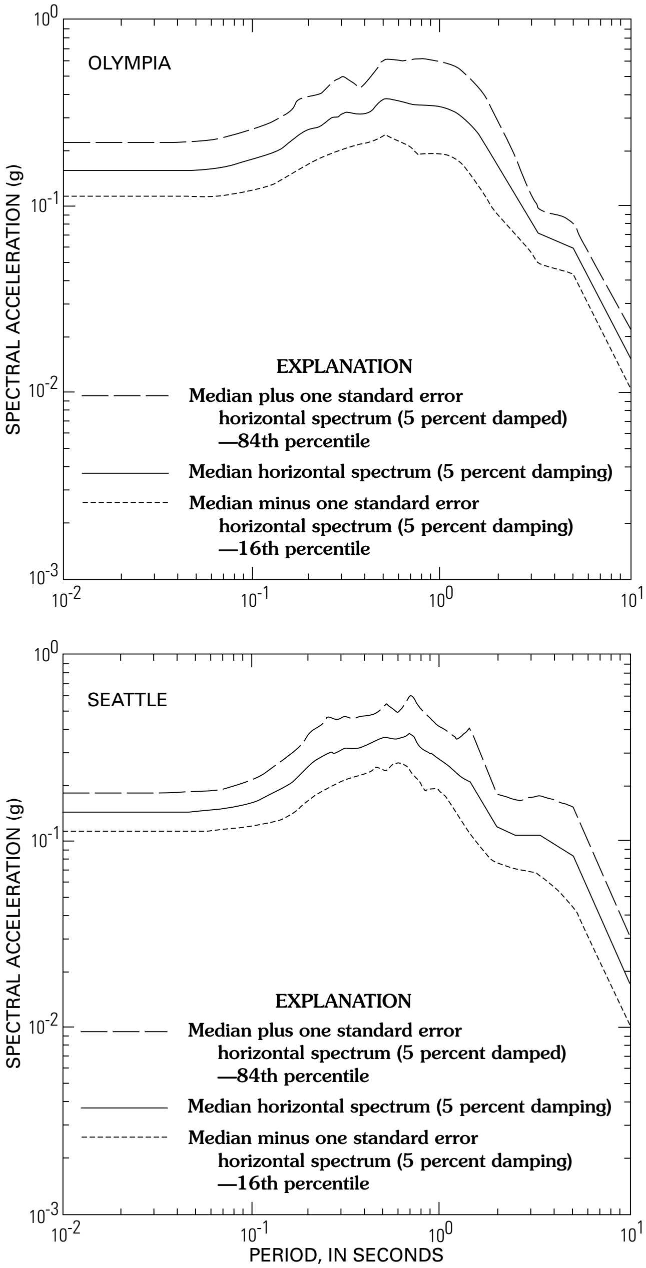

Figure 153. Predicted 5-percent-damped acceleration response spectra of a hypothetical M_w 8.5 Cascadia subduction-zone earthquake at the Olympia Highway Test Office and Seattle Federal Office Building sites.

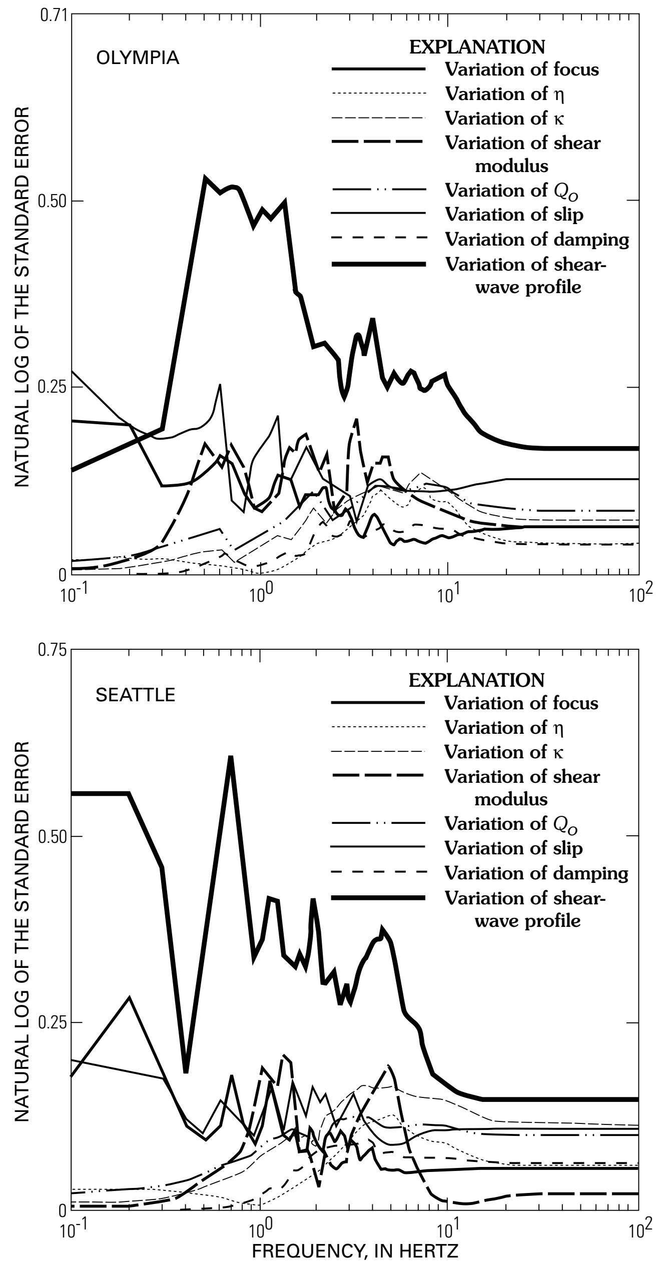

Figure 154. Parametric uncertainties in the band-limited-white-noise and random-vibration-theory computations of ground motions for a hypothetical M_w 8.5 Cascadia subduction-zone earthquake, as predicted for the Olympia Highway Test Office and Seattle Federal Office Building sites. The uncertainties are a result of varying each parameter shown in table 23.

were calibrated against actual recordings made at the Olympia Highway Test Office and Seattle Federal Office Building. An application of the methodology predicts median peak horizontal accelerations of 0.14*g* for the downtown Seattle site and 0.15*g* for the Olympia site from a postulated M_w 8.5 Cascadia subduction-zone earthquake. The uncertainty in these values is large and is driven by uncertainties in the shear-wave velocity profile beneath each site as well as the source-to site distance of the rupture zone of a future megathrust event. The need for more site-specific studies is exemplified by the observation that the site response at the Olympia Highway Test Office differs significantly from the site response at the Seattle Federal Office Building and by our inability to match, in absolute terms, the 1965 ground motions at Olympia. Based on this analysis, the effects of near-surface soils and the properties of the underlying rock likely exert a dominant influence on strong ground motions in the Puget Sound region and probably the Willamette Valley in Oregon.

Table 23. Model input parameters and uncertainties in parametric variations for a hypothetical M_W 8.5 Cascadia subduction-zone earthquake.
[(--), not required]

Parameter	Mean or median value	Distribution	Standard error (σ)[1]
Focus	Randomized in nucleation zone	--	--
Slip	Randomized models	--	--
Attenuation parameter (Q_o)	380	Lognormal	0.18
Attenuation parameter (η)	0.39	Normal	0.05
Near-surface attenuation (κ)	0.04 s (Olympia) 0.06 s (Seattle)	Lognormal	0.30
Shear-wave profile[2]	See figure 149	Lognormal	0.40
Shear-modulus reduction	See Electric Power Research Institute (1993, p. 7–A.41)	Lognormal	0.35
Shear-wave damping	See Electric Power Research Institute (1993, p. 7–A.42)	Lognormal	0.35

[1]For lognormal distributions, σ is actually σ_{ln}.
[2]Approximately lognormal based on a correlation model for velocity and layer thickness.

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SIMULATED STRONG GROUND MOTIONS FOR MAGNITUDE 8 EARTHQUAKES ON THE CASCADIA SUBDUCTION ZONE

By Brian Cohee[1] *and* Paul Somerville[2]

ABSTRACT

Strong ground motions from subduction-zone thrust earthquakes in western Washington and Oregon are estimated using a semi-empirical simulation procedure. The procedure is validated for large subduction earthquakes by modeling recorded acceleration seismograms and response spectra from the magnitude (*M*) 8 Michoacán, Mexico, and Valparaíso, Chile, earthquakes of 1985. We find that slip-distribution models derived from strong-motion and teleseismic velocity seismograms of these two earthquakes also explain higher frequency motions of the recorded accelerograms. Quantitative measures of the misfit between recorded and simulated response spectra are used to estimate the modeling uncertainty.

Ground motions are computed for two fault models representative of the two different subduction-zone geometries beneath Washington and Oregon. The most critical geometrical source parameter controlling ground motions in the urban regions of Puget Sound and Portland is the depth of the rupture on the plate interface. We used a geometry based on earthquake locations that places the downdip limit of rupture about 50 km west of both Seattle and Portland. A geometry in which the plate interface is arched at depths shallower than 40 km beneath western Washington would place the downdip limit beneath Seattle and result in larger ground-motion estimates in the Puget Sound area. Given the assumed fault location, the largest cause of uncertainty in the estimated ground motions is due to the distribution of slip (asperities) with depth on the fault plane. As their depth increases, the asperities approach the urban regions of Puget Sound and Portland and the ground motions increase. Also, with increasing asperity depth, the attenuation of peak acceleration with distance is more gradual. The fault dip of the Oregon model is about twice that of the Washington model, but the estimated ground motions are similar.

The attenuation of horizontal peak acceleration (PGA) with distance r from the fault asperity is given by

$$\ln(\mathrm{PGA})=15.6-3.34\ln(r+128)+0.79\gamma$$

where ln is the natural logarithm and γ is a site term (0 for rock and 1 for soil). This relation is appropriate for r greater than 25 km but less than 175 km and for *M* 8. When r is defined as the closest distance to the fault plane, the attenuation relation is

$$\ln(\mathrm{PGA})=2.8-1.26\ln(r)+0.79\gamma$$

This relation is appropriate for r greater than 30 km but less than 100 km and for *M* 8.

Formal estimates of uncertainty in the calculated ground motions are obtained by considering both parametric uncertainty (estimated from the range of source models of hypothetical Cascadia subduction-zone earthquakes) and modeling and random uncertainty (estimated from the misfit between recorded and simulated ground motions of the Michoacán and Valparaíso earthquakes). For periods less than 1 s, the estimated response spectral velocities at soil sites in the Seattle-Olympia region are about twice those recorded during the 1949 *M* 7.1 Olympia and 1965 *M* 6.5 Seattle earthquakes, and the durations of strong motion are significantly longer (45–60 s versus 10–15 s for rock sites).

INTRODUCTION

Strong-motion simulation procedures complement conventional empirical methods of estimating strong ground motion for seismic-hazard analyses. They augment the relatively sparse set of on-scale recordings close to large earthquakes, giving more confidence in the prediction of ground-motion characteristics for hazard evaluations. This additional information is especially valuable in regions such as the Pacific Northwest, where there had been no historical subduction-zone thrust earthquakes and, hence, no recorded

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strong ground motions prior to the magnitude (*M*) 7 Cape Mendocino, Calif., earthquake of April 25, 1992 (Oppenheimer and others, 1993). Simulation procedures also provide a means of estimating the dependence of ground motion on variations in specific fault parameters; in the empirical data, these dependencies are difficult to isolate from the many factors that determine strong-motion characteristics (Crouse, 1991). The uncertainty in ground-motion predictions from the modeling procedure can be quantified by comparisons between recorded and simulated motions and by parametric studies (Abrahamson and others, 1990). Simulation procedures also allow specific information to be included about the earthquake source, the wave-propagation path between the source and site, and the local site response. Seismograms can be generated whose wave composition, duration, and frequency content reflect these specific conditions rather than those contained in the empirical data. Such time series are of growing importance as methods for analyzing the nonlinear response of structures are developed.

When estimating seismic hazards in western Washington and Oregon, three earthquake source zones are relevant: (1) the shallow plate interface—if it has the potential to generate large subduction earthquakes, significant ground motions will occur throughout the region; (2) the intraslab (Wadati-Benioff) zone, the source of the largest earthquakes (the 1949 *M* 7.1 Olympia and 1965 *M* 6.5 Seattle events) and strongest ground motions in the region during this century; and (3) the shallow crustal zone, the likely source of the 1872 *M* 7.4 North Cascades earthquake. Ground motions from seismic events on the shallow plate interface are the subject of this report.

There is uncertainty in the size of the largest earthquakes that can occur on the Cascadia subduction zone. Comparison of Cascadia subduction characteristics with those of other subduction zones in the world led McCaffrey and Goldfinger (1995) to suggest that *M* 8 earthquakes are likely more characteristic of Cascadia subduction than less frequent *M* 9 megathrust earthquakes. Their conclusion is based on the oblique convergence angle between the plates, lateral segmentation of the downgoing slab, and inelastic deformation of the overriding plate.

Although the seismic potential of the Cascadia subduction zone remains uncertain, the plate interface did generate the *M* 7 earthquake beneath Cape Mendocino (Oppenheimer and others, 1993), and it may be able to generate great earthquakes (Heaton and Kanamori, 1984; Atwater, 1987; Rogers, 1988; Adams, 1990). In this report, we estimate ground motions in western Washington and Oregon from hypothetical *M* 8 earthquakes on the Cascadia subduction-zone plate interface. To prepare for the simulations and to estimate the modeling and random uncertainty, we modeled strong-motion recordings of the 1985 *M* 8 Michoacán, Mexico, and Valparaíso, Chile, subduction earthquakes (Somerville and others, 1991). Ground-motion estimates were then made for *M* 8 earthquakes on the Cascadia plate interface using a wide range of source parameters. These estimates are described in detail by Cohee and others (1991a, b). This report summarizes the method and uncertainty analysis from Somerville and others (1991) and the ground-motion estimates from Cohee and others (1991a, b), and identifies those aspects of the earthquake source that most strongly influence the estimates and their uncertainty.

The two reasons for selecting the Michoacán and Valparaíso earthquakes to estimate the modeling and random uncertainty are the similarity in subduction-zone geometry with that of the Cascadia subduction zone and the availability of near-source acceleration seismograms. In both earthquakes, the shallow plate interface dips at a relatively shallow angle, and much of the fault-rupture surface underlies land, which is similar to the Cascadia subduction zone. In addition to this geometrical compatibility, both earthquakes were well recorded by a large number of low-gain seismometers. Also, much is known about the earthquake source characteristics, including estimates of the rupture timing, slip-velocity function, and distribution of slip amplitude over the fault surface.

Several different methods for simulating strong ground motions have been tested against recordings of subduction-zone earthquakes by other investigators. The most common approach has been an empirical Green's-function summation method in which strong-motion recordings of smaller earthquakes are summed to simulate the rupture of a much larger earthquake (Kamiyama, 1988; Takemura and Ikeura, 1988). In this approach, the empirical Green's functions include both the source and wave-propagation effects. This approach is most appropriate when recordings suitable for use as empirical Green's functions are available in the region where the motions of the larger earthquake are to be simulated. Heaton and Hartzell (1989) applied this method to the Cascadia subduction zone using empirical source functions from Japanese subduction earthquakes.

In regions where no strong-motion recordings are available for use as empirical Green's functions, it is advantageous to calculate the wave-propagation effects using a crustal velocity model specific to the region of interest (Hadley and others, 1982). This approach was used by Day and others (1988) to simulate strong-motion recordings of the Michoacán earthquake and to estimate strong motions from Cascadia subduction earthquakes. They used ray theory to calculate Green's functions for a layered velocity model, and their source model was composed of a series of cracks represented by theoretical dislocation functions. The greatest shortcoming of this purely theoretical approach is that observed complexity in the recorded ground motion is not fully described by the theory. In our semi-empirical approach used to estimate ground motions, known aspects of the wave propagation are modeled theoretically and unknown aspects are modeled using stochastic effects and recorded seismograms (corrected empirical Green's functions).

The ground motion estimates in this report are specific to the velocity structure and fault geometry of the Cascadia subduction zone but do not include the local site response, which can be extremely important for sites on low-velocity material. The objective of the study is to predict response spectra for rock sites in the study area from a *M* 8 earthquake and to identify those earthquake parameters that lead to the largest variations in predicted motions. Estimates of response spectra for soil sites must include local site and basin effects for periods greater than about 1 s (for example, see King and others, 1990; and Ho and others, 1991).

ACKNOWLEDGMENTS

This work was supported by the U.S. Geological Survey under award #14–08–0001–G1516. Dr. Norman Abrahamson evaluated the uncertainty and Dr. Mrinal Sen assisted in the modeling of the Valparaíso earthquake. Reviews of the manuscript by Drs. Stephen Hartzell, Robert Youngs, and Albert Rogers are gratefully acknowledged.

SIMULATION PROCEDURE AND UNCERTAINTY

There are several methods for simulating high-frequency ground motion close to a fault. Some of these methods are described in Joyner and Boore (1988). They can be broadly classified into three categories: deterministic, stochastic, and hybrid. The deterministic methods (Aki, 1968; Haskell, 1969) use kinematic source models and require specification of the distribution of slip amplitude on the fault. This approach has been successful at long periods (greater than 1 s). The stochastic methods model the earthquake acceleration as random noise in the spectral band between the corner frequency and f_{max}, and the spectral shape is given by the Brune spectrum (Hanks and McGuire, 1981). These methods are computationally efficient but do not include wave-propagation effects rigorously. The hybrid approach draws on the particular strengths of the other two methods—known aspects of the wave propagation are modeled deterministically and unknown aspects are modeled stochastically.

The empirical Green's-function method described by Hartzell (1978) was the first of many hybrid techniques. Rupture propagation and radiation pattern are specified deterministically, and source radiation and propagation effects are included empirically by assuming that recorded aftershock seismograms contain this information. The methods proposed by Hadley and Helmberger (1980), Irikura (1983), and Heaton and Hartzell (1989) are modifications of Hartzell's (1978) method of summing empirical Green's functions. These methods require an adequate sampling in both distance and source depth of empirical Green's functions (Cohee and others, 1994), which is very difficult to obtain in most regions. In order to overcome this limitation, Hadley and others (1982) proposed an approach that uses empirical source functions convolved with theoretical Green's functions. The approach described below is derived from their work and uses simplified Green's functions that include the effects of geometrical spreading and exclude the effects of radiation pattern and receiver function.

The procedure is illustrated schematically in figure 155. The fault surface is divided into discrete elements, and the motions from these elements are summed at appropriate times to simulate the rupture propagation across the fault surface. The rupture front propagates at a fixed fraction of the shear-wave velocity; however, a stochastic component is included in the rupture velocity and the slip-velocity function to simulate heterogeneity in rupture dynamics. Large-scale asperities are introduced by varying the amplitude of slip on the fault surface.

The starting equation for the method is the representation theorem (Aki and Richards, 1980, equation 14.1) that describes the elastic displacement $\underline{u}(\underline{x},t)$ from a displacement discontinuity $[\underline{u}(\underline{\xi},\tau)]$ across an internal surface Σ as

$$u_i(\underline{x},t) = \int_{-\infty}^{\infty} d\tau \int_{\Sigma} \left[u_j(\underline{\xi},\tau) \right] c_{jkpq} G_{ip,q}(\underline{x},t;\ \underline{\xi},\tau)\ \nu_k\, d\Sigma \quad (1)$$

where c_{jkpq} are the elastic constants, G_{ip} is the impulse response of the medium (displacement Green's function), and ν is unit normal to the fault surface. The $\underline{\xi}$ represents a point on the fault plane, and $\underline{x}$ is the observation point. In the far field, the above integral can be written as

$$\underline{U}(\underline{x},t) = \int_0^L \int_0^W \dot{D}(\xi_1,\xi_2,t) * \underline{G}(\underline{x},\xi_1,\xi_2,t)\, d\xi_1 d\xi_2 \quad (2)$$

where L is the fault length, W is the fault width, $\dot{D}$ is the slip function, and * represents a convolution. When we use this equation to calculate ground motion from a large earthquake, we divide the large fault plane into small elements called subfaults. If we divide the fault plane into l subfaults (of length ΔL) along the length and m subfaults (of width ΔW) along the width of the fault plane, the integral reduces to

$$\underline{U}(\underline{x},t) = \sum_{i=1}^{l} \sum_{j=1}^{m} \int_0^{\Delta L} \int_0^{\Delta W} \dot{D}(\xi_1,\xi_2,\ t-\tau_r^{ij}) * \underline{G}(\underline{x},\xi_1,\xi_2,t)\, d\xi_1 d\xi_2 \quad (3)$$

where τ_r^{ij} is the time required for the rupture front to propagate from the hypocenter to the i,j subfault. The propagation time from the subfault to the observation point is included in the Green's function for that propagation path.

In most cases, the dislocation rise time increases with earthquake size (Hadley and Helmberger, 1980; Irikura,

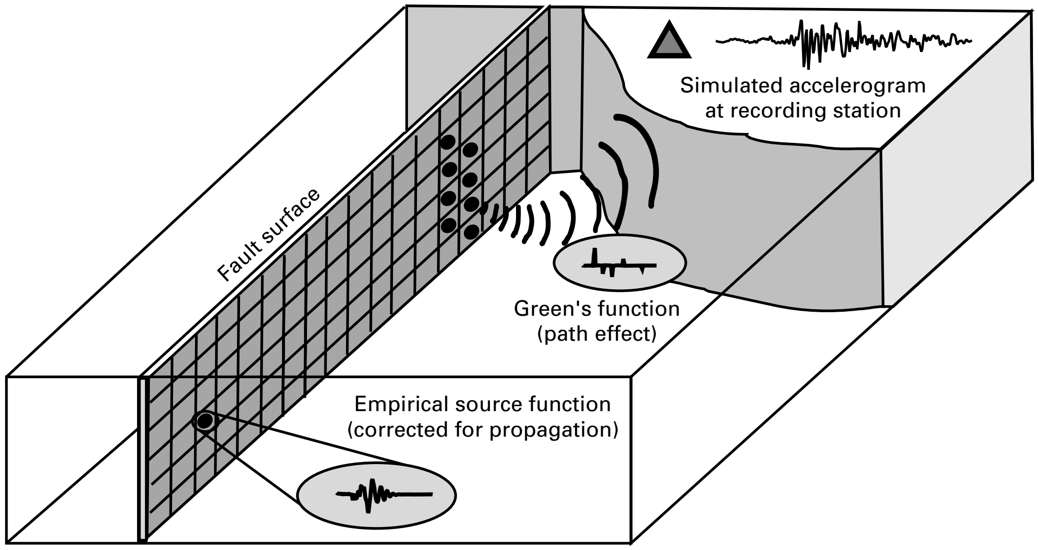

Figure 155. Schematic description of the strong ground motion simulation procedure. Contributions from the subfault elements (dots) are lagged and summed to produce a simulated accelerogram at a receiver at ground surface (triangle). The contribution from each subfault is the convolution of a corrected empirical source function with a Green's function that describes the wave propagation using the simulation geometry and velocity model.

1983). Based on a Haskell-type self-similar kinematic source model, we need to add as many sources per subfault as the ratio of the rise time of the large earthquake to that of the small earthquake from which the source function is derived. Then equation 3 reduces to the following form:

$$\underline{U}(\underline{x},t) = \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{nsrc}\int_0^{\Delta L}\int_0^{\Delta W}\dot{D}(\xi_1,\xi_2,\ t-\tau_r^{ij}-(k-1)\,\tau_e) \ast \underline{G}(\underline{x},\xi_1,\xi_2,t)\,d\xi_1 d\xi_2 \quad (4)$$

where *nsrc* is the number of subsources per subfault given by $nsrc=\tau_0/\tau_e$, and τ_0 and τ_e represent the rise time of the large and small earthquake, respectively.

The simulated motion of the large earthquake is then the summation of contributions from *l* fault elements along strike, *m* fault elements down dip, and *nsrc* time-lagged source functions on each subfault. If *l*, *m*, and *nsrc* are numerically identical, then the small and large earthquake have self-similar scaling (Irikura, 1983). In our simulations of the Michoacán and Valparaíso earthquakes, we do not use this constraint because it would greatly degrade the data fit; however, for both events, we maintain self similarity in the spectral shape between the small and large earthquakes using an ω^2 scaling relation (Joyner and Boore, 1986). To accomplish this scaling, the product of *l*, *m*, and *nsrc* must be the moment ratio of the large earthquake to the small earthquake taken to the four-thirds power.

Although the form of the radiated source spectrum may be specified deterministically, high-frequency details are generally unknown and are therefore included empirically using the empirical source function. The empirical source function is a strong-motion recording of an aftershock that has been corrected using a simplified Green's function. The correction that is most consistent with the intended use of the source function is a deconvolution of the recording with a theoretical Green's function; however, due to zeros in the spectrum, deconvolution is often unstable. The Green's function potential is usually very simple (a step function) because the aftershock recordings are from horizontal distances less than one source depth, and most of the energy is in the direct arrival. The deconvolution is then approximately equivalent to division by scalar G_0, which is the amplitude of the displacement Green's function *G(t)*. For a recorded seismogram *S(t)*, the corrected empirical source function is then

$$S_E(t) = \frac{S(t)}{G_0} \quad (5)$$

G_0 can be measured directly, but it is better to use the ratio of the maximum seismogram amplitude to the maximum amplitude after convolution with *G(t)*:

$$G_0 = \frac{\max(S(t)\ast G(t))}{\max(S(t))} \quad (6)$$

The empirical source functions must also be corrected for the surface velocity and incidence angles found in the aftershock geometry. That is, they include the angular decomposition of the *P*, *SV*, and *SH* wavefields into vertical, radial, and tangential components (P_Z, P_R, SV_Z, SV_R, SH_T) as well as amplification due to the surface velocity. These traits of the aftershock recordings are inappropriate and must be removed, and the appropriate receiver function must be introduced. This correction is performed by multiplying the empirical source function by the ratio of theoretical whole-space receiver functions. For empirical source functions denoted by P_Z, P_R, SV_Z, SV_R, and SH_T, the corrected source functions are simply

$$
\begin{aligned}
P'_Z &= \frac{1}{2}\left(\frac{\alpha_1 \cos i_2}{\alpha_2 \cos i_1}\right)P_Z + \frac{1}{2}\left(\frac{\alpha_1 \cos i_2}{\alpha_2 \sin i_1}\right)P_R \\
P'_R &= \frac{1}{2}\left(\frac{\alpha_1 \sin i_2}{\alpha_2 \cos i_1}\right)P_Z + \frac{1}{2}\left(\frac{\alpha_1 \sin i_2}{\alpha_2 \sin i_1}\right)P_R \\
SV'_Z &= \frac{1}{2}\left(\frac{\beta_1 \sin i_2}{\beta_2 \sin i_1}\right)SV_Z + \frac{1}{2}\left(\frac{\beta_1 \sin i_2}{\beta_2 \cos i_1}\right)SV_R \qquad (7) \\
SV'_R &= \frac{1}{2}\left(\frac{\beta_1 \cos i_2}{\beta_2 \sin i_1}\right)SV_Z + \frac{1}{2}\left(\frac{\beta_1 \cos i_2}{\beta_2 \cos i_1}\right)SV_R \\
SH'_T &= \left(\frac{\beta_1 \sin i_2}{\beta_2 \sin i_1}\right)SH_T
\end{aligned}
$$

where α_1, β_1, and i_1 are the P and S velocities and incidence angle at the source-function receiver, and α_2, β_2, and i_2 are the same parameters at the site recording the simulated earthquake.

The empirical source function contains other effects in addition to that of the source, including anelastic absorption, unmodeled wave-propagation effects such as scattering, and characteristics of the local site response. Because our knowledge of the attenuation structure of subduction zones is sufficiently poor and the dependence of attenuation on path length is sufficiently weak, we assume that attenuation characteristics of the region where the empirical recording was made are similar to those of the simulation region. The site effect is represented empirically by using source functions recorded on the desired site conditions (rock or soil).

Green's functions are computed using generalized ray theory (Helmberger and Harkrider, 1978). The response is computed for a point source located at the center of each subfault with propagation through a layered medium. Contributions from the direct P and S waves and primary reflections from each layer interface beneath the source are included. Mode conversions, reverberations, and surface waves are not included. The Green's functions do not include the radiation pattern and receiver function because they are implicitly included in the corrected empirical source function. The Green's functions are thus the response of the medium for P, SV, and SH potentials described by the following equations:

$$\text{for } P,\ \Phi(t) = \frac{M_0}{4\pi^2\rho_0}\sqrt{\frac{2}{r}}\left[\frac{1}{\sqrt{t}} * \sum_{i=1}^{n} \mathrm{Im}\left(\frac{\sqrt{p}}{\eta_\alpha}\Pi(p)\frac{dp}{dt}\right)_i\right];$$

for SV,

$$\Omega(t) = \frac{M_0}{4\pi^2\rho_0}\sqrt{\frac{2}{r}}\left[\frac{1}{\sqrt{t}} * \sum_{i=1}^{n} \mathrm{Im}\left(\frac{\sqrt{p}}{\eta_\beta}\Pi(p)\frac{dp}{dt}\right)_i\right]; \qquad (8)$$

and for SH,

$$\chi(t) = \frac{M_0}{4\pi^2\rho_0}\sqrt{\frac{2}{r}}\left[\frac{1}{\sqrt{t}} * \sum_{i=1}^{n} \mathrm{Im}\left(\frac{\sqrt{p}}{\eta_c}\Pi(p)\frac{dp}{dt}\right)_i\right]$$

where $\eta_c = \sqrt{\left(\frac{1}{c}\right)^2 - p^2}$, c=α or β, and the quantity in brackets is evaluated over the Cagniard contour for each of the n rays. Three step responses (P, SV, and SH) are computed for each propagation path.

The radiation pattern is not included in the Green's function for two reasons. First, the empirical source functions are recorded at distances comparable to the aftershock's fault dimensions and thus already contain an averaged radiation pattern. Second, there is evidence that the coherence of the radiation pattern becomes weaker as periods become shorter than about 0.5 s (Liu and Helmberger, 1985) due to scattering and short-wavelength heterogeneity.

Each subfault begins to radiate energy when the rupture front reaches it. In order to avoid artificial periodicities due to the discretization of the fault surface and to introduce small irregularities in the velocity of rupture propagation, we include a stochastic variable in the rupture time of each subfault. As schematically illustrated in figure 156, the turn-on time t_0, is a random number taken from a Gaussian probability distribution centered about $(t_b - t_a)/2$, where t_a and t_b are the arrival and departure times of the rupture front, respectively. The probability that T_0 is between t_a and t_b was set at the three-standard-deviation level, or at a confidence level of 99.7 percent.

The form of the slip function at each point on the fault is a ramp described by the slip amplitude and the rise time (following Haskell, 1964). The slip function of the simulated earthquake is built up by summing *nsrc* empirical source functions as described above. A stochastic component is included in the slip function in order to avoid undesirable periodicity corresponding to the source function rise time and to simulate roughness in the slip function. Accordingly, in addition to lagging the source functions at integer multiples of the source function rise time T_e, a random perturbation is also included, as illustrated in figure 156. The probability that the initiation time ts_i of a given source function lies between t_i and t_{i+1} is also set at the 99.7 percent confidence level.

Implementation of the simulation procedure requires estimates of several source parameters, some of which (such as rupture dimensions) are known for the specific earthquake in question and others of which (such as rupture velocity) are assigned reasonable values. In principle, there are no free

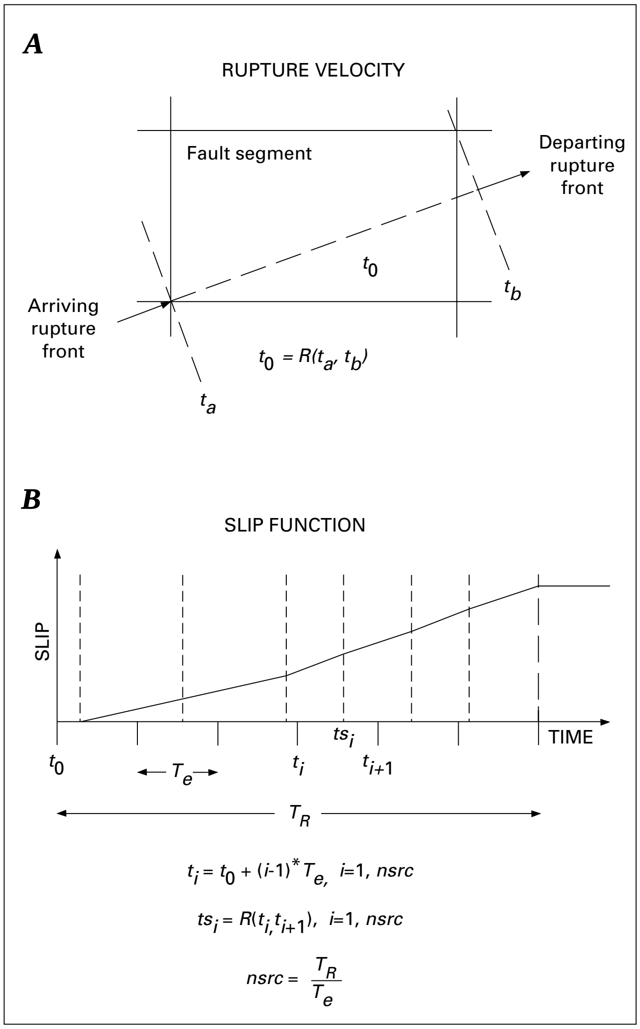

Figure 156. Schematic diagrams illustrating the random component of rupture velocity and the slip function. *A*, The rupture onset time for each fault element (t_0) is a random number (*R*) taken from a Gaussian distribution centered between arrival (t_a) and departure (t_b) times of the rupture front. *B*, The total number of source functions (*nsrc*) that are summed for each fault element is determined by ratio of rise time of the simulated event (T_R) to rise time of the empirical source function (T_e). Initiation time for each source function (ts_i) is a random number from a Gaussian distribution centered on evenly spaced intervals of T_e, shown in figure as dashed vertical lines.

parameters involved in the procedure. This was true for the Michoacán earthquake, where estimates of source parameters (including rise time) were available from other studies. There was no independent estimate of the rise time of the Valparaíso earthquake, so it was treated as a free parameter to be optimized.

To use predicted strong ground motions computed by the simulation procedure in engineering analyses, an estimate of their uncertainty is required that is analogous to that given for empirical ground-motion-prediction equations. The total uncertainty in the predicted strong ground motion should include all sources of uncertainty: modeling uncertainty (describing the adequacy of the simulation procedure in representing the processes that generate the strong ground motions), random uncertainty (describing earthquake-to-earthquake and station-to-station variability that is not accounted for in the source and wave-propagation models), and parametric uncertainty (describing uncertainty in the source parameters of future earthquakes).

A procedure for estimating these uncertainties was introduced by Abrahamson and others (1990). The modeling and random component of uncertainty is estimated from the misfit between recorded and simulated ground motions for the Michoacán and Valparaíso earthquakes. The contribution of parametric uncertainty to the misfit between recorded and simulated motions is assumed to be negligible if the gross fault parameters of the earthquakes are known. The parametric uncertainty is determined in the process of simulating ground motions. It is measured from the variability in the predicted ground motions caused by varying unknown earthquake source parameters. The overall uncertainty is obtained by combining the modeling and random uncertainty with the parametric uncertainty.

MODELING AND RANDOM UNCERTAINTY—SIMULATION OF MICHOACÁN AND VALPARAÍSO EARTHQUAKES

Before using the numerical model to simulate *M* 8 thrust earthquakes in the Cascadia subduction zone, we tested the method against recorded strong ground motions of the *M* 8 Michoacán and Valparaíso subduction-zone earthquakes. Recordings of *M* 7 aftershocks of both earthquakes, corrected for wave propagation, were used as the empirical source functions. We discovered that slip amplitude distribution models derived from near-source and teleseismic velocity seismograms by Mendoza and Hartzell (1988) for the Michoacán earthquake and Houston (1987) for the Valparaíso earthquake are for the most part consistent with the higher frequency motions of the near-source accelerations.

The five near-source recordings of the Michoacán earthquake (fig. 157) are from rock sites. The station-to-station accelerogram variability observed for this earthquake is mostly reproduced in the simulated accelerograms, reflecting the influence of the heterogeneous slip distribution and the southeasterly direction of rupture propagation. These simulations use the Caleta de Campos source function and show good agreement with the recorded duration, frequency content, and peak acceleration. Not surprisingly, simulations using a constant slip model do not produce the two large-amplitude wave packets most obvious on the La Villita accelerogram (at 15 s and 40 s), but these are produced by two asperities in the Mendoza and Hartzell (1988) slip model. A

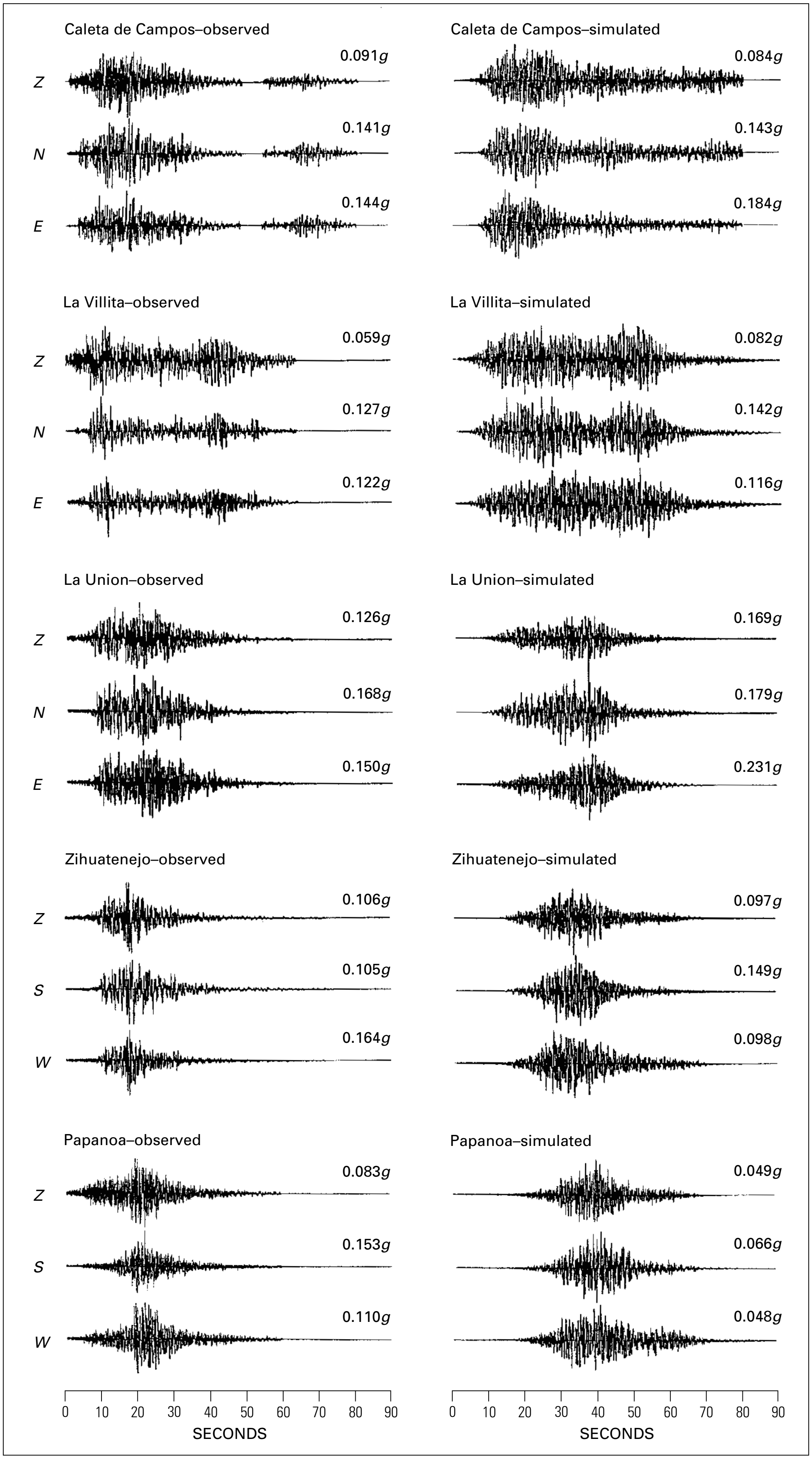

Figure 157. Comparison of recorded and simulated three-component acceleration time series for the September 19, 1985, Michoacán earthquake at rock sites Caleta de Campos, La Villita, La Union, Zihuatanejo, and Papanoa, Mexico. The peak accelerations are expressed as a fraction of acceleration due to gravity (*g*). Note good agreement in peak acceleration and duration between observed and simulated accelerograms. The three components of motion are labeled *Z* for vertical, *N* or *S* for north-south horizontal, and *E* or *W* for east-west horizontal.

uniform slip model yields longer duration accelerograms with lower peak amplitudes. A comparison of the recorded and simulated response spectra, averaged over the five rock-site stations, shows good agreement over the 0.1–3 s period (fig. 158*A*).

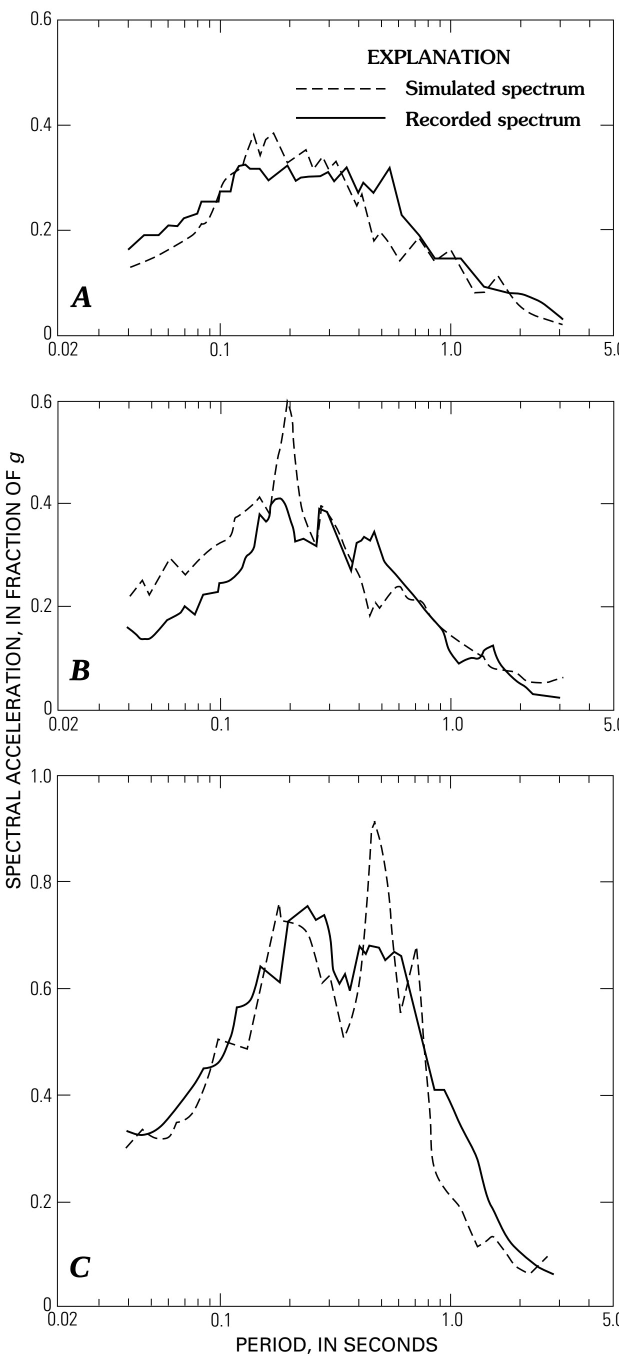

Figure 158. Comparison of recorded and simulated acceleration response spectra at 5-percent damping for *A*, the 1985 Michoacán earthquake at five rock sites in coastal Mexico (averaged values); *B*, the 1985 Valparaíso earthquake at the one rock site in Chile; and *C*, the 1985 Valparaíso earthquake at five soil sites in Chile (averaged values).

In contrast with the Michoacán earthquake, the Valparaíso earthquake was mostly recorded on soil sites. The mean soil-site amplitudes are about twice those of the one rock site. This is seen in the recorded spectral acceleration for the rock site, shown in figure 158*B*, and the mean of the five soil sites, shown in figure 158*C*. The simulated seismograms are generated using a rock-site source function for the one rock site and a soil-site source function for the five soil sites. The peak at 0.2 s in the simulated spectrum of figure 158*B* is due to a peak in the rock-site source spectrum at the same period. The peak in the spectrum at 0.5 s in figure 158*C* is also due to a peak in the soil-site source spectrum at the same period. As before, a uniform slip model produces accelerograms with longer durations and lower peak amplitudes than those in the recorded data.

The misfit between recorded and simulated response spectra is used as an estimate of the modeling and random uncertainty. The response spectra of the simulated motions have little or no significant bias in the period range of 0.05–2 s for either earthquake, and the peak acceleration, duration, and envelope shape of the acceleration seismograms are in good agreement with the recorded seismograms. We found that rock-site source functions recorded in Mexico or Chile could be used interchangeably with comparable uncertainty—the uncertainty was not appreciably different when a source function from one subduction zone was used to simulate ground motions in the other subduction zone. The standard error associated with the use of each empirical source function, expressed as the natural logarithm of the spectral acceleration, is shown in figure 159. More details about the

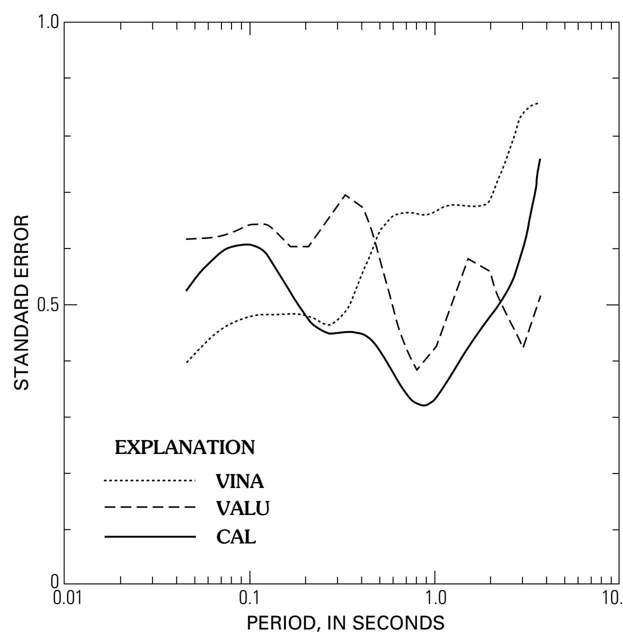

Figure 159. Estimates of the standard error (natural logarithm of spectral acceleration) in the simulation procedure that is associated with using each of the three empirical source functions, two from rock sites (VALU in Chile, CAL in Mexico) and one from a soil site (VINA in Chile).

modeling of the Michoacán and Valparaíso strong ground motions and the windowed time series, response spectra, and model bias for each of the empirical source functions is given by Somerville and others (1991).

PREDICTION OF GROUND MOTIONS FOR WESTERN WASHINGTON AND OREGON

The simulation procedure was used to predict strong ground motions from hypothesized *M* 8 thrust earthquakes on the Cascadia subduction zone. Plausible fault models for the western Washington and Oregon regions and also seismic-velocity models were adapted from published regional studies (fig. 160). The surface projections of the two fault geometries, subdivided into subfault elements, are shown in figure 160*A*. A cross section perpendicular to the strike of the western Washington geometry shows the plate interface dipping at 11°(fig. 160*B*). The fault surfaces that ruptured in the Michoacán and Valparaíso earthquakes are superimposed on the cross section. The western Washington model has a dip similar to the 14° dip of the Michoacán fault plane, and the Oregon model has a dip of 21°, similar to the Valparaíso fault plane (25°). The western Washington and Oregon fault models have different downdip widths, fault lengths, and depths to the top of the fault (17 km and 13 km, respectively).

The actual plate interface is not imaged well because it has been historically aseismic. Instead, the geometry of the plate interface is inferred from refraction profiles (Taber and Lewis, 1986) and the inclined zone of hypocenters within the shallow part of the downgoing Juan de Fuca plate. The most critical source parameter influencing the ground motions for line **f** (fig. 160*A*), which includes the most heavily urbanized regions in the study area, is the depth extent of rupture. There is general agreement that the downgoing Juan de Fuca plate is arched at depth beneath Puget Sound, as shown by the 54-km-depth contour in figure 160*A* (Crosson and Owens, 1987; Weaver and Baker, 1988). To infer the plate interface at shallower depth, we used the model of Weaver and Baker (1988) that is based on hypocentral locations within the downgoing slab. In their model, the 40-km-depth contour is not arched. If we assume this seismicity is confined beneath the oceanic Moho, then the 40-km-depth contour, inferred to be the easternmost edge of the rupture surface, lies about 50 km west of Seattle (fig. 160). However, Crosson and Owens (1987) prefer an interpretation where the shallow plate interface is also arched. Using their interpretation places the eastern extent of the fault beneath Puget Sound. The ground motion estimates that result from using the Crosson and Owens (1987) model may be approximated by simply shifting the station grid (described below) 50 km to the east.

A two-dimensional velocity profile across the subduction zone, adapted from Spence and others (1985), is shown in figure 161. To compute the ray-theory Green's functions, we approximate this two-dimensional model with a different layered model for each subfault depth. These one-dimensional models have an oceanic Moho 6 km below the source. The adequacy of approximating the more realistic two-dimensional model with a series of one-dimensional models was tested by comparing ray-theory seismograms computed in the layered models with finite-difference seismograms for the two-dimensional model. In both calculations, which are shown in figure 162, the largest phases are the direct *S*-wave and the *S*-wave critically reflected from the oceanic Moho of the subducting plate (*SmS*). The ray-theory approximation does an adequate job of reproducing the seismic response of the Spence and others (1985) model in the passband of interest.

Although the dip of the western Oregon fault model is about twice that of the western Washington model, the ground motions for the two regions are very similar. Given the assumed location of the potential rupture surface, the largest cause of uncertainty in the predicted ground motions is due to uncertainty in the distribution of slip amplitude with depth on the plate interface. We performed simulations for three generalized asperity models in which 60 percent of the total moment is released in the upper, middle, and lower third of the fault (termed the shallow, middle, and deep slip models). The size and strength of the asperities and their distribution along strike are similar to the pattern of slip amplitude variation in the Michoacán and Valparaíso earthquakes.

Ground-motion simulations are computed at the points shown as open squares on the grid in figure 160*A*. The grid is made up of seven lines, labeled **a–g**, parallel to the strike of the fault and 20 km apart. The dependence of the predicted ground motions on the asperity depth is shown in figure 163 for the Washington geometry and in figure 164 for the Oregon geometry. These accelerograms are from an east-west profile of stations that intersect the surface projection of the fault near the maximum slip amplitude and are representative of maximum ground motions that could be used in a deterministic hazard analysis. As the asperities become deeper, the portion of the fault radiating the strongest energy becomes closer to the station grid, causing larger accelerations. With increasing asperity depth, the attenuation of peak acceleration with distance becomes more gradual. The variability of peak ground acceleration across rows **a–g** of the Oregon grid is shown in figure 165.

The attenuation of peak acceleration can be described by the equation

$$\ln(\mathrm{PGA})=a+b\ln(r+c)+d\gamma \quad (9)$$

where r is the distance to the nearest asperity in kilometers, PGA is the maximum horizontal acceleration (in fraction of g), and γ is the site term (1 for soil and 0 for rock). The least-squares solution, averaged over the two fault geometries and

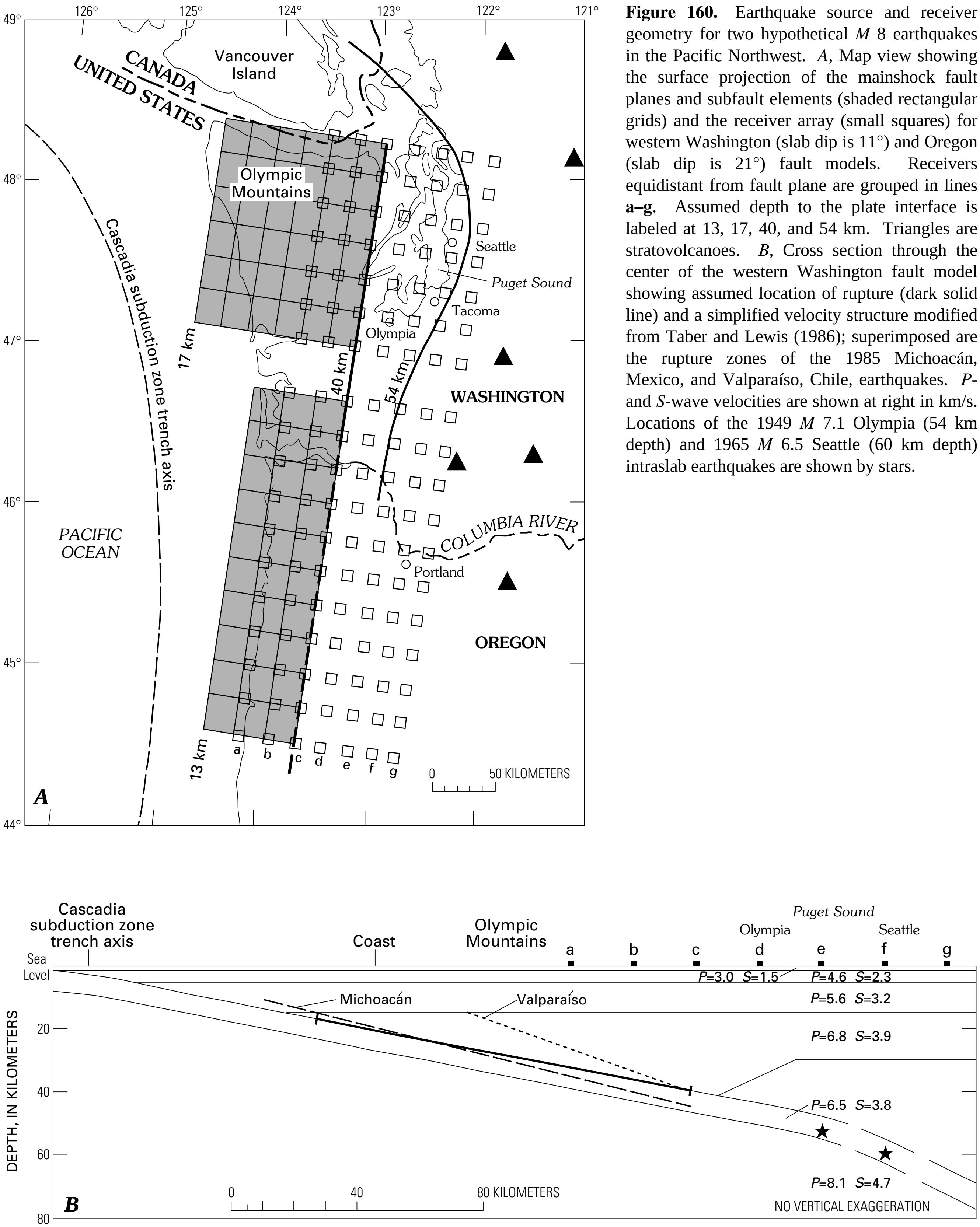

Figure 160. Earthquake source and receiver geometry for two hypothetical *M* 8 earthquakes in the Pacific Northwest. *A*, Map view showing the surface projection of the mainshock fault planes and subfault elements (shaded rectangular grids) and the receiver array (small squares) for western Washington (slab dip is 11°) and Oregon (slab dip is 21°) fault models. Receivers equidistant from fault plane are grouped in lines **a–g**. Assumed depth to the plate interface is labeled at 13, 17, 40, and 54 km. Triangles are stratovolcanoes. *B*, Cross section through the center of the western Washington fault model showing assumed location of rupture (dark solid line) and a simplified velocity structure modified from Taber and Lewis (1986); superimposed are the rupture zones of the 1985 Michoacán, Mexico, and Valparaíso, Chile, earthquakes. *P*- and *S*-wave velocities are shown at right in km/s. Locations of the 1949 *M* 7.1 Olympia (54 km depth) and 1965 *M* 6.5 Seattle (60 km depth) intraslab earthquakes are shown by stars.

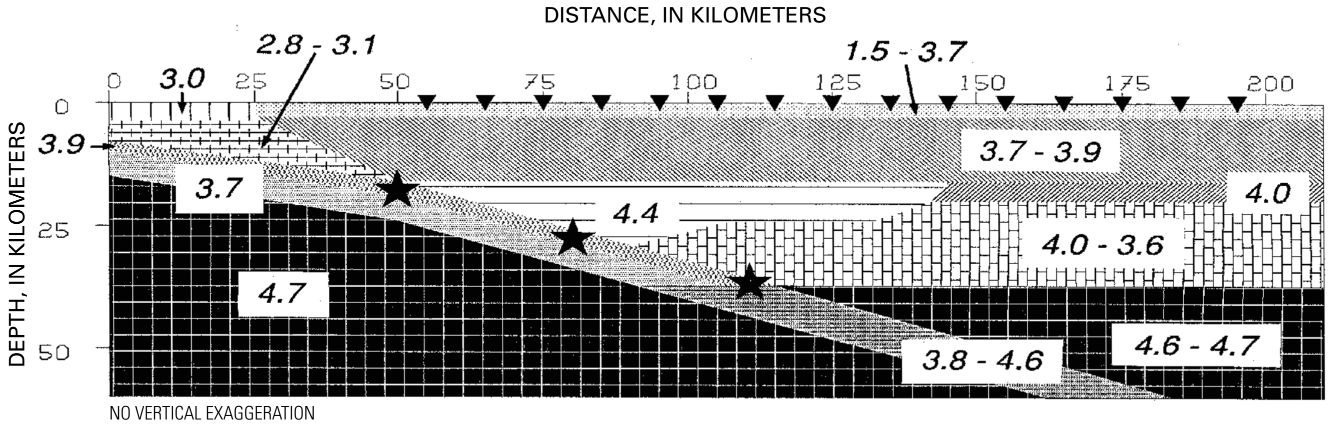

Figure 161. Generalized east-west velocity model of Cascadia subduction zone (adopted from Spence and others, 1985) used in finite-difference computations for the three seismic source locations at 18, 27, and 36 km depth (stars). The diagonal polygons represent the down-going slab of the Juan de Fuca plate. Numbers in italics are *S*-wave velocities for each polygon, in km/s. Receiver locations are shown by inverted triangles.

the three slip models, yields a=15.6, b=–3.34, c=128, and d=0.79, with a standard error of 0.32 (natural logarithm of the peak acceleration). All parameters are significant at the 95-percent confidence level. This relation is appropriate for r greater than 25 km but less than 175 km and for M_w 8. Combining the modeling and random standard error (0.51) derived from the fit to the Michoacán and Valparaíso earthquakes with the parametric uncertainty (0.32) yields a total standard error of 0.60.

It is difficult to use an attenuation relation when the distance is measured to the nearest asperity because it is impossible to anticipate the distribution of moment release on the fault surface. The closest distance to the fault is a more useful distance measure although it is accompanied by greater uncertainty in predicting the ground motion. A regression using the same functional form yields a=2.8, b=–1.26, c=0, and d=0.79, with a standard error of 0.40. The increase in the standard error from 0.32 to 0.40 reflects the increased variability in the ground-motion amplitude due to variability in the depth of slip. In this case, the total standard error is 0.65. This result is appropriate for r greater than 30 km but less than 100 km and for M_w 8. We do not present results for shorter distances because the fault is shallow only in the offshore region. At distances less than 30 km, the slope of the attenuation relation would likely decrease, as suggested by the trend of peak acceleration for r less than 40 km in figure 166.

The median values of the three asperity models are compared with an empirical attenuation relation (based on average properties of global recordings of subduction earthquakes) in figure 166. Youngs and others (1988) and Washington Public Power Supply System (1988) present attenuation relations for rock and soil sites, respectively. The separation between the empirical rock and soil curves is in close agreement with the site term ($e^{0.79}$) in our attenuation relations (soil-site accelerations are 2.2 times larger than rock-site accelerations), but the slopes of the attenuation relations are different. Our predicted PGA values at close distance (30–40 km) are larger than the empirical result, and the decay of PGA with distance is more rapid in the numerical simulations. The western Oregon fault model has slightly larger motions than the western Washington model for a given value of closest distance to the fault. This small difference is due to the steeper dip and narrower fault width of the Oregon geometry, which brings more of the fault closer to a surface site.

Figure 167 shows smoothed, median, 5-percent damped, pseudospectral-velocity (PSV) curves for the Washington and Oregon fault models. These results are averages of separate simulations using the three slip models and the two rock-site source functions for each line of stations (**a–g**) shown in figure 160*A*. We estimate the uncertainty in the response spectral estimates using the procedure outlined by Abrahamson and others (1990). An estimate of parametric uncertainty is derived from the ground-motion variability due to differences in the slip model and the position of each site relative to the asperities. The modeling and random uncertainty is derived from the misfit between recorded and simulated motions of the Michoacán and Valparaíso earthquakes, which is summarized in figure 159. The overall uncertainty, which combines the two estimates, is used to determine the 84th-percentile response spectra shown in figure 167. The median and 84th-percentile values are listed in tables 24 and 25.

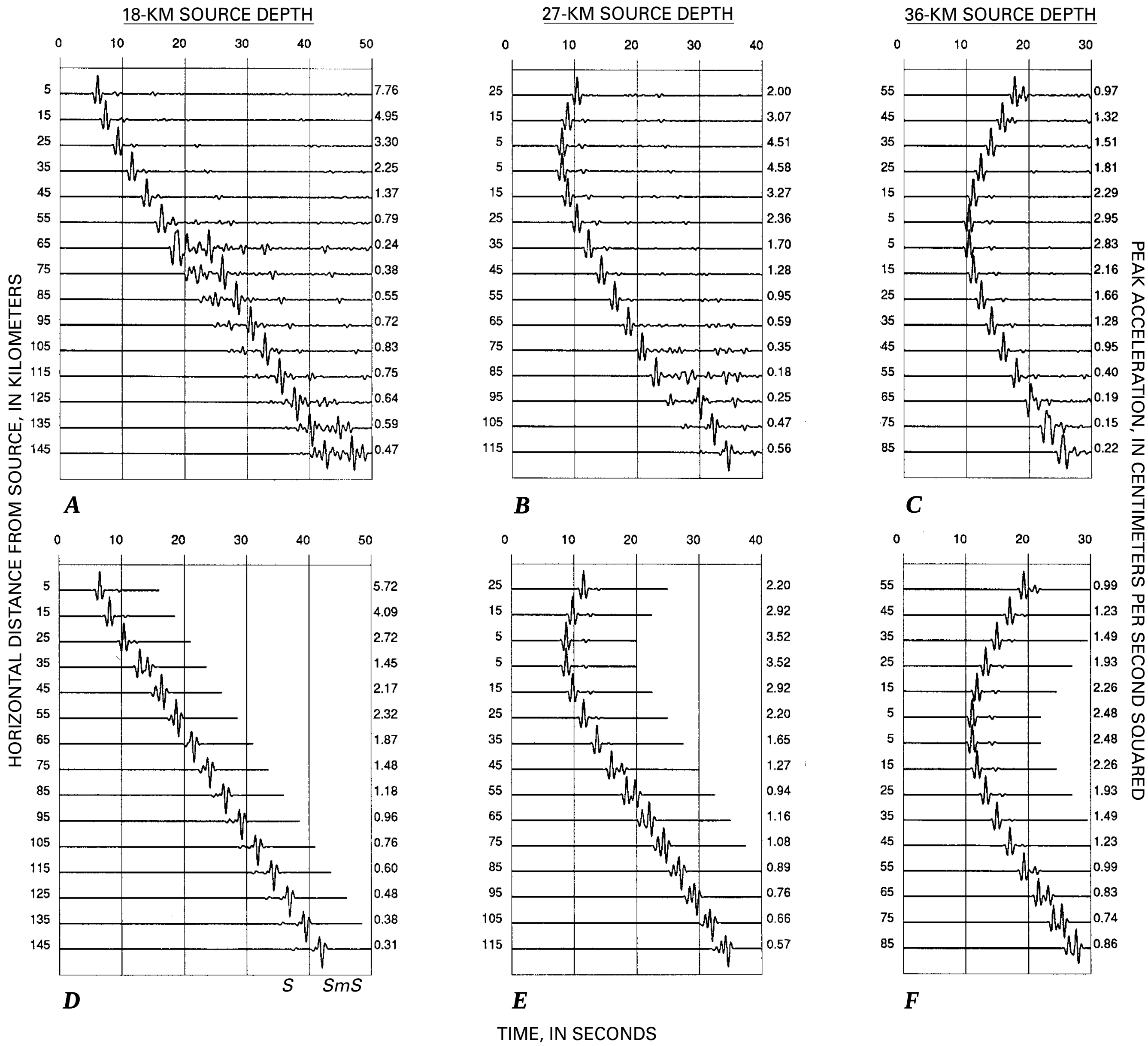

Figure 162. Comparison between two-dimensional finite-difference (*A–C*) and one-dimensional ray-theory (*D–F*) theoretical seismograms for the 15 receiver locations and 3 sources shown in figure 161; source depths are 18 km (*A* and *D*), 27 km (*B* and *E*), and 36 km (*C* and *F*). The finite-difference seismograms are for the velocity model shown in figure 161, and the ray-theory seismograms are for the simplified velocity model shown in figure 160*B*. Note increase in the Moho-reflected *S* (*SmS*) amplitude as the wave field turns postcritical. The finite-difference seismograms contain greater complexity, but amplitude and timing of the *S* and *SmS* arrivals are similar using either method.

In figure 168*A*, we compare the simulated soil-site response spectrum with estimates from two empirical studies. The first was derived by Crouse and others (1988) using regression methods (30-km source depth, 120 km to the center of energy release). The second was derived by Heaton and Hartzell (1989) from averages of strong-motion recordings from *M* 7.6–8.2 subduction earthquakes in the two epicentral-distance ranges of 50–100 km and 100–150 km. The simulated estimates are for the shallow slip model, the deep slip model, and the log mean of the three asperity models from Washington line **f** (fig. 160*A*), which includes Seattle. For this comparison, we use a soil-site source function. The empirical estimates span the range between the estimates for the average and shallow asperity models obtained from numerical modeling. We cannot predict motions at periods longer than 1 s for soil sites without information about the site-response and modeling of long-period wave propagation in realistic three-dimensional velocity structures.

Strong-motion recordings were made of two Benioff-zone earthquakes in 1949 and 1965. The locations of these

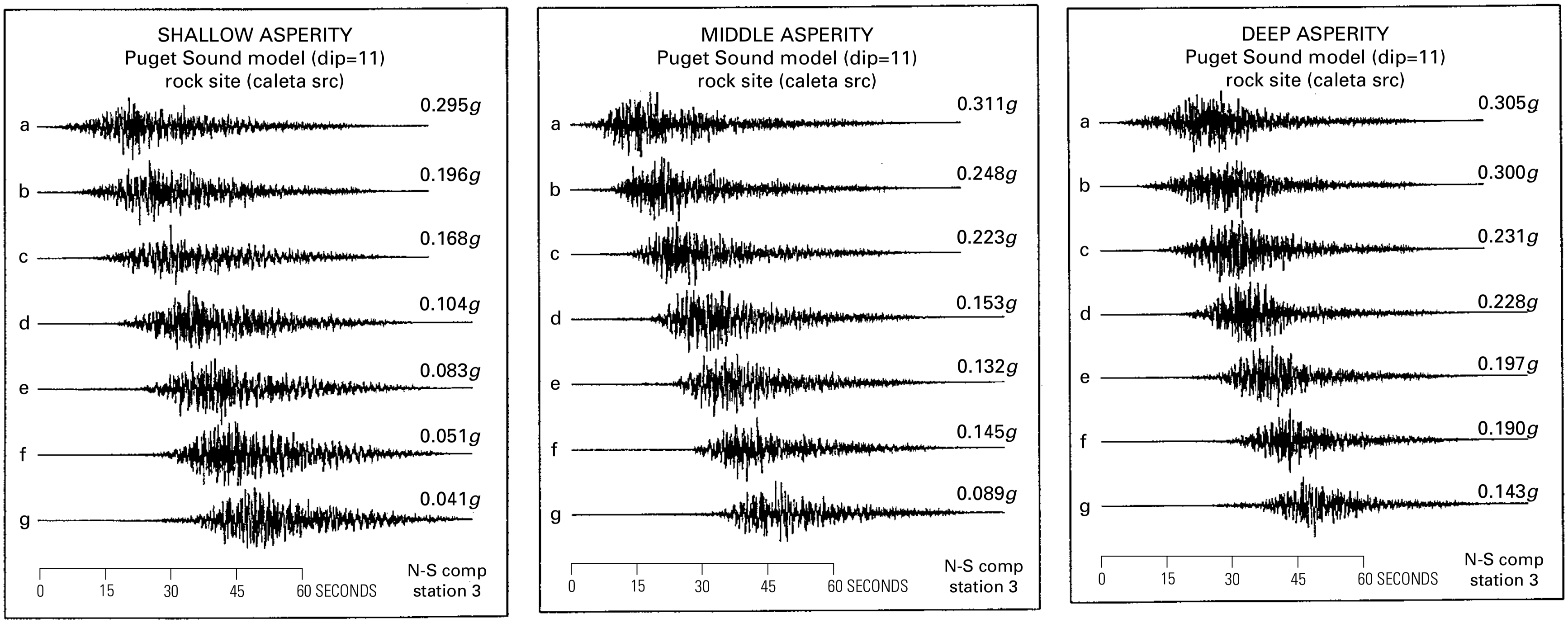

Figure 163. Horizontal acceleration seismograms for shallow, middle, and deep slip distributions using the western Washington fault model and a rock-site empirical source function. The seismograms are from receivers in lines **a–g** shown in figure 160*A*. In this example, the receivers are in close proximity to the areas of greatest slip amplitude on the fault and, thus, the waveforms are characteristic of the largest amplitudes predicted for rock sites in Washington. Numbers to right are peak accelerations, in fraction of *g*.

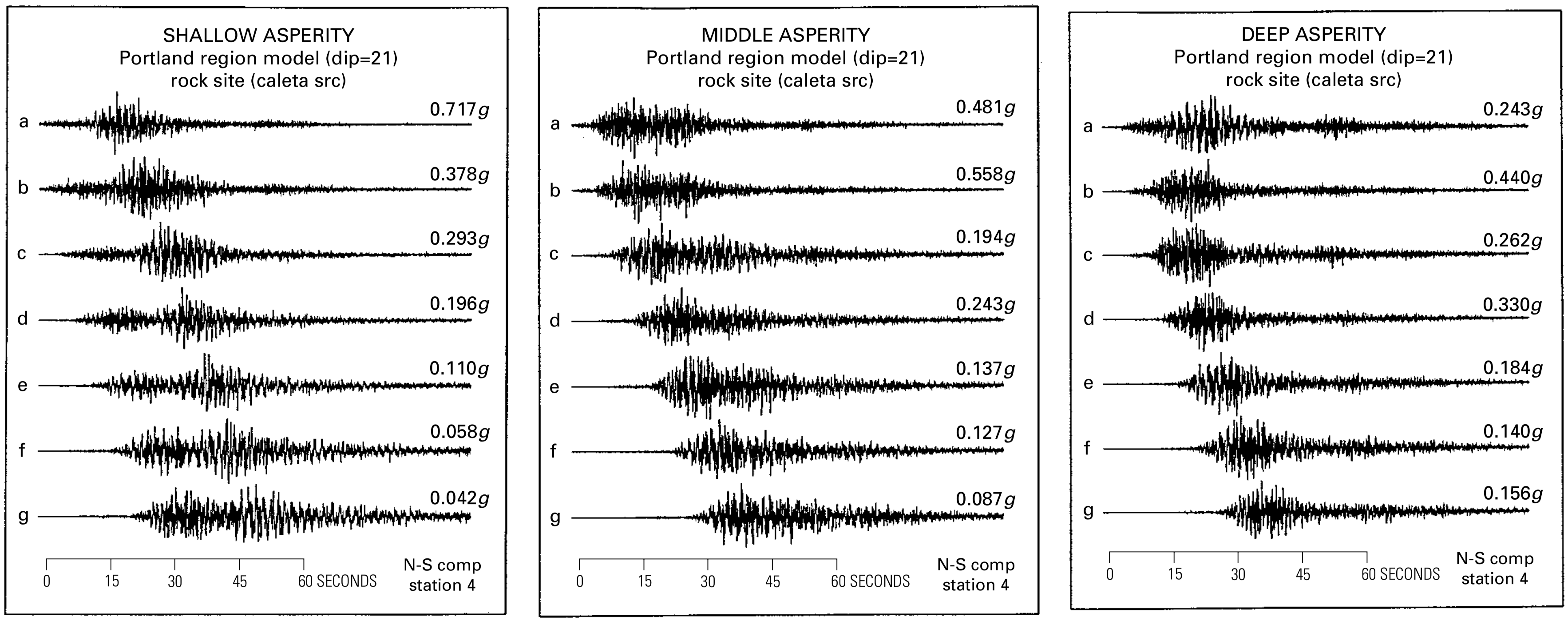

Figure 164. Example horizontal accelerograms for shallow, middle, and deep slip distributions using the western Oregon fault model and a rock-site empirical source function. The seismograms are from receivers in lines **a–g** shown in figure 160*A*. The receivers are in close proximity to the areas of greatest slip on the fault and, therefore, the waveforms are characteristic of the largest amplitudes predicted for rock sites in Oregon. Numbers to right are peak accelerations, in fraction of *g*.

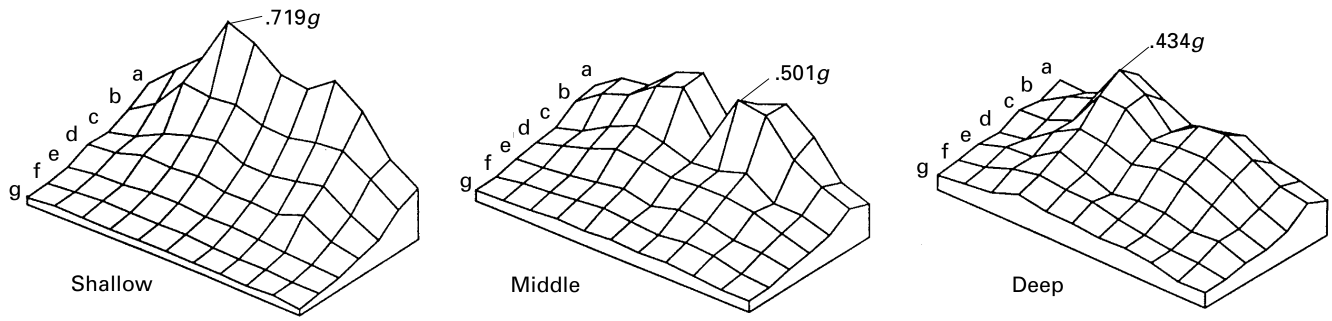

Figure 165. Mean horizontal peak acceleration for each receiver location in the Oregon fault model for shallow, middle, and deep slip-distribution models. The lines represent receiver lines **a–g** shown in figure 160*A*. The widest range of peak accelerations is produced using the shallow model, when slip is concentrated in top third of fault plane. The deep slip model produces more uniform amplitudes across the receiver array. Accelerations (in fraction of *g*) are plotted on a common scale.

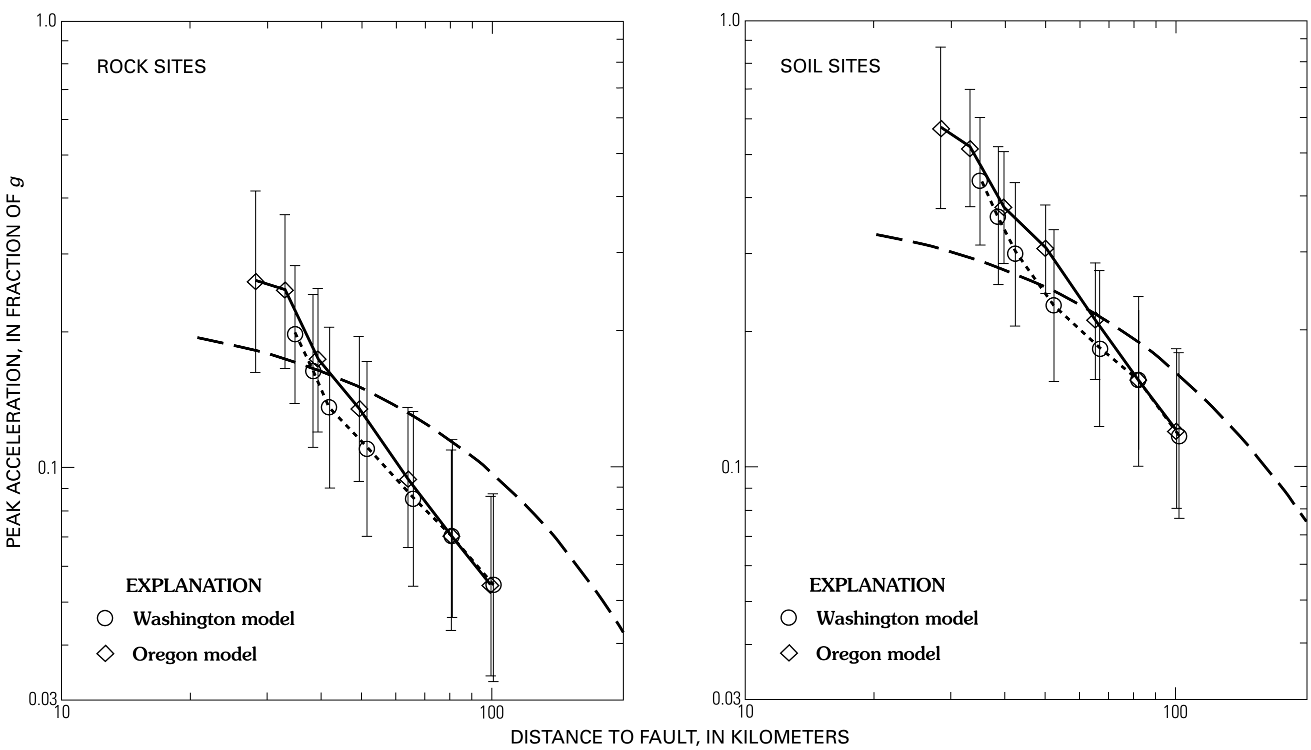

Figure 166. Comparison of peak horizontal acceleration (PGA) attenuation relations derived in this study with relations derived for, left, rock sites (long-dashed line, data from Youngs and others, 1988) and right, soil sites (long-dashed line, data from Washington Public Power Supply System, 1988) in the Pacific Northwest. Circles, logarithmic mean PGA values for western Washington model; diamonds, logarithmic mean PGA values for Oregon fault model. Standard deviation of the mean is less than 5 percent. Standard deviation of each population shown by the vertical error bars.

earthquakes are shown by stars in the cross section of the subduction zone in figure 160*B*. They occurred within the lower part of the subducting Juan de Fuca plate beneath the cities of Seattle and Tacoma at depths greater than the downdip limit of rupture (40 km) in our fault models. Their recorded motions are compared with the simulated motions for a *M* 8 earthquake in figure 168*B*. The averaged PSV response of 10 horizontal recordings from the two earthquakes were derived from Seattle and Olympia records for April 13, 1949 (*M* 6.5), and Seattle, Tacoma, and Olympia records for April 29, 1965 (*M* 7.1). The simulated PSV curve is the mean for the three locations weighted appropriately using a soil-site source function. For periods less than 1 s, the estimated response

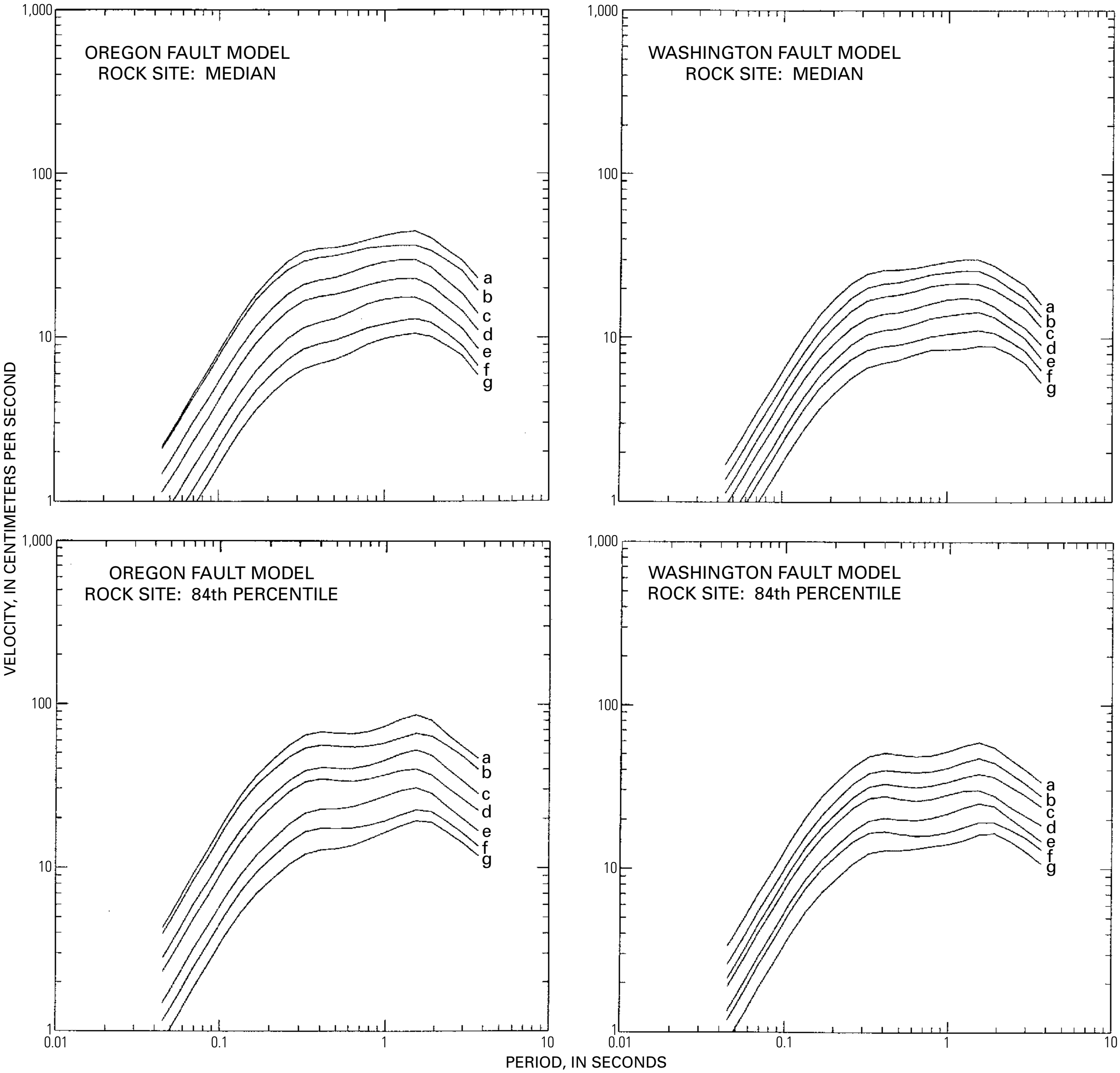

Figure 167. Median and 84th-percentile pseudovelocity response spectra (at 5-percent damping) for each line of stations (**a–g**) shown in figure 160*A*.

spectral velocities in the Seattle-Olympia region are about twice those recorded during the 1949 and 1965 earthquakes, and the durations of strong motion are significantly longer (45–60 s versus 10–15 s).

CONCLUSIONS

Slip-distribution models of the Michoacán and Valparaíso earthquakes derived from near-source and teleseismic velocity seismograms are generally consistent with the higher frequency motions of recorded accelerograms. Simulated ground motions show close agreement in the overall duration of strong motion, the frequency content, and the peak accelerations of the recorded motions. Measurements of the misfit between the simulated and recorded response spectra are used to estimate modeling and random uncertainty in the simulation procedure.

Determining the depth extent of rupture on the plate interface is the most critical geometrical source parameter influencing ground motions, as this extent controls the

Table 24. Spectral velocities at rock sites from a simulated *M* 8 Cascadia subduction-zone earthquake in the western Washington fault model.

[Velocities are in centimeters per second]

	Period (seconds)	Velocity at specified line of receivers in model array[1] Line a	Line b	Line c	Line d	Line e	Line f	Line g
Median	0.030	0.93	0.77	0.64	0.52	0.40	0.33	0.25
	.045	1.69	1.37	1.13	.93	.71	.59	.45
	.056	2.40	1.95	1.61	1.34	1.01	.85	.65
	.069	3.43	2.79	2.31	1.91	1.45	1.23	.93
	.087	4.90	3.99	3.33	2.73	2.09	1.77	1.34
	.108	7.08	5.73	4.83	3.91	3.03	2.56	1.94
	.135	10.14	8.14	6.89	5.53	4.33	3.65	2.74
	.168	13.85	11.08	9.30	7.45	5.84	4.90	3.68
	.210	17.72	14.29	11.90	9.46	7.44	6.17	4.65
	.261	21.51	17.56	14.64	11.50	9.10	7.41	5.67
	.326	24.58	20.20	16.90	13.20	10.50	8.43	6.56
	.407	25.90	21.39	17.92	14.00	11.15	8.89	7.02
	.507	26.05	21.92	18.35	14.36	11.47	9.09	7.33
	.632	26.66	23.01	19.33	15.17	12.23	9.58	7.91
	.789	27.93	24.32	20.65	16.30	13.18	10.22	8.44
	.984	29.09	25.12	21.36	17.15	13.73	10.56	8.51
	1.227	30.11	25.80	21.56	17.59	14.14	10.87	8.57
	1.530	30.20	25.76	21.37	17.31	14.43	11.21	8.94
	1.908	27.68	23.44	19.76	15.64	13.52	10.78	8.90
	2.380	24.00	20.21	17.26	13.29	11.64	9.61	8.07
	2.968	20.98	17.59	15.13	11.56	9.95	8.36	7.02
	3.701	16.16	13.58	11.73	9.13	7.56	6.37	5.35
84th percentile	.030	1.73	1.46	1.22	1.01	.78	.67	.51
	.045	3.36	2.59	2.13	1.90	1.36	1.19	.87
	.056	4.87	3.78	3.12	2.78	1.99	1.75	1.27
	.069	7.03	5.48	4.56	4.05	2.90	2.57	1.86
	.087	10.15	7.93	6.66	5.87	4.25	3.76	2.71
	.108	14.72	11.45	9.73	8.48	6.21	5.46	3.93
	.135	20.77	16.03	13.66	11.85	8.72	7.65	5.49
	.168	27.37	21.04	17.79	15.48	11.33	9.93	7.13
	.210	34.17	26.55	22.14	19.25	14.00	12.20	8.83
	.261	41.57	32.75	27.14	23.34	16.99	14.60	10.75
	.326	48.12	37.88	31.37	26.68	19.57	16.53	12.42
	.407	50.56	39.60	32.69	27.52	20.37	16.91	13.02
	.507	49.29	38.93	31.83	26.54	19.90	16.26	12.99
	.632	48.19	38.49	31.25	25.92	19.79	15.88	13.27
	.789	49.03	39.09	31.99	26.61	20.45	16.11	13.78
	.984	51.75	41.02	33.71	28.23	21.64	16.74	14.15
	1.227	56.18	44.54	35.98	29.75	23.43	17.89	14.90
	1.530	59.08	47.02	37.72	30.00	25.05	19.25	16.23
	1.908	54.91	44.14	36.04	27.69	23.96	19.16	16.50
	2.380	46.41	37.97	31.57	23.68	20.31	17.33	14.81
	2.968	39.83	32.84	27.82	20.96	17.33	15.46	12.82
	3.701	33.42	27.63	23.78	18.47	14.76	13.11	10.74

[1]See figure 160*A* for location of model and orientation of receiver array.

closest approach of the rupture surface to urban districts in the Puget Sound area. We use the model of Weaver and Baker (1988), which places the 40-km depth contour on the plate interface (inferred to be the easternmost edge of the rupture surface) 50 km west of Puget Sound. An alternative model proposed by Crosson and Owens (1987) places the eastern margin of the rupture surface directly beneath Puget Sound and produces larger ground motions in the Puget Sound area.

Given the assumed location of the rupture surface, the largest cause of uncertainty in the estimated motions is due to the distribution of slip amplitude with depth on the fault surface. As the large slip moves deeper, it approaches the urban areas of Puget Sound and Portland, causing larger

Table 25. Spectral velocities at rock sites from a simulated *M* 8 Cascadia subduction-zone earthquake in the western Oregon fault model.

[Velocities are in centimeters per second]

	Period (seconds)	Velocity at specified line of receivers in model array[1] Line a	Line b	Line c	Line d	Line e	Line f	Line g
Median	0.030	1.22	1.16	0.81	0.63	0.44	0.33	0.26
	.045	2.15	2.09	1.47	1.14	.78	.58	.45
	.056	3.08	2.97	2.10	1.60	1.11	.82	.64
	.069	4.43	4.23	3.00	2.27	1.58	1.16	.91
	.087	6.38	6.05	4.26	3.26	2.26	1.68	1.30
	.108	9.30	8.75	6.10	4.72	3.24	2.44	1.88
	.135	13.40	12.51	8.65	6.76	4.60	3.49	2.67
	.168	18.33	16.94	11.72	9.23	6.23	4.71	3.61
	.210	23.58	21.43	15.02	11.83	8.01	5.99	4.57
	.261	28.86	25.65	18.29	14.45	9.87	7.32	5.54
	.326	33.04	28.95	20.93	16.62	11.47	8.48	6.40
	.407	34.63	30.52	22.27	17.67	12.36	9.14	6.92
	.507	35.06	31.37	23.13	18.21	13.05	9.61	7.30
	.632	36.55	32.96	24.80	19.30	14.36	10.44	8.06
	.789	39.07	34.78	27.02	20.78	15.97	11.41	9.07
	.984	41.43	35.69	28.57	21.91	16.97	12.04	9.81
	1.227	43.53	36.32	29.60	22.79	17.49	12.58	10.29
	1.530	44.21	36.37	29.72	22.87	17.49	13.01	10.59
	1.908	40.32	33.67	26.74	20.62	15.89	12.30	10.09
	2.380	34.10	29.33	22.07	17.19	13.39	10.57	8.89
	2.968	29.36	25.43	18.42	14.52	11.31	8.89	7.70
	3.701	22.79	19.26	13.95	11.06	8.52	6.68	5.85
84th percentile	.030	2.44	2.21	1.53	1.19	.83	.64	.51
	.045	4.31	3.95	2.80	2.32	1.50	1.16	.86
	.056	6.28	5.75	4.09	3.34	2.18	1.67	1.26
	.069	9.13	8.33	5.93	4.82	3.16	2.42	1.83
	.087	13.30	12.07	8.53	7.00	4.58	3.53	2.65
	.108	19.48	17.53	12.25	10.20	6.60	5.16	3.85
	.135	27.69	24.63	17.12	14.43	9.20	7.26	5.40
	.168	36.62	32.08	22.37	19.05	11.99	9.46	7.04
	.210	45.94	39.58	27.85	23.82	14.98	11.72	8.69
	.261	56.19	47.40	33.84	28.93	18.37	14.26	10.48
	.326	64.88	53.82	38.90	33.17	21.39	16.49	12.09
	.407	67.68	56.05	40.79	34.52	22.66	17.37	12.86
	.507	66.28	55.30	40.33	33.76	22.79	17.25	13.04
	.632	65.73	54.67	40.30	33.43	23.48	17.43	13.66
	.789	68.12	55.38	41.99	34.60	25.14	18.13	14.91
	.984	73.31	57.74	45.13	36.63	27.13	19.19	16.34
	1.227	80.93	62.26	49.39	38.96	29.27	20.80	17.88
	1.530	86.11	66.41	52.29	39.90	30.54	22.44	19.26
	1.908	79.64	63.96	48.56	36.63	28.31	21.91	18.84
	2.380	65.44	55.66	40.19	30.58	23.57	19.02	16.47
	2.968	54.94	47.95	33.68	26.15	19.89	16.24	14.17
	3.701	46.37	39.60	28.03	22.19	16.70	13.55	11.85

[1]See figure 160*A* for location of model and orientation of receiver array.

ground motions. Deeper slip models produce more gradual attenuation of peak acceleration with distance. The dip of the western Oregon fault model is about twice that of the western Washington model, but the predicted ground motions for the two regions are not very different.

Quantifying the uncertainty allows ground-motion estimates to be used in probabilistic seismic-hazard calculations. An estimate of the parametric uncertainty is derived from the variability in the ground motions due to differences in the position of a station along fault strike and in the along-strike

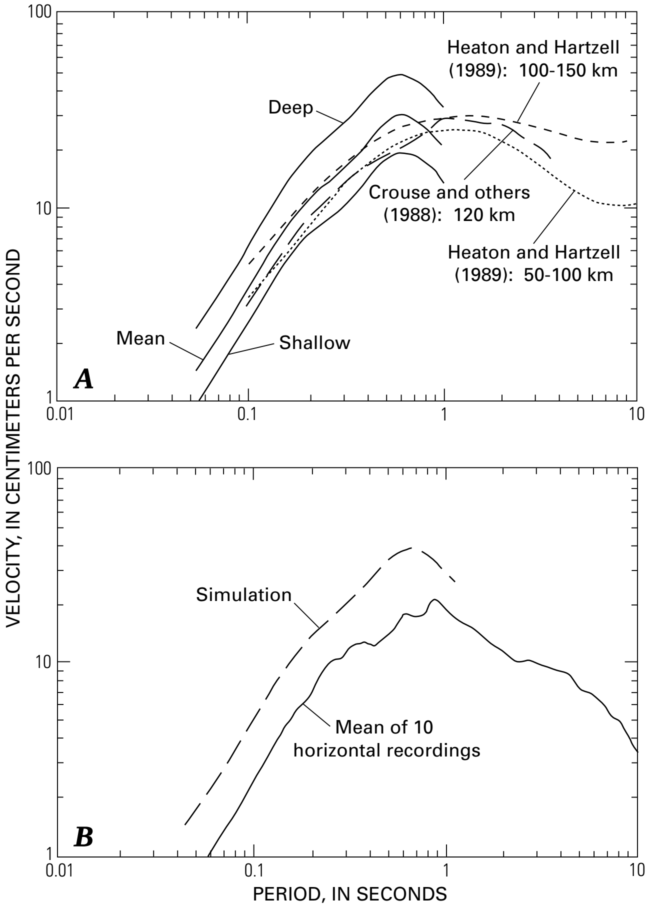

Figure 168. *A*, Comparison of simulated horizontal response spectra for *M* 8 subduction earthquakes at soil sites in Seattle with estimates derived from globally recorded data. The three simulated results (solid lines) are obtained using three different slip models (shallow, deep, and the log mean of shallow, middle, and deep results). The empirical estimates from two studies (dashed and dotted lines, labeled with the epicentral-distance ranges) are obtained from recordings of *M* ~ 8 subduction earthquakes. *B*, Comparison of simulated horizontal response spectra for soil sites in Seattle-Olympia region for a *M* 8 earthquake with mean of 10 horizontal components recorded in Seattle, Tacoma, and Olympia during the 1949 (*M* 7.1) and 1965 (*M* 6.5) earthquakes.

and downdip location of slip on the fault. An estimate of modeling and random uncertainty is derived from the misfit between recorded and simulated motions of the Michoacán and Valparaíso earthquakes. The total uncertainty is represented by the 84th-percentile response spectra.

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EARTHQUAKE GROUND-RESPONSE STUDIES IN WEST AND SOUTH SEATTLE, WASHINGTON

By David L. Carver,[1] Kenneth W. King,[1] Robert A. Williams,[1] and David M. Worley[1]

ABSTRACT

The characteristics of seismic ground response in West and South Seattle were determined using recordings of three local earthquakes at temporary seismograph sites. The recording sites were located at or near those that experienced Modified Mercalli VIII intensities during the 1965 Seattle earthquake. The highest ground-response functions (GRFs) calculated ranged from 5 to 12 at Harbor Island, which had a Modified Mercalli intensity of VIII during the 1965 earthquake. Harbor Island is underlain by manmade fill. A similar relationship between GRF values and 1965 earthquake intensities was observed at manmade fill sites in Olympia, Wash. GRFs for other sites in West and South Seattle were much lower, ranging from 2.1 to 4.4. No site in Olympia experienced an intensity of VII or more in the 1965 earthquake without a GRF of 5.7 or greater. We conclude that ground amplification probably did not cause the anomalously high intensities in West Seattle during the 1965 earthquake. Almost all of the observations that led to West Seattle receiving a Modified Mercalli intensity of VIII were based on damage to chimneys. Close inspection of chimneys in the area of greatest damage revealed many with extremely deteriorated mortar, which perhaps contributed to the damage during the 1965 earthquake and, thus, inflated the local intensity values for West Seattle. Therefore, the original Modified Mercalli intensity of VIII at West Seattle was probably more in the range of intensity VII, which includes damage to weak masonry.

INTRODUCTION

Urban areas in the Puget Sound, Washington, area are subject to significant seismic risk. The largest recorded earthquakes in the Puget Sound area (fig. 169) occurred in 1946, 1949, and 1965 (Thorsen, 1986). The 1949 earthquake near Olympia caused a Modified Mercalli (MM) intensity of VIII in both Seattle and Olympia. MM intensity VIII includes damage to unreinforced masonry, fall of stucco and some masonry walls, and twisting or falling chimneys. The epicenter of the 1965 earthquake was about 25 km south of Seattle (Algermissen and Harding, 1965). It caused widespread damage, although the maximum MM intensity of VIII was concentrated in the Harbor Island and West Seattle areas (fig. 170) (Hake and Cloud, 1967). Mullineaux and others (1967) suggested that Harbor Island and West Seattle may have also experienced higher intensities than surrounding areas during the 1949 earthquake.

This study was designed to determine if near-surface geophysical factors exist that may cause Harbor Island and West Seattle to experience greater ground shaking during earthquakes than other nearby areas. Six ground-response monitoring sites were set up (fig. 170), and we recorded ground motion from three small earthquakes (fig. 169). These records were used to compute ground-response functions (GRFs) for the six sites. GRF is the amplification of ground motion at a site of interest (usually underlain by unconsolidated sediments) relative to ground motion recorded at a standard, or reference, site (usually on rock). This method has been applied in several areas including Los Angeles, San Francisco, and Olympia (Borcherdt and Gibbs, 1976; Rogers and others, 1979, 1985; and King and others, 1990). Seismic-refraction lines were also recorded at each of the six sites. The refraction lines provided information on the compressional-wave seismic velocity characteristics of the site from 0 to 90 m depth. Finally, to answer the question of whether the houses and chimneys in West Seattle were more susceptible to earthquake shaking than those in surrounding areas, we determined the natural frequencies and damping coefficients of 10 local one-story residences.

DATA COLLECTION AND PROCESSING

From November 1987 to December 1988, we operated six portable digital seismographs in West and South Seattle to record site-specific ground response. The recording sites

[1]U.S. Geological Survey, Box 25046, MS 966, Federal Center, Denver, CO 80225.

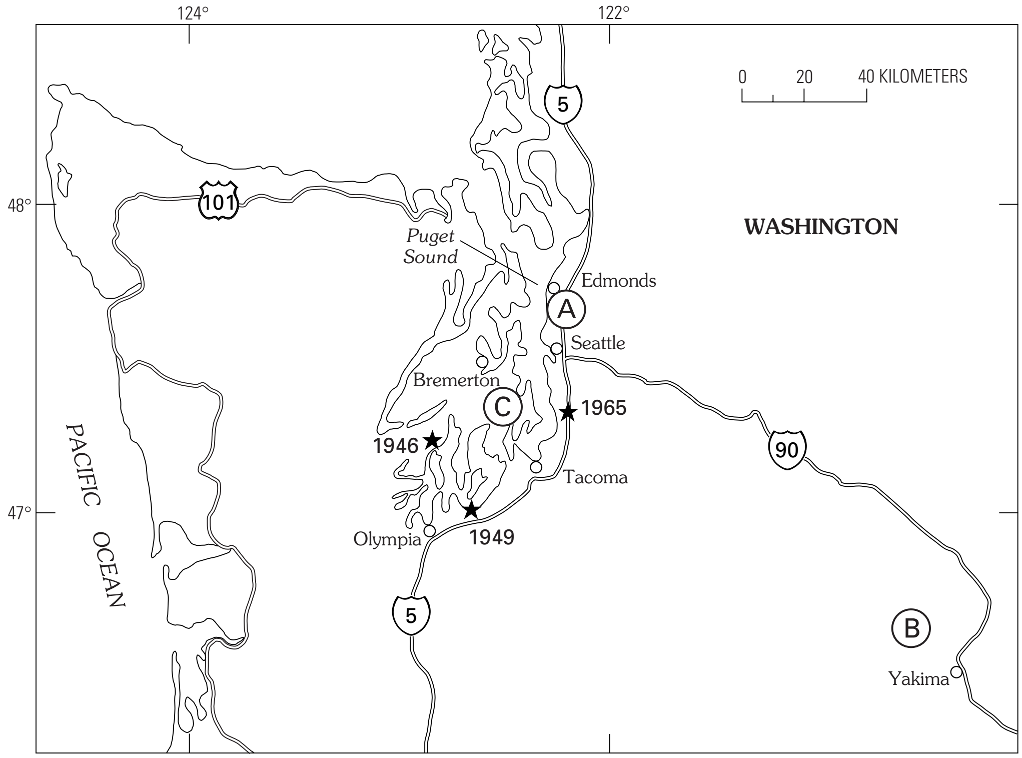


Figure 169. Map showing epicenters (circled letters) of three small earthquakes in Washington used as seismic-shaking sources for computation of ground-response functions. Locations were calculated by the University of Washington permanent seismograph network and are listed in table 26. Stars, epicenters of the 1946, 1949, and 1965 earthquakes.

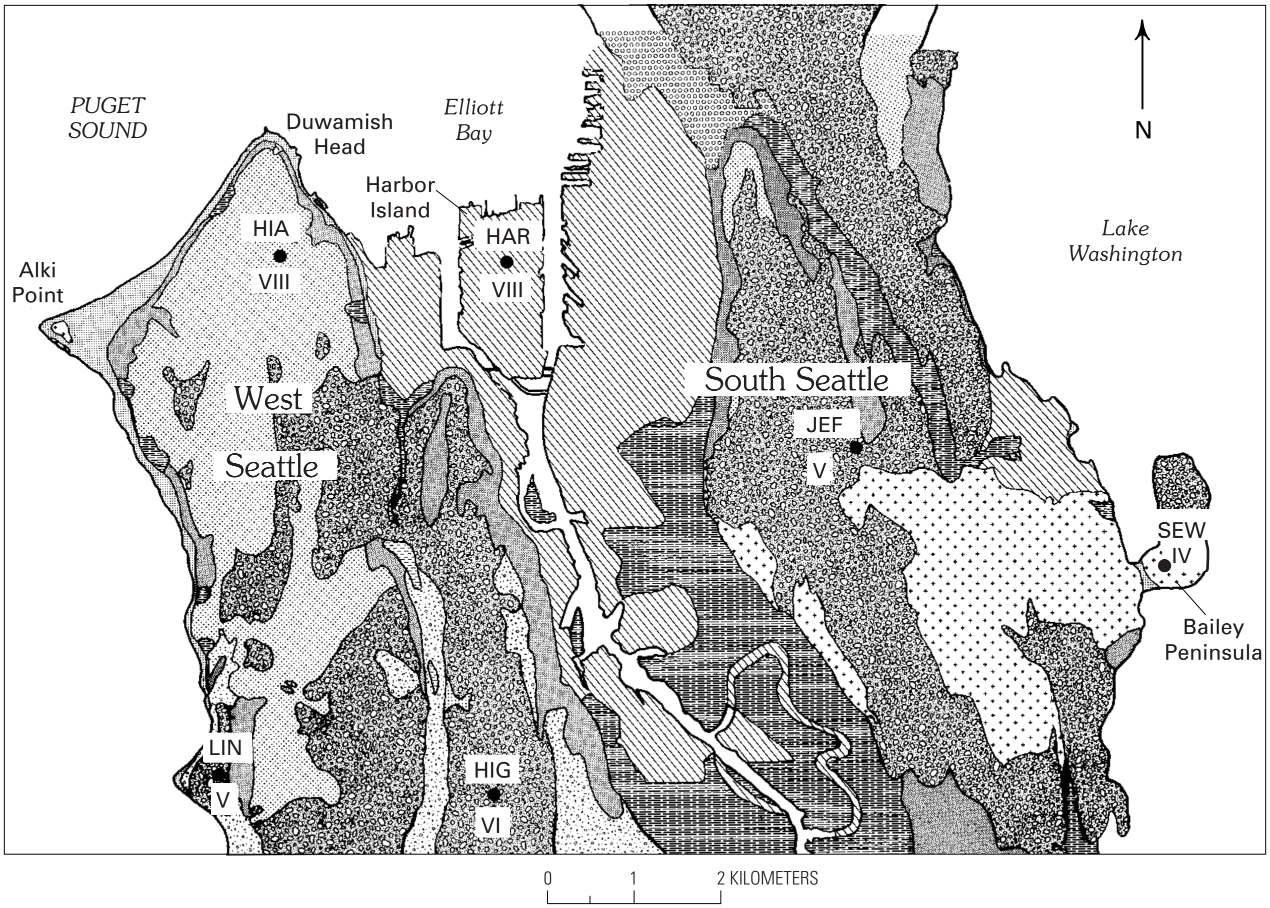
Table 26. Epicenter locations of small earthquakes in Washington detected by seismograph sites during the study. Data are from the University of Washington hypocenter computer data file.
[M_L, local magnitude]

Earthquake	Latitude N.	Longitude W.	Depth (kilometers)	Size (M_L)	General location
A	47°49.04'	122°21.76'	50	2.8	Edmonds, Wash.
B	46°40.49'	122°41.03'	18	4.1	Yakima, Wash.
C	47°32.94'	122°44.59'	19	2.8	Bremerton, Wash.

were primarily chosen because they were at or near documented 1965 earthquake intensity observations. We also wanted sites that represented different surficial geologic units and a broad spacial distribution across the West and South Seattle areas. Another consideration in recording-site selection was finding sites that had sufficient space to allow seismic reflection and refraction lines.

All sites except the one used as the standard (SEW) were located at or near locations where MM intensities of V, VI, and VIII were reported as a result of the 1965 earthquake. There were no historical data for the SEW site because no inhabited structures existed there at the time; however, surrounding areas within two blocks of the site had intensity reports of IV or less. It is assumed that the probable intensity at the SEW site, which was placed directly on Tertiary fine-grained sandstone, would also have been IV or less (Hake and Cloud, 1967). Sites HAR and HIA experienced MM intensity of VIII; at site HIG, intensity values of VI had been reported; and sites JEF and LIN had experienced intensity V (fig. 170).

Our seismographs registered the three small earthquakes that were also recorded and located by the University of Washington permanent seismograph network. Two local-magnitude (M_L) 2.8 earthquakes were located in the Puget Sound area and the third, registering M_L 4.1, occurred near Yakima, Wash. (fig. 169, table 26) (University of Washington hypocenter computer data file, unpub. data).



EXPLANATION

f m

Artificial fill, f and modified land, m—Modified land: areas leveled by cut and fill and fill frequency

Qa

Alluvium—Chiefly sand and silt but includes clay and peat. South of Renton and Tukwila these sediments are 15–25 ft thick and overlie sand and gravel. Mostly sand and gravel in Cedar River valley

Qb

Beach deposits—Chiefly sand; may include interbedded organic material; deposits in places are veneers of sand and gravel less than 2 ft thick on older deposits

Qsc

Lacustrine sediments—Chiefly unconsolidated silt, clay, and fine sand generally less than 10 ft thick

Qys

Younger gravel—Chiefly sand and pebble gravel; commonly overlies Qt; as much as 100 ft thick

Qt

Vashon till—Compact, concrete-like mixture of silt, sand, gravel and clay, as much as 150 ft thick, but generally less than 50 ft. Upper 2–5 ft generally a loose, silty sand and gravel

Qog

Older gravel—Chiefly sand and pebble gravel; lies beneath Qt; as much as 200 ft thick

Qos

Older sand—Chiefly medium sand; loose, as much as 300 ft thick

Qc

Older clay, till, and gravel—Silt, clay, fine sand, and till, very compact; locally includes lenticular sand and gravel shown as Ocg where mappable

Tb

Sedimentary rocks of Oligocene age—Chiefly tuffaceous sandstone and conglomerate; compact but poorly cemented; at least 2,500 ft thick

Figure 170. Surficial geologic map of West and South Seattle area (modified from Waldron and others, 1962). Dots and three-letter codes, locations of ground-response recording sites. Roman numerals, Modified Mercalli intensities observed at these locations during the 1965 earthquake.

The portable digital seismographs used triaxial velocity-sensitive transducers with a natural frequency of 1.7 Hz and a damping coefficient of 0.6 of critical. The seismometers were leveled, oriented, and calibrated at each site using standardized procedures outlined in Carver and others (1986). The seismographs used an internal trigger algorithm that discriminates between ground shaking induced by earthquakes and that caused by local disturbances such as traffic. Data were recorded digitally on cassette tapes that were subsequently played back into a computer for analysis using spectral-analysis software developed by Cranswick and others (1989).

The earthquake records were first displayed as amplitude-normalized seismograms to allow inspection and selection of a standardized portion of the time series for analysis. This window was the same for all of the records; therefore, it was unnecessary to normalize spectral amplitudes for window length. A 20-s time window was chosen beginning with the *P*-wave arrival and including most of the coda. The data time window was tapered with a whole-cosine bell (Hanning window) before being transformed by a standardized Fast Fourier Transform (FFT) computer program. Spectral amplitudes and ratios were smoothed using a moving-average window with a Hanning taper and a width of 0.15 Hz. The earthquake smoothed spectra were then compared with the pre-event smoothed spectra to determine the signal-to-noise ratio. All of the data used in this report had a signal-to-pre-event noise ratio of at least 1.5. The GRF was calculated, using smoothed spectra, by the following equations:

$$\mathrm{GRF}_{ia}=0.5(R_{i,2,a}+R_{i,3,a}) \tag{1}$$

and

$$R_{i,j,a}=(S_{i,j,a})/(S_{o,j,a}) \tag{2}$$

where i is the recording site on unconsolidated sediments;
o is the standard recording site (SEW);
j is the horizontal component (2=north-south, 3=east-west);
R is the spectral ratio;
S is the smoothed Fourier amplitude spectrum; and
a is the frequency band (0.5–1.0 Hz; 2–4 Hz; and 4–8 Hz).

Figures 171, 172, and 173 show the process of deriving the GRF. Figure 171 shows typical seismograms with amplitudes normalized so that all components are displayed at the same scale. Figure 172 shows smoothed Fourier amplitude spectra for the sites on unconsolidated sediments and standard rock site SEW. Figure 173 and table 27 summarize the GRF, the surficial geology, the MM intensity observed from the 1965 earthquake for each site, and the seismic-velocity structure.

Both earthquakes A and C were recorded at sites LIN and SEW. Figure 174 shows the derived spectral ratios for these earthquakes. The similarity of the two plots indicates a high degree of repeatability of GRF values for different shaking sources.

BUILDING STUDIES

Immediately following the 1965 earthquake, Algermissen and Harding (1965) conducted a block by block survey of West Seattle in which they calculated the ratio of damaged to undamaged chimneys resulting from the earthquake. One possible explanation for the large number of damaged chimneys is that they were tuned to the same frequency as the earthquake shaking at that location. We selected 10 houses within two blocks of site HIA (fig. 170) in the area of maximum former chimney damage and installed seismometers on chimneys, roof tops, and at the midpoints of bearing walls. Several minutes of ambient

Table 27. Calculated ground-response functions (GRFs) for three small Washington earthquakes detected by seismograph sites in West and South Seattle during the study.

[All values given relative to site SEW. Tb, Tertiary sedimentary rocks, sandstone; Qt, Vashon till, compact silt, sand, gravel; Qos, Vashon outwash, older sand, medium sand, loose; af, artificial fill]

Site	Earthquake	Average horizontal ground-response function				Geology[1]	Modified Mercalli intensity[2] (1965 earthquake)	Average *P*-wave velocity (meters/second)	Depth interval (meters)
		0.5–10 Hz	1–2 Hz	2–4 Hz	4–8 Hz				
SEW	A, B, C	1	1	1	1	Tb	IV	2,600	1–15
JEF	A	3.7	3.5	2.8	2.3	Qt	V	2,200	1–55
HIG	C	3.3	2.9	2.1	2.2	Qt	VI	1,470	1–10
LIN	A	3.8	3.2	2.3	2.3	Qt	V	1,460	1–14
LIN	C	3.5	3.0	3.2	2.4	Qt	V	1,460	1–14
HIA	B	4.4	3.9	4.0	2.5	Qos	VIII	1,520	1–10
HAR	B	11.7	8.8	4.9	4.8	af	VIII	1,370	1–90

[1]From Waldron and others (1962).
[2]Margaret Hopper, U.S. Geological Survey, written commun.

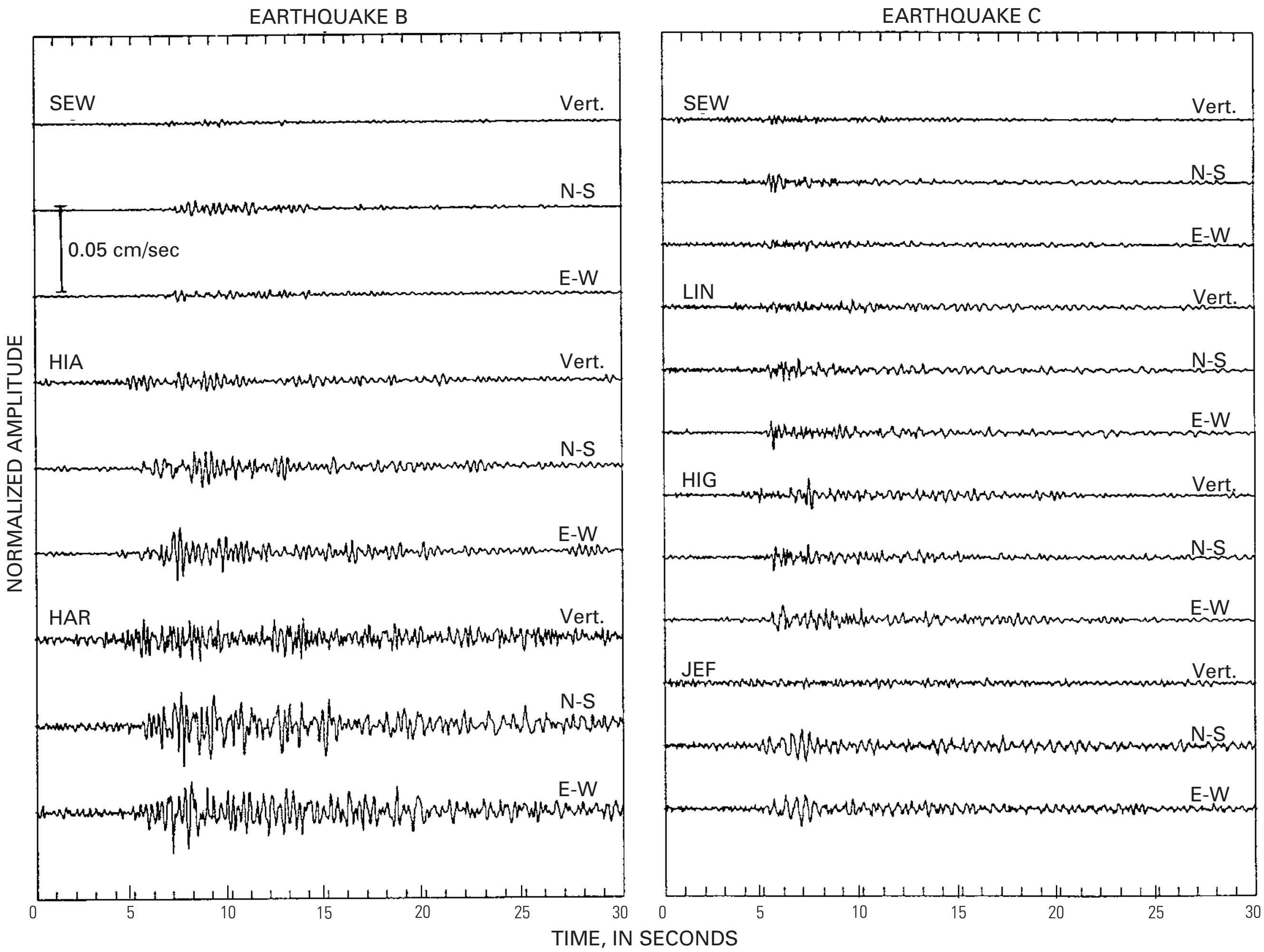


Figure 171. Representative seismograms recorded at the West and South Seattle recording sites for earthquakes B and C (epicenters are given in table 26). Three components of motion are shown for each recording site. Vert., vertical; N-S, north-south; E-W, east-west.

Table 28. Natural frequencies and damping coefficients of West Seattle houses constructed on Quaternary unconsolidated sediments.

[All buildings are one-story structures located within two blocks of seismograph site HIA. Data are derived from seismic and man-induced vibration sources]

Building	Natural frequency, long axis (Hz)	Natural frequency, short axis (Hz)	Damping coefficient (percent critical)	Natural frequency, chimney
1	7.2	11.4	3.5	7.0
2	8.2	8.6	1.4	6.2
3	5.5	5.4	3.0	8.6
4	6.8	7.0	2.5	10.0
5	8.6	11.1	1.8	13.7
6	10.2	13.6	2.2	12.5
7	7.0	14.0	2.5	7.8–11.7
8	9.8	10.6	3.8	9.4
9	10.5	14.8	2.4	9.0–10.2
10	5.3	11.7	2.9	6.1–9.8

seismic background noise and several man-induced vibration events were recorded. The natural frequency (first mode) was determined by calculating an FFT on the time-series data (examples are shown in fig. 175). The

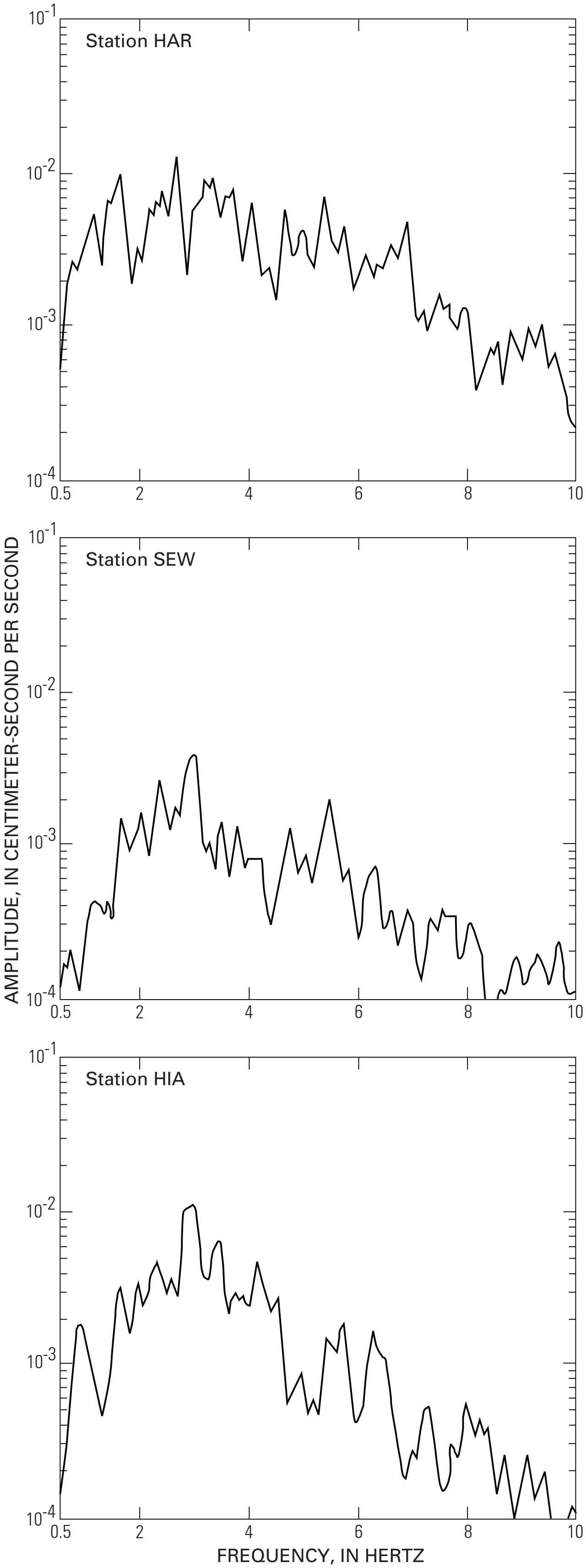


Figure 172. Horizontal, north-south components of velocity spectra for the three recording stations in West and South Seattle that recorded earthquake B. The ground-response functions are the result of computing the ratios of the spectra of sites on unconsolidated sediments (HAR and HIA) to the standard site (SEW) located on rock.

damping ratio was obtained by using

$$D=1/(2\pi)[-\ln(X_{n+1}/X_n)] \tag{3}$$

where D is the percent of critical damping and X_n is the velocity amplitude of the nth cycle of motion (Dowding and others, 1980). The results of these tests are shown in table 28.

SITE INVESTIGATIONS USING SEISMIC REFRACTION

High-resolution *P*-wave seismic-refraction profiles were acquired at the six sites to characterize their near-surface velocity characteristics. A 12-gauge shotgun or gasoline-powered earth tamper was used as the seismic source, and the signal was recorded by a 24-channel digital seismograph with 100-Hz geophones spaced 1.5–3.0 m apart. The slope-intercept method of analysis was used to interpret the recordings. The results provide information on the compressional-wave seismic-velocity structure of a site at the depth range of 0–10 m for the shorter profiles and down to 90 m for longer profiles. Because surface-wave velocity is only a few percent slower than shear-wave velocity (Aki and Richards, 1980), we used the surface waves generated by the 12-gauge and tamper sources at some of the sites to estimate the near-surface *S*-wave velocity. The surface wave was identified on the vertical-component refraction records as a high-amplitude dispersed wavetrain on each record. The surface-wave velocity was then determined from the slope of the highest velocity (first arrival group) surface wave on a time versus distance seismogram. For *S*-wave velocity calculations, we assumed that the surface-wave velocity was 10 percent slower than the *S*-wave velocity. We also assumed that this surface-wave velocity applies to a depth of about one wavelength of the surface wave (Sheriff and Geldart, 1982). Because we only had vertical-component refraction data, it's possible that we were measuring the *S*-wave direct arrival and not the highest velocity surface wave. Therefore, we may have overestimated the *S*-wave velocity by about 10 percent; however, the relative differences in *S*-wave velocity between the sites would remain the same. Results of the refraction profiles are summarized in table 27.

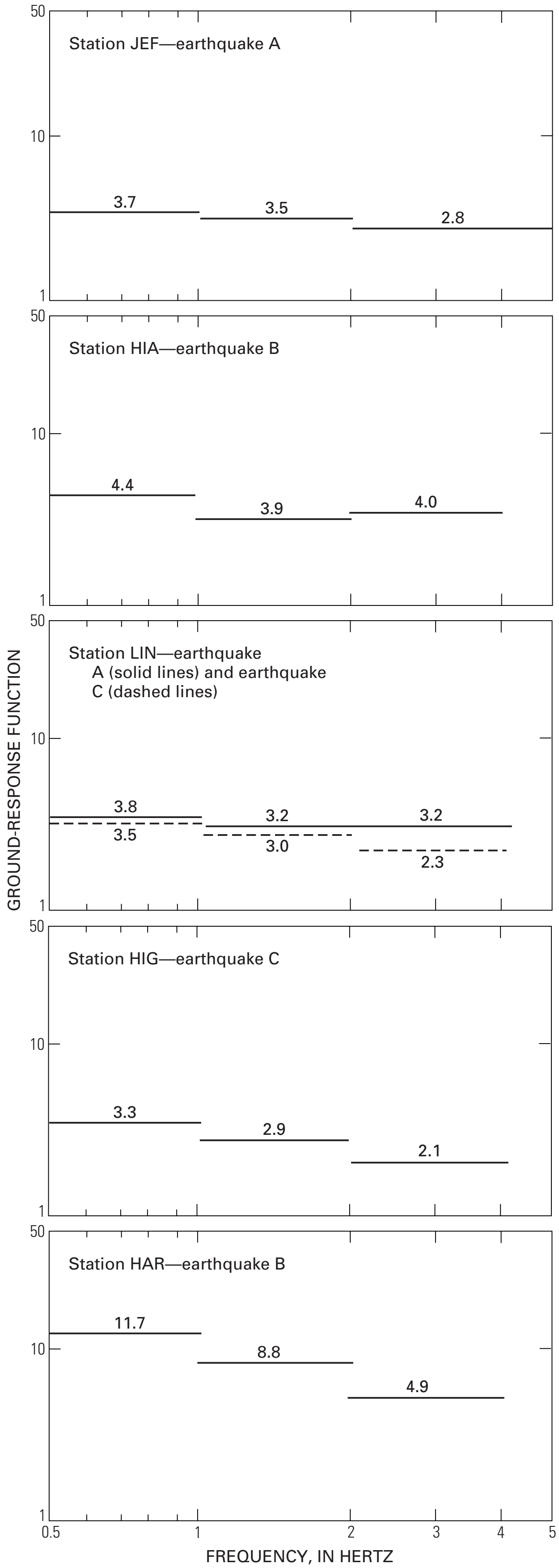


Figure 173. Average horizontal ground-response functions calculated from seismograms for three small earthquakes recorded at all the monitoring sites in West and South Seattle. Values are spectral ratios relative to standard site SEW. Site LIN was the only one other than the standard site to record more than one earthquake.

Standard site SEW, in Seward Park on Bailey Peninsula, was underlain by a fine-grained sandstone with a compressional-wave velocity of about 2,600 m/s to at least 15 m depth. This is the highest *P*-wave velocity observed at any of the recording sites.

Site HAR was located on fill material in the Duwamish River waterway with a uniform 1,371 m/s *P*-wave seismic velocity to a minimum depth of 90 m. The surface-wave data translate to a very slow 150 m/s *S*-wave velocity in the upper 6 m of fill.

Sites JEF and LIN were located on Vashon till, which in this area is a graded mixture of clay to gravel. The seismic-velocity data indicate that these two sites are located on relatively firm ground with *P*-wave seismic velocities increasing from 1,470 m/s at about 2 m depth up to 2,220 m/s at 30–55 m depth. The *S*-wave velocity at LIN was about 300 m/s at 5 m depth whereas at JEF it was about 740 m/s at about 15 m depth. Site HIG was located on a well-sorted and poorly graded gravel that has a *P*-wave seismic-velocity structure similar to LIN. Site HIA was located on older uncemented sand of Quaternary age with a *P*-wave seismic-velocity structure also similar to LIN.

DISCUSSION AND CONCLUSIONS

The low velocities at site HAR confirmed that the fill material is unconsolidated, saturated, and probably forms a high impedance contrast at its base, which would influence seismic-wave amplification. Not surprisingly, site HAR had a GRF value 5–12 times greater than standard rock site SEW. This result is in accordance with the MM intensity VIII damage experienced at Harbor Island during the 1965 earthquake. Similar sites in Olympia (King and others, 1990), underlain by artificial fill and unconsolidated saturated sediments, also have very low seismic velocities and high GRF values and have experienced MM intensity VIII damage from the 1965 earthquake.

There has been considerable interest in explaining why West Seattle experienced MM intensity VIII shaking in the 1965 earthquake. Some investigators (Langston and Lee, 1983; Ihnen and Hadley, 1986) have used velocity models and ray tracing to create synthetic accelerograms for the Puget Sound region. They concluded that the shaking was enhanced in both West Seattle and Harbor Island by basin-geometry wave focusing as well as by near-surface ground response.

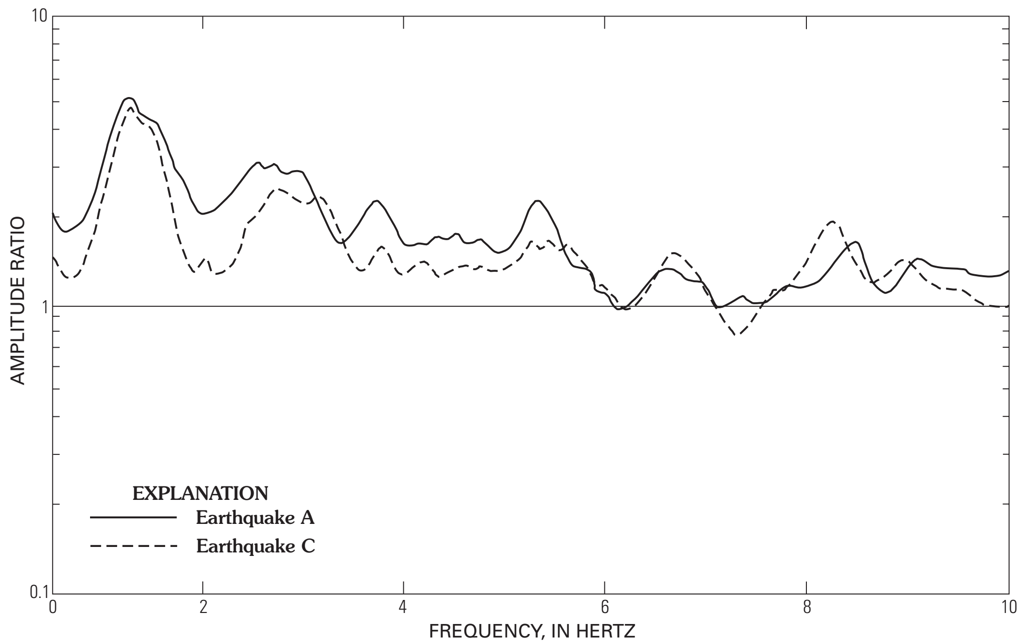


Figure 174. Average horizontal velocity spectral ratios of two earthquakes recorded at site LIN in West Seattle relative to standard site SEW in South Seattle. Similarity of the curves shows reproducibility of the ground-response functions despite different shaking sources.

We located site HIA in West Seattle, in the center of the MM intensity VIII damage from the 1965 earthquake. The GRFs recorded at HIA are not significantly higher than those at the other West and South Seattle sites that experienced MM intensity V and VI shaking. Compared to HAR, all of the other sites had relatively low GRF values, and their *P*-wave seismic-velocity structures were similar. Furthermore, no sites in Olympia experienced MM intensity VII or greater without having a GRF of at least 5.7 (King and others, 1990). Thus, the near-surface geophysical data we have collected indicates that ground response was probably not a factor in producing higher intensities near site HIA in West Seattle compared with those sites in the surrounding neighborhoods.

Tests of residential structures in West Seattle show that the natural frequencies at which their walls and chimneys are most sensitive to damage range from 5 to 15 Hz (table 28). The frequency range of the building resonance only marginally overlaps with our earthquake data frequency band. However, the GRF for site HIA suggests that the houses are subjected to ground-motion amplification factors of about 2.5 near their resonance frequencies (table 27). Again, our data from Olympia indicate that this GRF would not be high enough to explain the MM intensity VIII reported for this neighborhood.

A possible explanation for the high MM intensity became apparent as we talked with homeowners during the building-vibration phase of our fieldwork. We asked people who experienced the 1965 earthquake what other effects they had observed. None of them, even those whose houses had chimney damage, said that they had experienced any other damage. One man who had been a building contractor in the area stated that a poor grade of mortar containing salty sand had originally been used in many of the chimneys of West Seattle. Of 15 houses on which we tried to measure chimney vibration, 5 had chimneys in such poor condition that we deemed it unsafe to place a small single-component seismometer on the top. Of the 10 houses we did test, one-half of the chimneys had significant deterioration of the mortar. Two of the 10 chimneys exhibited loose bricks when we installed the seismometer. We believe that the original intensity rating could have been biased because many chimneys were in very poor condition before the earthquake occurred. The MM intensity VII standard (Richter, 1958) includes "damage to masonry D (weak materials, poor mortar) including cracks. Weak chimneys broken off at roof line." The true intensity of shaking at West Seattle might therefore be better characterized by an MM intensity of VII.

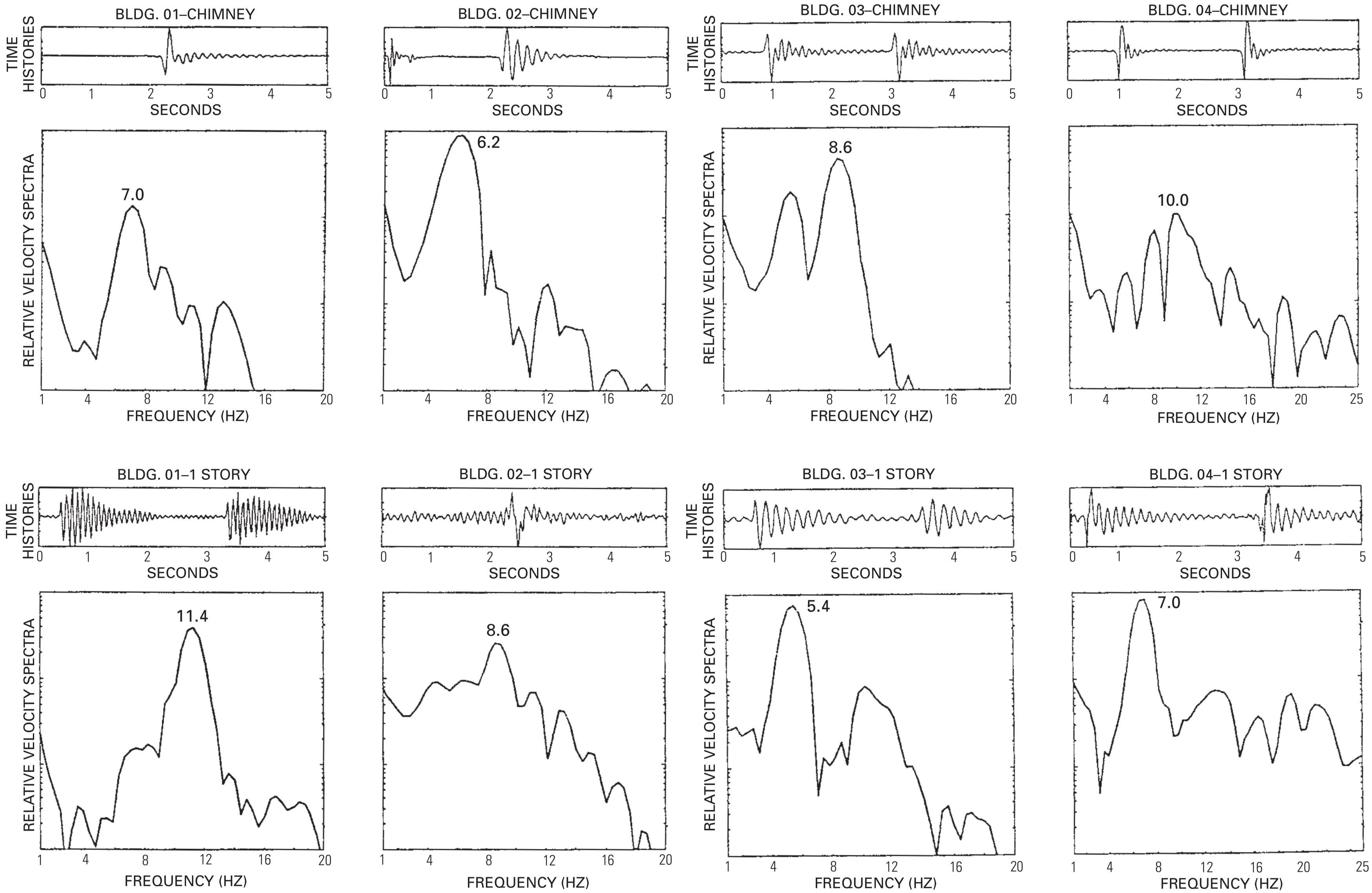


Figure 175. Seismograms and velocity spectra used to derive natural frequencies and damping coefficients of four representative houses in West Seattle. Seismometers were placed on chimneys and bearing walls. The time history seismograms graph velocity versus time. Results for all buildings tested are shown in table 28.

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EARTHQUAKE-HAZARD GEOLOGIC MAPS OF THE PORTLAND, OREGON, METROPOLITAN AREA

By Ian P. Madin[1]

ABSTRACT

Earthquake-hazard geologic maps have been produced based on eight 1:24,000-scale quadrangle maps covering most of the Portland, Oregon, metropolitan area. The map data are derived from published and unpublished geologic mapping and interpretation of several thousand borehole logs. The maps depict the distribution and thickness of four units of poorly consolidated fine-grained Quaternary sedimentary materials that may amplify ground shaking or liquefy during earthquakes. The four units are Pleistocene catastrophic flood deposits, fine-grained facies; Holocene alluvium; Holocene artificial fill; and Pleistocene loess.

The maps also depict other Quaternary and bedrock geologic units, faults, and contoured depth-to-basement data. They show that the northwest-trending Portland and Tualatin basins are bordered by faults on their margins and separated by the folded and faulted basement rocks of the Tualatin Mountains (Portland Hills). Northwest-trending anticlines of the Portland Hills are cut by parallel and transverse high-angle faults and by southwest-dipping thrust faults. Although numerous northwest- and northeast-trending faults have been mapped in the area, none have yet been shown to cut Holocene deposits. However, some faults do cut Pleistocene rocks.

INTRODUCTION

In 1987, the Oregon Department of Geology and Mineral Industries (DOGAMI) began a 5-year program to assess earthquake hazards in the Portland, Oreg., metropolitan area with funding provided by the U.S. Geological Survey through the National Earthquake Hazards Reduction Program. In recognition of the importance of local geology in assessing earthquake hazards, a mapping program with two major goals has been carried out. The first goal of the mapping program was to identify faults that may cut young geologic deposits; the second goal was to map the distribution and thickness of fine-grained unconsolidated sedimentary deposits that may amplify ground shaking or liquefy during an earthquake. The final maps are based on compilation of existing maps, new surface mapping by the author, M.H. Beeson, and T.L. Tolan, and examination and interpretation of more than 5,000 borehole logs by the author. The maps (figs. 177–185, beginning on p. 362) are reductions of the U.S. Geological Survey's Beaverton, Gladstone, Hillsboro, Lake Oswego, Linnton, Mt. Tabor, Portland, and Scholls 1:24,000-scale topographic quadrangles (fig. 176).

The maps depict all major geologic units and identify Quaternary sedimentary units with high earthquake-hazard potential. Where there are sufficient data, the thickness of these sedimentary deposits is depicted with isopach lines. The maps also depict contoured depth-to-basement data and faults inferred from subsurface data.

All of the area covered in this study has been previously mapped at a variety of scales. The earliest small-scale work was a map by Treasher (1942) at a scale of 1:62,500. This was followed by a detailed map at the same scale by Trimble (1963). Several subsequent maps have involved compilation of existing surface data with water-well data (Mundorff, 1964; Hart and Newcomb, 1965; Hogenson and Foxworthy, 1965). The southwestern part of the area was first mapped in detail by Schlicker and Deacon (1967), and the Gladstone and Lake Oswego quadrangles (fig. 176) were compiled at 1:24,000 by Schlicker and Finlayson (1979). Parts of the area have been included in a 1:100,000-scale compilation by the Washington Department of Geology and Earth Resources (Phillips, 1987).

The mapping presented in this report differs from the previous mapping in varying degrees. On some quadrangles (Gladstone, fig. 185), there are significant changes in stratigraphy and structure. Other maps (Hillsboro and Scholls, figs. 178 and 182, respectively) differ little from the previous mapping. Significant departures from the previous mapping occur only where there is good field or subsurface evidence for the change.

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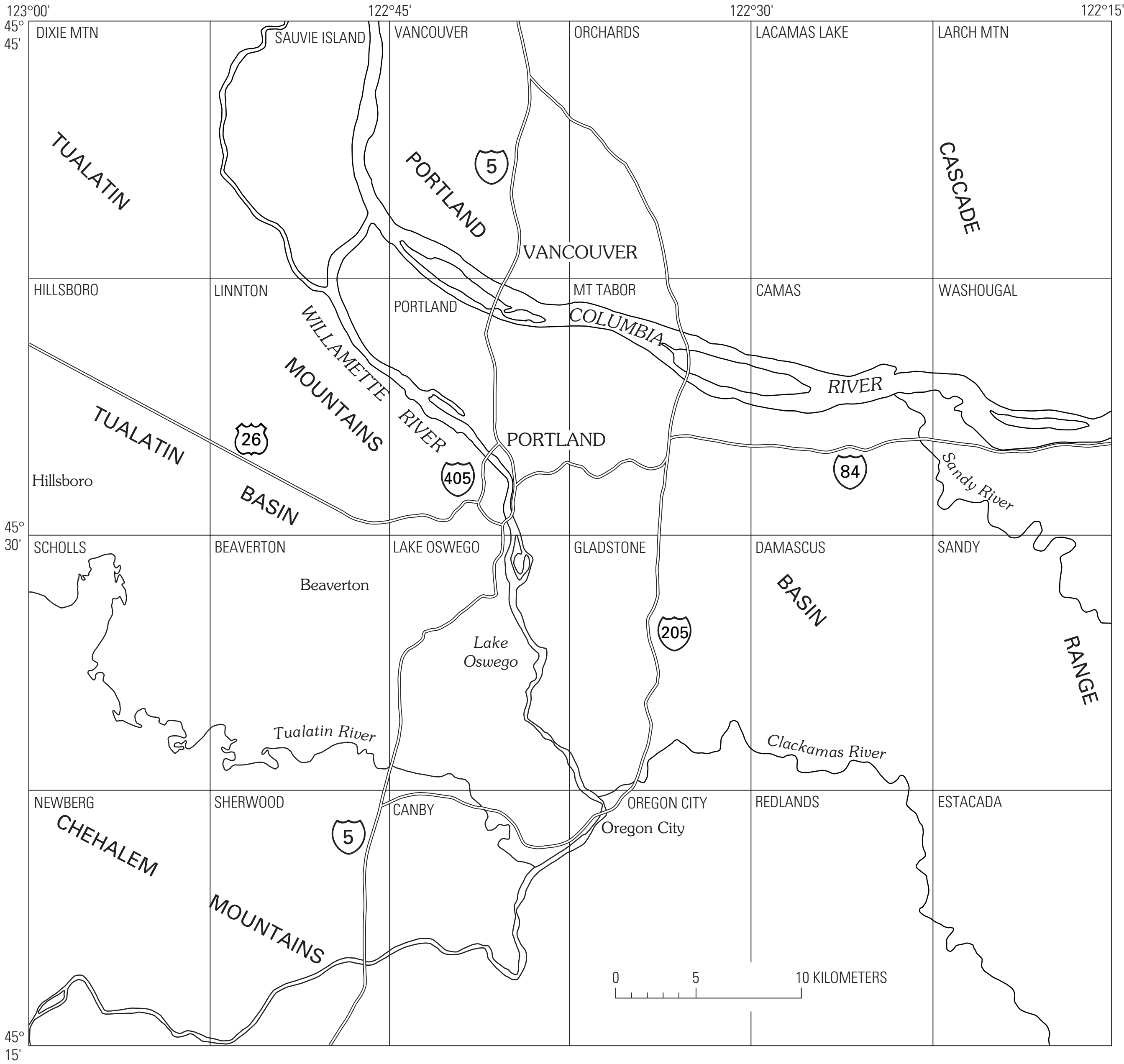

Figure 176. Index map of the Portland, Oreg., metropolitan area showing major cities, highways, and geographic features. The grid represents the U.S. Geological Survey's 1:24,000-scale topographic map coverage of the area. The quadrangle names are in the upper left-hand corner of each rectangle.

ACKNOWLEDGMENTS

The following organizations contributed immensely to this project by allowing access to their files of subsurface data: City of Portland Bureau of Buildings, Oregon Department of Transportation (Region 1, Office and Bridge Division), U.S. Geological Survey Water Resources Division, Port of Portland, Dames and Moore, Shannon & Wilson, Rittenhouse-Zeman Associates, Kelly-Strazer Associates, L.R. Squier Associates, and Geotechnical Resources Inc. Dr. Marvin H. Beeson and Mr. Terry L. Tolan provided unpublished geologic mapping data for the southwest corner of the Gladstone quadrangle. Evan Thoms and Tom Popowski assisted in field work in the Washington County areas. Reviews by Rod Swanson, Bob Deacon, Marv Beeson, Terry Tolan, Ken Robbins, Steve Personius, John Tinsley, and George Priest were greatly appreciated. Paul Staub provided valuable cartographic assistance. This work was funded by U.S. Geological Survey cooperative agreement No. 14–08–0001–A0512 as part of the National Earthquake Hazards Reduction Program.

STRATIGRAPHY AND NOMENCLATURE

The stratigraphy of the Neogene sedimentary rocks that fill the Portland and Tualatin basins is still very poorly understood, and the nomenclature of these units is an unresolved issue. The nomenclature and stratigraphy used in this report are more completely discussed by Madin (1990). Nomenclature for the volcanic rocks of the region follows Beeson, Tolan, and Anderson (1989) except that the rocks of the Columbia River Basalt Group are not subdivided in this report.

DEPOSITS WITH HIGH EARTHQUAKE-HAZARD POTENTIAL

Poorly consolidated Quaternary deposits commonly amplify ground motions or fail due to liquefaction during major earthquakes. These phenomena enhanced the damage caused by many recent earthquakes such as those in Mexico City in 1985 (Seed and others, 1988), Armenia in 1988 (Borcherdt and others, 1989), and San Francisco in 1989 (Plafker and Galloway, 1989). Poorly consolidated deposits of sand, silt, or clay that overlie more competent materials are most likely to amplify ground shaking. Deposits of poorly consolidated saturated sand and silt are most likely to liquefy during strong ground shaking. Both types of deposits are widely distributed in the Portland area, as originally recognized by Schlicker and others (1964). The ground-shaking amplification at any site will depend on the thickness and seismic-velocity profile of the sedimentary column beneath the site. Earthquake-induced liquefaction of the sedimentary materials at any site will depend on the strength and duration of local ground shaking as well as hydrologic conditions at the site. The data in this report provide one essential element for the quantitative modeling of ground-shaking amplification or earthquake-induced liquefaction, but these data alone are not sufficient to make a reliable, quantitative estimate of potential earthquake hazards at any site.

Many of the deposits in the Portland area may be susceptible to earthquake-induced landsliding. However, the mapping of potentially unstable slopes or existing landslides that may reactivate during an earthquake is beyond the scope of this report.

The following four Quaternary geologic units in the Portland metropolitan area may have high amplification or liquefaction potential:

- Pleistocene loess
- Pleistocene catastrophic flood deposits, fine-grained facies
- Holocene alluvium
- Holocene artificial fill

Of the four units, only the fine-grained facies of the catastrophic flood deposits and the alluvium are sufficiently uniform in thickness to be mapped using isopachs. The remaining geologic units on the maps (Pleistocene gravels and older sedimentary and volcanic rocks) typically have relatively low potential for amplification of earthquake ground motion or liquefaction. The nature and distribution of the units with high earthquake-hazard potential are described below and in figure 177.

PLEISTOCENE LOESS (Ql)

This unit consists of loessal silt that mantles higher slopes in the Portland area. The loess is difficult to distinguish from the silts of the Pleistocene catastrophic flood deposits (Qff), and the lower boundary of the unit is mapped on the assumption that the loess is either buried by unit Qff or has been eroded by catastrophic flooding below an altitude of 90 m. Previous workers (Trimble, 1963; Schlicker and Deacon, 1967; Lentz, 1977) have generally depicted the loess as thicker on ridgecrests and thinner on valley walls and floors. Field work for this study indicates that the valley walls of minor drainages are typically covered with in-place or colluvial loess and that exposure of underlying bedrock units is rare except in stream channels. Limited subsurface data indicate that the loess is widely variable in thickness, reaching a maximum of 30 m along the crest of the Tualatin Mountains (Portland Hills). Loess 6–12 m thick is common along the slopes of the Tualatin Mountains and substantially thinner deposits are present on the Chehalem Mountains (fig. 182), Mt. Scott (fig. 185), and Cooper and Bull Mountains (figs. 182 and 183). As a result of the variable distribution and thickness of the loess, it has been mapped over the underlying bedrock units only in the areas in which significant (1.5 m or greater) loess can be expected to occur. The loess is notoriously landslide prone when saturated and represents a significant earthquake-induced landslide hazard.

PLEISTOCENE CATASTROPHIC FLOOD DEPOSITS, FINE-GRAINED FACIES (Qff)

This unit consists of crudely to complexly layered, poorly consolidated, coarse sand to silt deposited by one or more phases of catastrophic floods from late Pleistocene Glacial Lake Missoula. The catastrophic flood deposits occur along the Willamette and Columbia Rivers and throughout the Tualatin basin. The thickness of the catastrophic flood deposits is typically 9–18 m, with a maximum thickness of 55 m in the map area. The catastrophic flood sediments were deposited beneath regionally ponded floodwaters, the highest of which reached an elevation of approximately 122 m above sea level, based on the distribution of ice-rafted erratics (Allison, 1935). However, the catastrophic flood deposits are typically found no higher than 75–90 m above sea level. Ponding of floodwaters to 122 m above sea level may not have happened sufficiently often or for a sufficient length of time to allow significant sediment deposition at higher elevation. It is difficult to distinguish the catastrophic flood deposits from loess in most outcrops and well logs, so the contact between the two units is commonly drawn following the 90 m contour in the absence of site-specific data.

Evidence of liquefaction is commonly observed in good exposures of unit Qff in the form of silt and sand dikes. Some of the liquefaction dikes cut earlier dikes and bedding planes and paleosol layers in the catastrophic flood deposits. It is not clear whether liquefaction occurred during multiple catastrophic flood events, subsequent earthquakes, or both.

HOLOCENE ALLUVIUM (Qal)

Quaternary alluvium consists of poorly consolidated sand, silt, clay, and gravel deposited by the Columbia and Willamette Rivers and their tributaries. In the Willamette and Columbia Rivers, sand and silt predominate although organic material and clay are locally abundant, and gravel deposits are rare with the exception of Ross Island, a major gravel bar in the Willamette River (figs. 180 and 184), and scattered gravels at the base of deposits in the Columbia and Willamette Rivers. The channels of the Columbia and Willamette Rivers have been filled with as much as 55 m of fine-grained alluvium. The upper limit of the fine-grained alluvial deposits is apparently restricted to a maximum elevation of 10 m above modern sea level, an elevation that corresponds to the maximum level of historical floods. Alluvium deposited by the Clackamas River (fig. 185) is dominantly volcaniclastic gravel and sand. Alluvium deposited by the Tualatin River (figs. 182–184) is predominantly sand, silt, clay, and organic material. In both the Clackamas and Tualatin River drainages, alluvial deposits are largely restricted to channels incised into the catastrophic flood deposits. Limited subsurface data suggest that alluvium deposited by minor tributaries thins rapidly away from the stream channels and is generally less than 1–2 m thick on floodplains. The alluvium deposited by these tributaries has been omitted from the maps in this report for the sake of clarity.

HOLOCENE ARTIFICIAL FILL (Qaf)

Artificial fill is widespread in developed areas along the floodplains of the Columbia and Willamette Rivers and in gullies in the downtown and East Portland areas. Although the most common material is sand dredged from the river, older fills contain significant amounts of construction rubble, mill ends, and sawdust. Unit Qaf is mapped only where fill material has eliminated lakes, sloughs, or gullies delineated during the 1898 survey for the earliest topographic map of Portland (U.S. Geological Survey, 1905). This unit was mapped by comparing the 1:24,000-scale U.S. Geological Survey topographic maps with the 1:62,500-scale U.S. Geological Survey topographic map (U.S. Geological Survey, 1905) and is therefore only depicted on the Portland (fig. 180), Mt. Tabor (fig. 181), and Linnton (fig. 179) quadrangles. Artificial fill 1.5–5 m thick is common in the developed areas of the Columbia and Willamette River floodplains, but its thickness and distribution are highly variable and cannot be accurately depicted at the scale of these maps.

STRUCTURE

A primary goal of this program was to identify potentially active faults in the Portland area. Two general classes of faults have been mapped in this study. Faults designated on the maps by a long dash pattern are inferred from the offset of well-defined stratigraphic units, and these faults are largely confined to the Lake Oswego quadrangle (fig. 184) and the southwest quadrant of the Gladstone quadrangle (fig. 185) where the stratigraphy of the Columbia River Basalt Group has been mapped in detail (M.H. Beeson and T.L. Tolan, unpublished mapping, 1988; Beeson, Tolan, and Madin, 1989). Faults designated with dotted lines in these areas represent buried faults mapped by Beeson, Tolan, and Madin (1989). Faults designated by dotted lines on the other quadrangles are mapped along relatively abrupt changes in elevation of a single contact. There is clearly significant erosional relief on many of the major contact surfaces, particularly the top of the Columbia River Basalt Group that is incised by buried paleochannels up to 152 m deep. The interpretation of any particular change in contact elevation as a fault rather than buried paleotopography is based on examination of regional trends, neighboring structures, and geomorphology.

The sense of vertical offset on faults is generally obvious from the change in the elevation of the contact. The amounts of fault offset indicated by depth-to-bedrock contours on the maps are estimates based on limited borehole data. The vertical offset on many faults appears to die out or change sense along strike.

Horizontal offset cannot be proved or disproved on any of the mapped faults. Exposed fault planes are rare, but subhorizontal slickensides have been found on fault planes in the Columbia River Basalt Group in the southeastern part of the Lake Oswego quadrangle (fig. 184) (M.H. Beeson, oral commun., 1989).

All of the faults mapped clearly cut the Columbia River Basalt Group and, therefore, have been active since middle to late Miocene time. Several faults cut the upper Miocene to Pliocene Sandy River Mudstone and Troutdale Formation. The youngest faulted rocks in the area are the upper Pliocene to Pleistocene basalt flows of the Boring Lavas. The exact age of faulted Boring Lavas flows in the map area is not yet known. Outside the map area, flows in the Damascus quadrangle (fig. 176) as young as 510±23 ka are faulted (Madin, 1994). Offsets of the Pleistocene loess, the fine-grained facies of the Pleistocene catastrophic flood deposits, or Holocene alluvium have not yet been determined.

The Tualatin Mountains are a narrow northwest-trending range that rises about 305 m above the adjacent basins. Mapping in the Lake Oswego quadrangle (fig. 184) (Beeson, Tolan, and Madin, 1989) has shown the range to be a folded and complexly faulted structural high composed of the Columbia River Basalt Group. Broad anticlinal folds are cut by numerous high-angle faults both transverse and parallel to the main northwest structural axis. The structural high is also cut by several southeast-dipping thrust faults. Schlicker and others (1964) and Balsillie and Benson (1971) suggested that the Tualatin Mountains were the result of uplift along a hypothetical Portland Hills Fault. The mapping of Beeson, Tolan, and Madin (1989) and Beeson, Tolan, and Madin (1991) indicates that the Tualatin Mountains may best be considered a major fault zone.

The large-scale structure of the Portland and Tualatin basins is fairly well understood, and this report only adds detail to the models previously proposed by Swanson and others (1993), Hammond and others (1974), and Hart and Newcomb (1965).

The Tualatin basin is a broad northwest-trending syncline that is faulted along the eastern margin where it meets the Tualatin Mountains (figs. 179 and 183). Intrabasin faulting occurs along the north and east edges of the Bull and Cooper Mountain anticlines (figs. 182 and 183).

The Portland basin is clearly fault bounded along its west edge from the Clackamas River as far north as downtown Portland (figs. 180, 184, and 185). A fairly abrupt step of about 100 m occurs in the top of the basement (units Tcr and Twh) as far north as downtown Portland (fig. 180). Northwest of downtown Portland, this abrupt step is poorly defined or absent. However, the unusually steep and straight front of the Tualatin Mountains and also gravity data by Beeson and others (1975) imply a continuation of a fault in this area, as suggested by Schlicker and others (1964) and Balsillie and Benson (1971). The east edge of the Portland basin is outside the area of this study, but it also appears to be fault bounded with an abrupt step in the top of the basement along much of its margin (Mundorff, 1964; Davis, 1986; Hartford and McFarland, 1989; Swanson and others, 1993). Data on the depth to bedrock are absent in the center of the basin, but limited gravity data (Perrtu, 1980) and proprietary seismic data suggest that the top of the basement is fairly flat through the center of the basin and about 487 m deep. A northwest-trending basement high (Hogenson and Foxworthy, 1965; Swanson and others, 1993; Madin, 1994) occurs south and east of the map area (Damascus quadrangle, fig. 176). Gravity data and limited subsurface data suggest that this high extends to the northwest beneath Mt. Scott, Kelly Butte, Mt. Tabor, and Rocky Butte. The amount of structural relief on this buried feature has been estimated at 91 m based on gravity data of Perrtu (1980). Faulting identified on the Mt. Tabor quadrangle near Rocky Butte and Mt. Tabor (fig. 181) is probably associated with this feature. No depth to basement data are available for the Mt. Tabor or Gladstone quadrangles (figs. 181 and 185, respectively) except along the westernmost edges of both. Depth to bedrock on the remainder of these two quadrangles is a matter of conjecture, and contours have not been drawn.

CONCLUSIONS

The earthquake-hazard geologic maps described in this report indicate that large portions of the Portland metropolitan area are covered by poorly consolidated Quaternary sand, silt, and clay deposits. These deposits may significantly amplify ground shaking or liquefy in future earthquakes, and the maps provide the basic geologic data necessary to estimate the potential for these damage-enhancing effects. Earthquake hazard maps based on these geologic maps have been published for the Portland (Mabey and others, 1993), Mt. Tabor (Mabey, Madin, Meier, and Palmer, 1995), Gladstone (Mabey, Madin, and Meier, 1995b), Lake Oswego (Mabey, Madin, and Meier, 1995c), and Beaverton (Mabey, Madin, and Meier, 1995a) quadrangles.

The earthquake-hazard geologic maps also demonstrate that there are numerous faults in the Portland metropolitan area, although none have been shown to be Holocene in age. The faults depicted by these maps should not necessarily be considered hazardous without further investigation.

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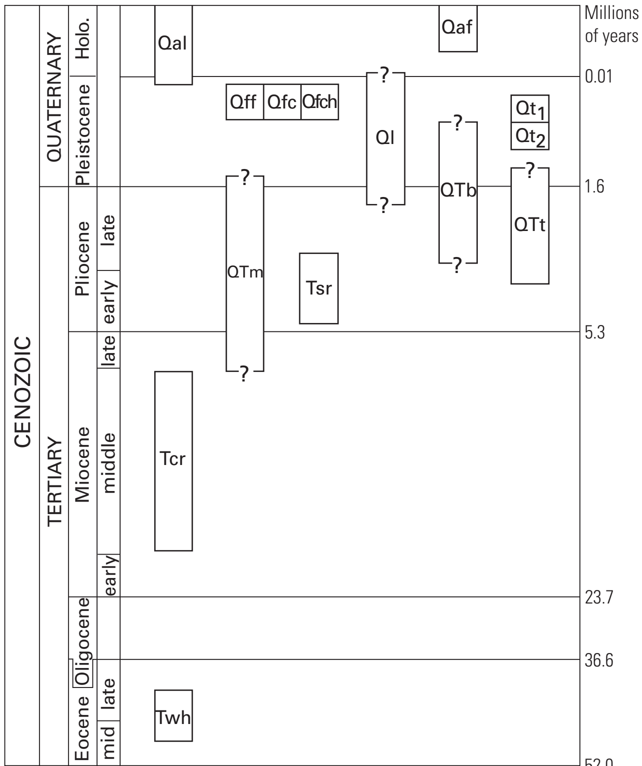
CORRELATION OF MAP UNITS



[1]Time scale after Berggren and others (1985)

DESCRIPTION OF MAP UNITS

(Condensed and revised from Madin, 1990)

Qaf **Artificial fill (Holocene)—**Sand and silt fill that locally includes rock, gravel, construction rubble, sawdust, and mill ends

Qal **Alluvium (Holocene)—**Poorly consolidated river and stream deposits of silt, sand, clay, and gravel confined to channels and floodplains of the major rivers and tributary streams

Catastrophic flood deposits (Pleistocene)—Boulders, gravels, sandy gravels, and sands containing high percentages of clasts derived from the Columbia River Basalt Group and representing high-energy, subfluvial deposition during catastrophic floods caused by repeated failure of the ice dam that impounded Glacial Lake Missoula (Bretz and others, 1956; Baker and Nummedal, 1978; Waitt, 1985; Allen and others, 1986). The age of the most recent catastrophic flood is estimated as 15,500–13,000 yr B.P. (Mullineaux and others, 1978; Waitt, 1987; Beeson, Tolan, and Madin, 1989). Within the study area, catastrophic flood sediments are subdivided into three facies:

Qfch **Channel facies—**Poorly consolidated, complexly interlayered and variable silts, sands, and gravels deposited in major floodways by catastrophic flood events.

Qff **Fine-grained facies—**Coarse sand to silt deposited by catastrophic floods. Finer sedimentary materials are predominantly quartz and feldspar and also contain white mica. Coarser sedimentary materials are mostly fragments derived from the Columbia River Basalt Group

Qfc **Coarse-grained facies—**Poorly consolidated pebble to boulder gravel with silt and coarse sand matrix. Coarse sedimentary materials are poorly sorted and moderately to well rounded. Coarse deposits range from openwork gravel to gravel with considerable fine-grained matrix

Qt_1 Qt_2 **Clackamas River terrace surfaces (Pleistocene)—**Erosional terrace surfaces cut by the Clackamas River across semiconsolidated Pleistocene conglomerates of unit QTt. The surfaces are differentiated by their height relative to the modern Clackamas River. Unit Qt_2 surfaces are higher than unit Qt_1 surfaces. Includes the Estacada Formation of Trimble (1963)

Ql **Loess (Pleistocene)—**Poorly to moderately consolidated, massive, brown to red-brown or gray, quartzomicaceous silt. The exact age is uncertain; Lenz (1977) considered its age as between 700 and 34 ka based on relations with the Boring Lavas and catastrophic flood deposits. Includes the upland silt of Schlicker and Deacon (1967) and undifferentiated sediments of Beeson, Tolan, and Madin (1989)

QTt **Troutdale Formation (Pleistocene? and Pliocene)—**Moderately to well-lithified conglomerates with minor interbeds of sandstone, siltstone, and claystone and volcanic ash and debris flows. The conglomerates typically consist of well-rounded pebbles and cobbles derived from the Columbia River Basalt Group, high-alumina basalt from the High Cascades and Boring Lavas, andesite, dacite, and exotic metamorphic and plutonic rocks. The sand and silt conglomerate matrix and interbeds contain varying amounts of feldspathic, quartzomicaceous, and volcanic lithic and vitric sedimentary materials. Includes the Gresham and Walters Hill Formations of Trimble (1963) and unnamed conglomerate of Beeson, Tolan, and Madin (1989)

QTb **Boring Lavas (Pleistocene to Pliocene)—**Light-gray to gray, diktytaxitic, olivine-(less commonly, plagioclase-)phyric basalt and basaltic andesite flows erupted from a series of local vents. Swanson (1986) reports K/Ar age dates for Boring Lavas of 1.33 Ma (fig. 181, Rocky Butte, Mt. Tabor quadrangle) and 2.6 Ma (fig. 176, Oregon City area). Madin (1994) reports an age for Boring Lavas from the Damascus and Gladstone quadrangles (figs. 176 and 185) of 3,146±62 to 510±8 ka

QTm **Mudstone and sandstone (Pleistocene? to middle Miocene?)—**Moderately to poorly lithified mudstone and sandstone that fills the Tualatin basin; lithologically equivalent to the Sandy River Mudstone. The unit is poorly exposed, but cuttings from a few deep wells consist of blue-gray and brown quartzomicaceous silt and very fine sand. Well logs typically describe blue-gray and brown or red-brown sand and clay and, rarely, gravel. Includes the Troutdale Formation and Sandy River Mudstone of Trimble (1963), Helvetia Formation of Schlicker and Deacon (1967), and undifferentiated sediments of Beeson, Tolan, and Madin (1989)

Tsr **Sandy River Mudstone (Pliocene)—**Moderately to poorly lithified quartzomicaceous mudstone and sandstone in the Portland basin. Organic material is common, including branches and logs. Volcanic ash layers and pumice sands occur locally. Rocks are commonly finely laminated and locally ripple laminated and cross bedded

Tcr **Columbia River Basalt Group (middle Miocene)—**Tholeiitic flood-basalt flows that were erupted from long linear fissure systems in northeastern Oregon, eastern Washington, and western Idaho from about 17 to 6 Ma (Swanson and others, 1979; Hooper, 1982). Members and units belonging to the Wanapum and Grande Ronde Basalts, two of the five formations of the Columbia River Basalt Group, are present within the mapped area

Twh **Basalt of Waverly Heights and associated undifferentiated sedimentary rocks (Eocene)—**Subaerial basaltic lava flows and associated sediments that uncomformably underlie flows of the Columbia River Basalt Group. Two flows have yielded K/Ar dates of about 40 Ma (Beeson, Tolan, and Anderson, 1989)

Contact—Approximately located

Fault—Inferred from offset of well-defined stratigraphy; bar and ball on downthrown side

Fault—Inferred from offset of a single contact (on the Lake Oswego quadrangle and southwest corner of the Gladstone quadrangle, buried fault inferred from offset of well-defined stratigraphy); bar and ball on downthrown side

Thrust fault—Inferred from offset of well-defined stratigraphy; dotted where concealed; sawteeth on upper plate

30 **Isopach of Qff or Qal—**Measurement in feet

300 **Depth to basement contour—**Measurement in feet

Area overlain by more than 1.5 m of Ql

Anticline—Arrowhead on axis indicates direction of local plunge

5 **Strike and dip of beds**

Subsurface data points

△ **Borehole bottoms in units Qal, Qff, or Ql**

\+ **Borehole bottoms in units Qfc, Qfch, QTt, QTm, QTb, or Tsr**

□ **Borehole bottoms in units Tcr or Twh**

Figure 177. Explanation for earthquake-hazard geologic quadrangle maps in figures 178–185.

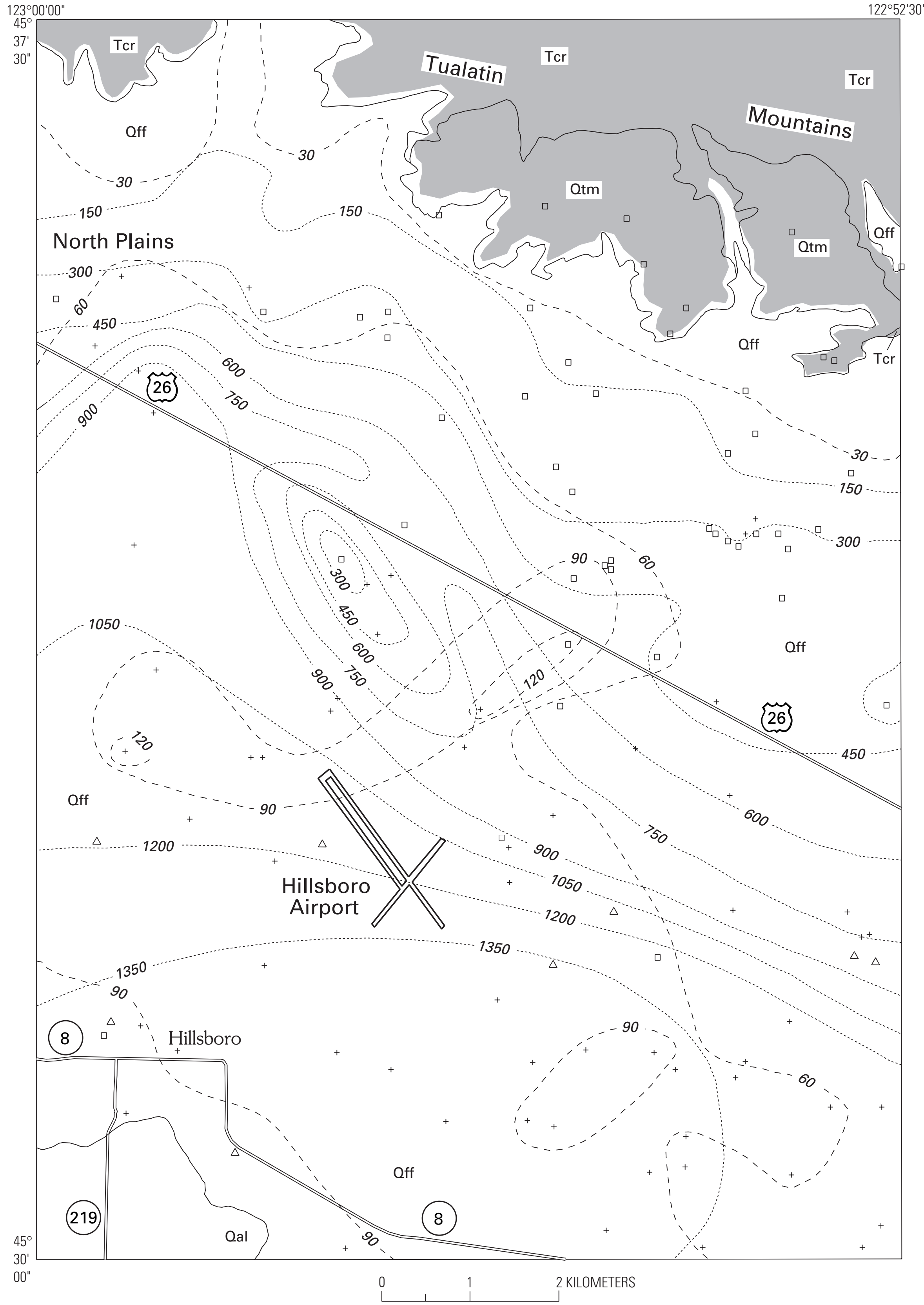


Figure 178. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Hillsboro quadrangle. From Madin (1990).

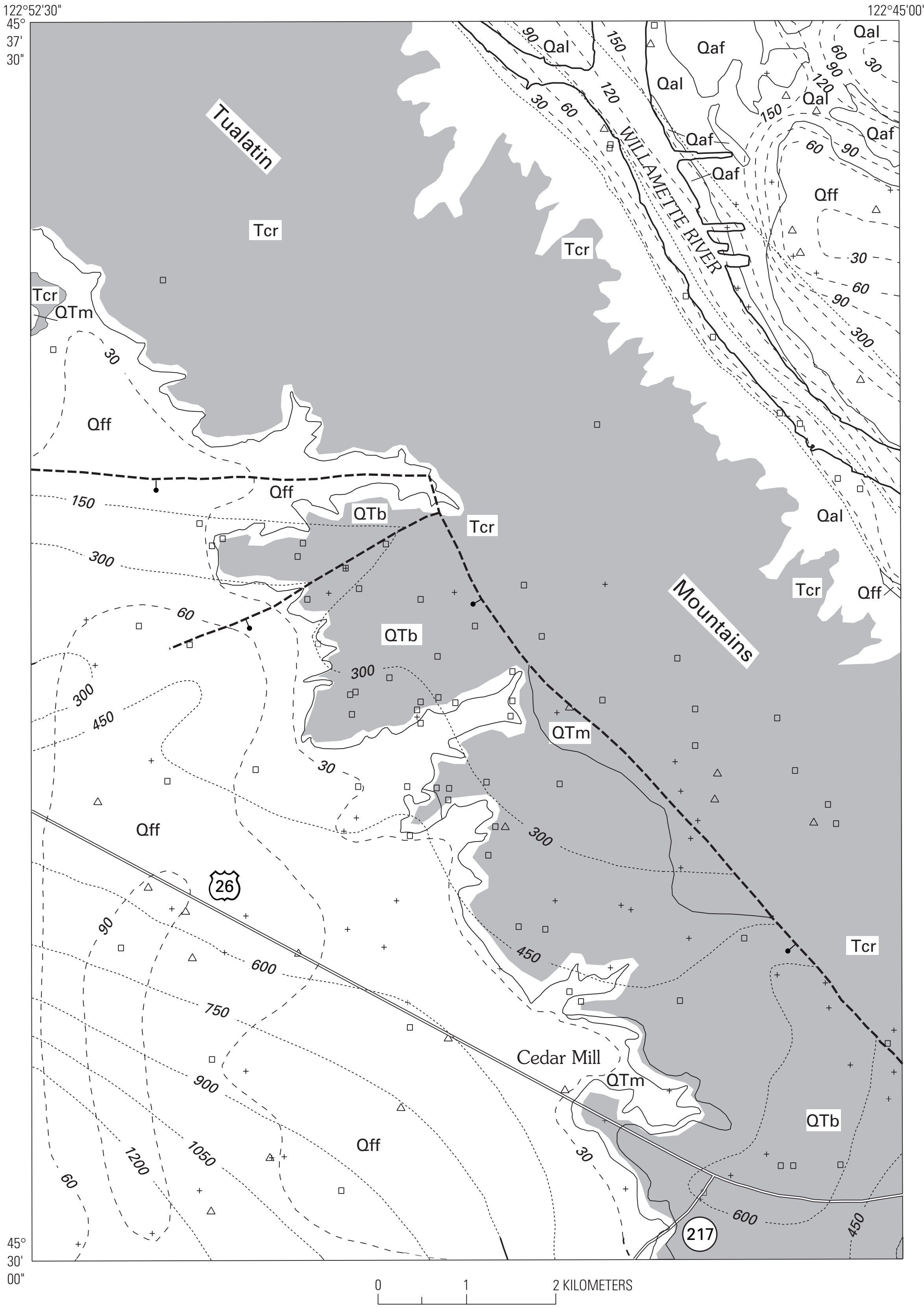


Figure 179. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Linnton quadrangle. From Madin (1990).

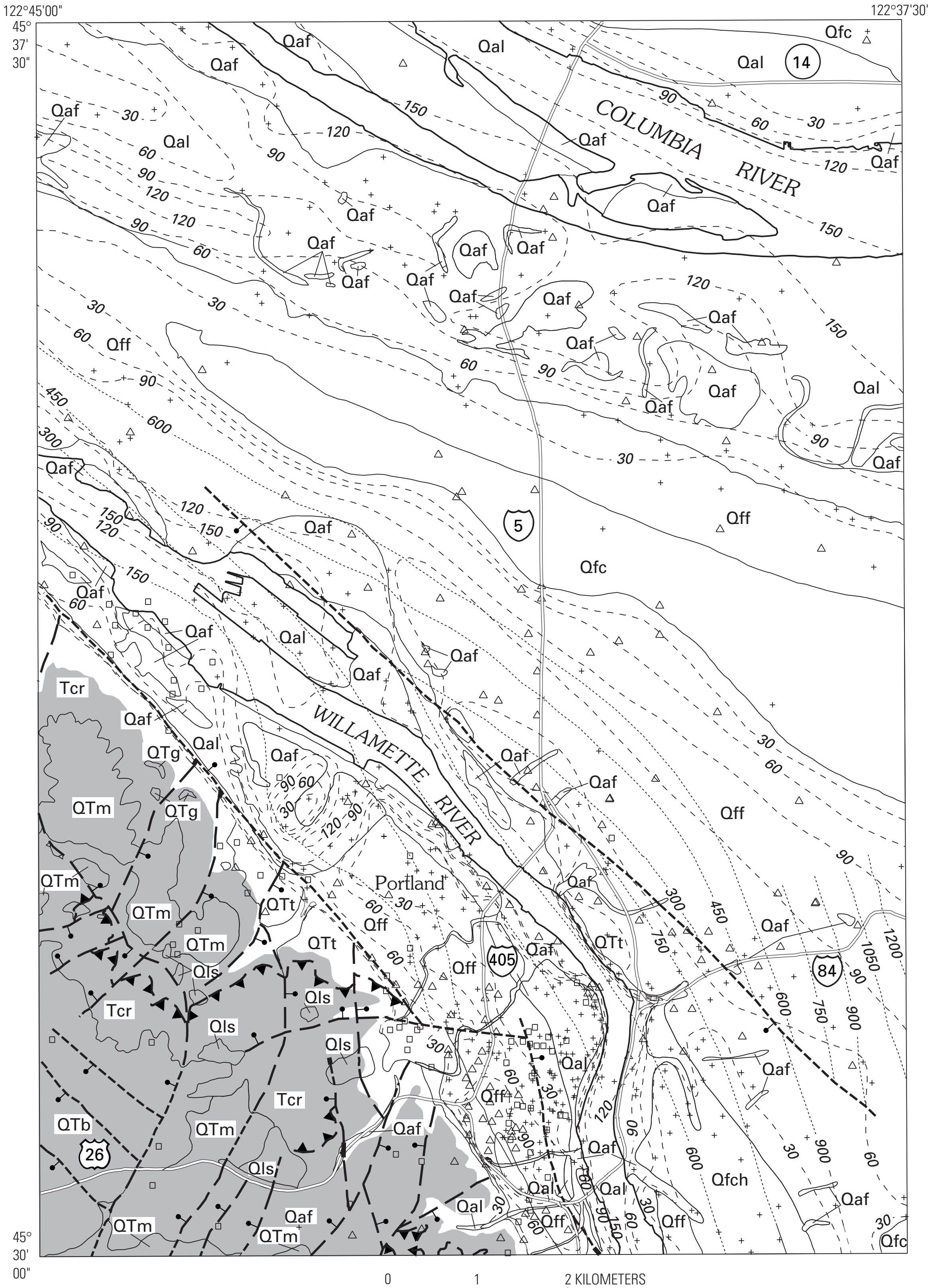


Figure 180. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Portland quadrangle. From Madin (1990).

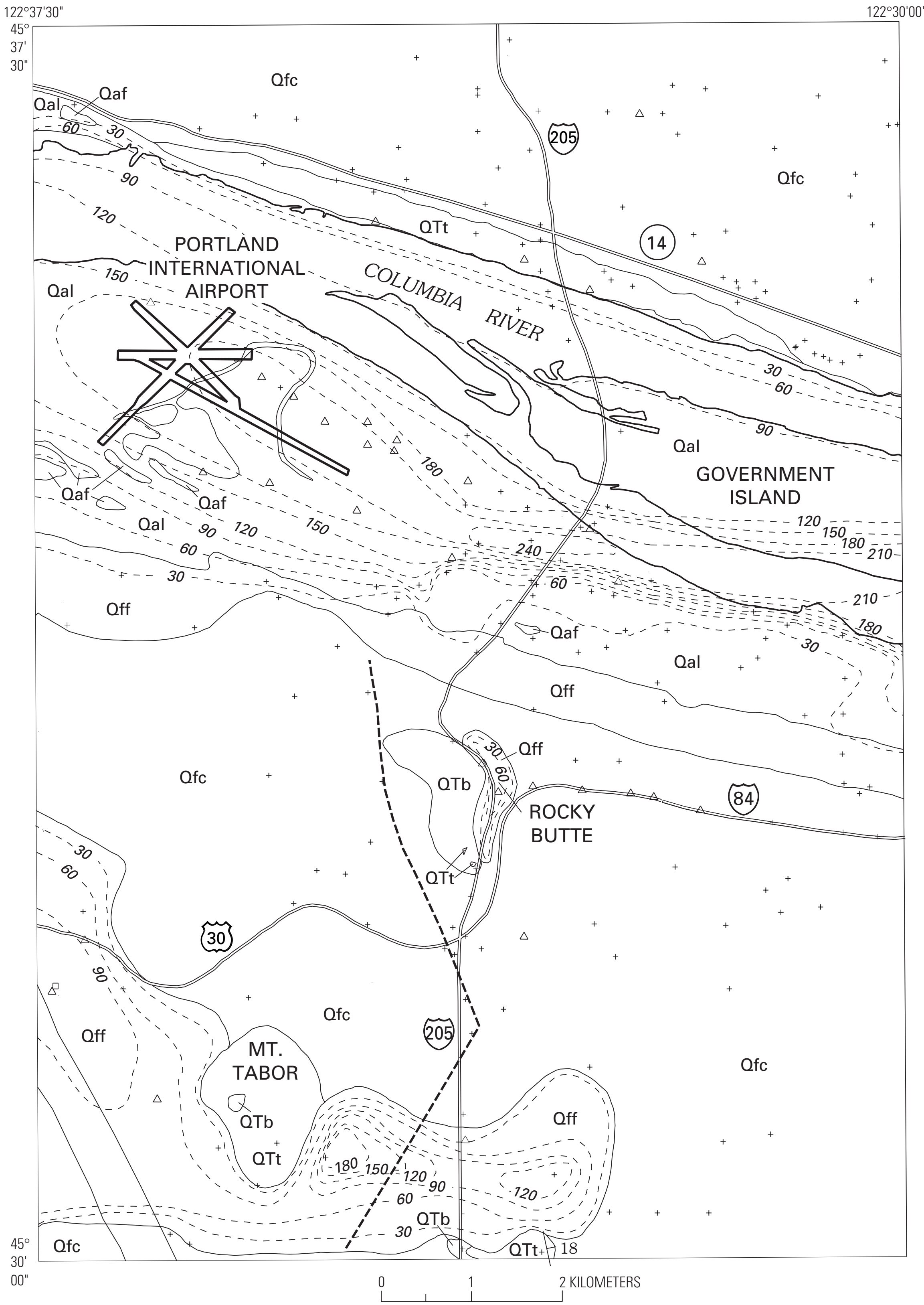


Figure 181. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Mt. Tabor quadrangle. From Madin (1990).

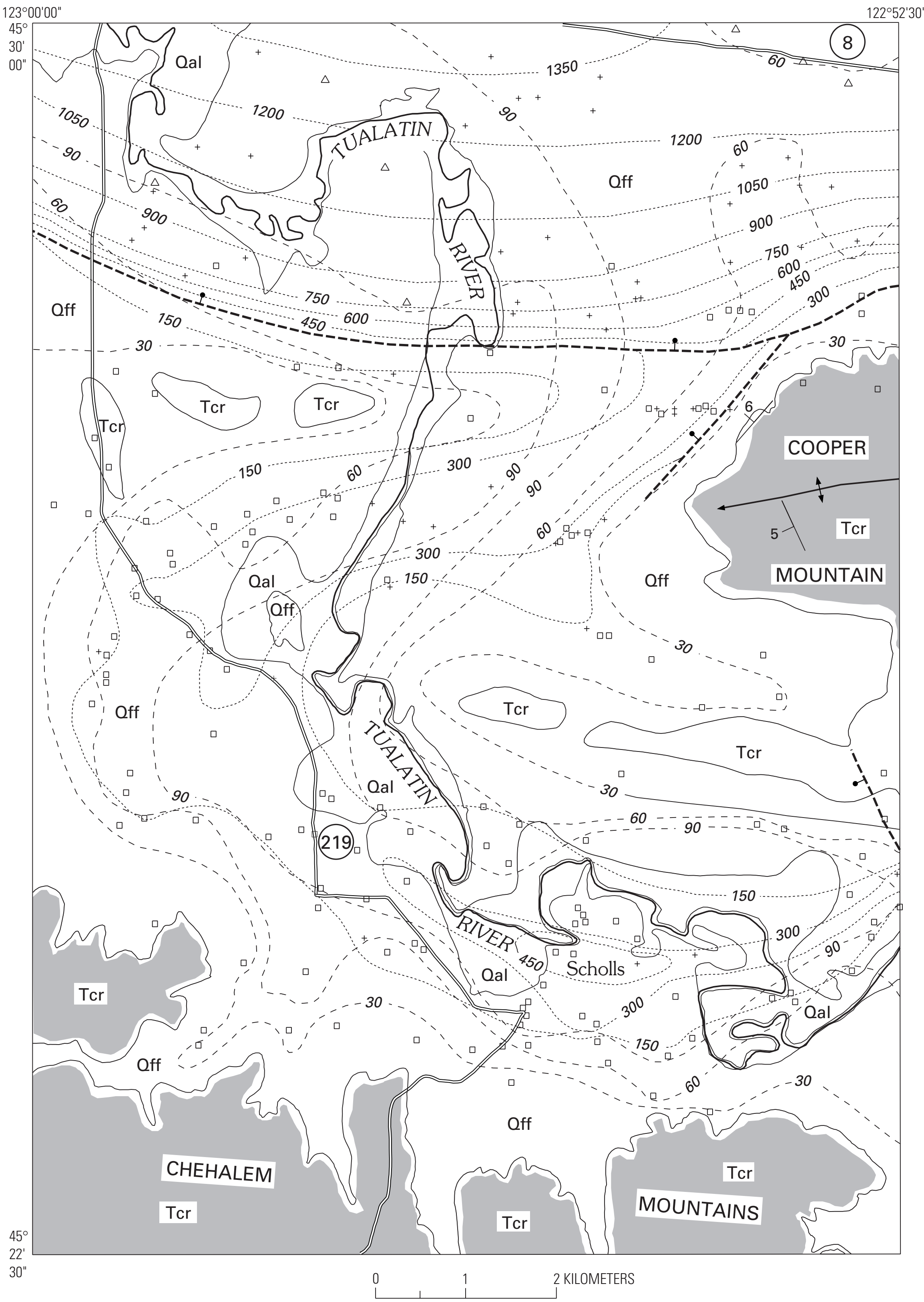


Figure 182. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Scholls quadrangle. From Madin (1990).

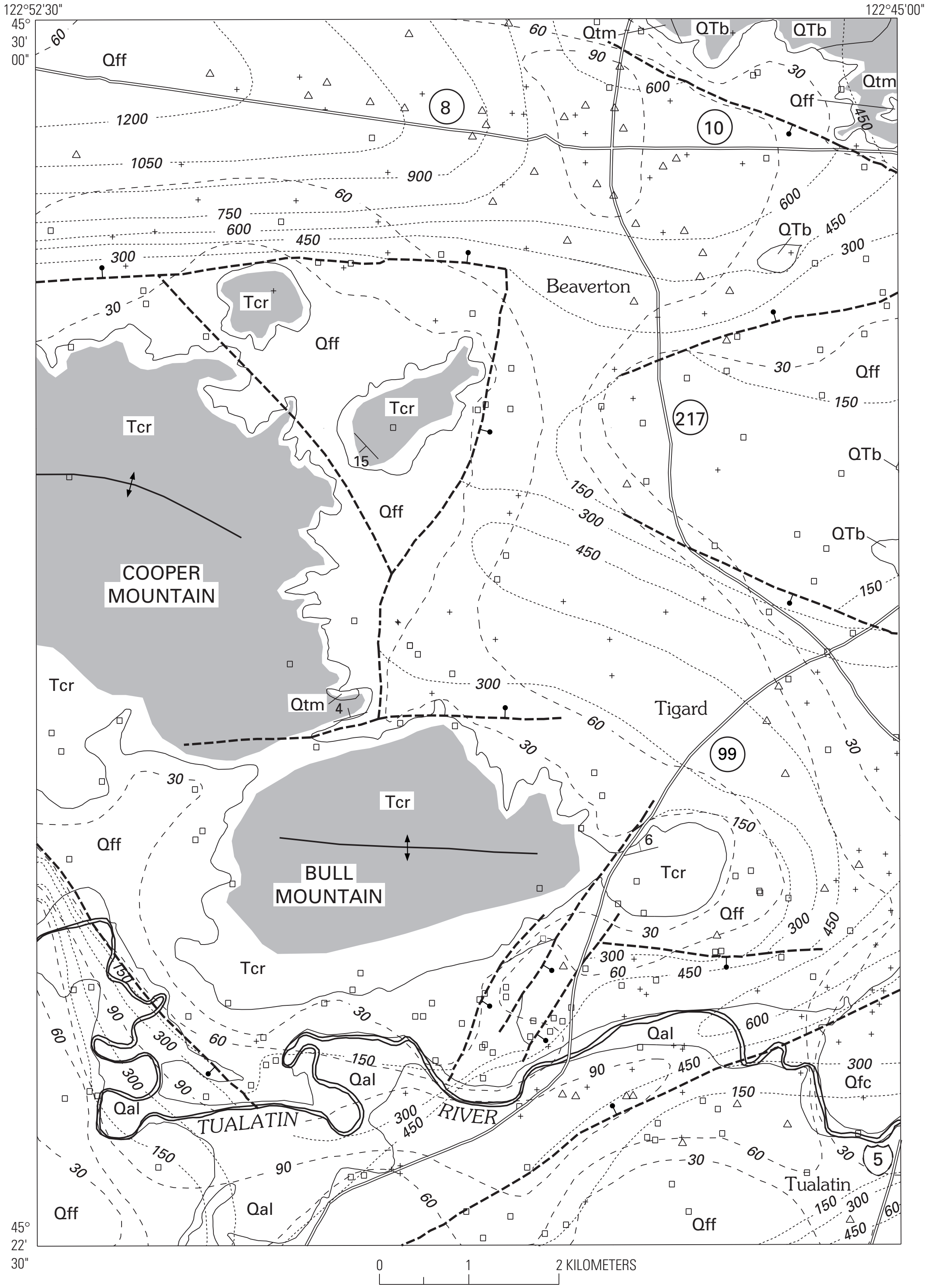


Figure 183. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Beaverton quadrangle. From Madin (1990).

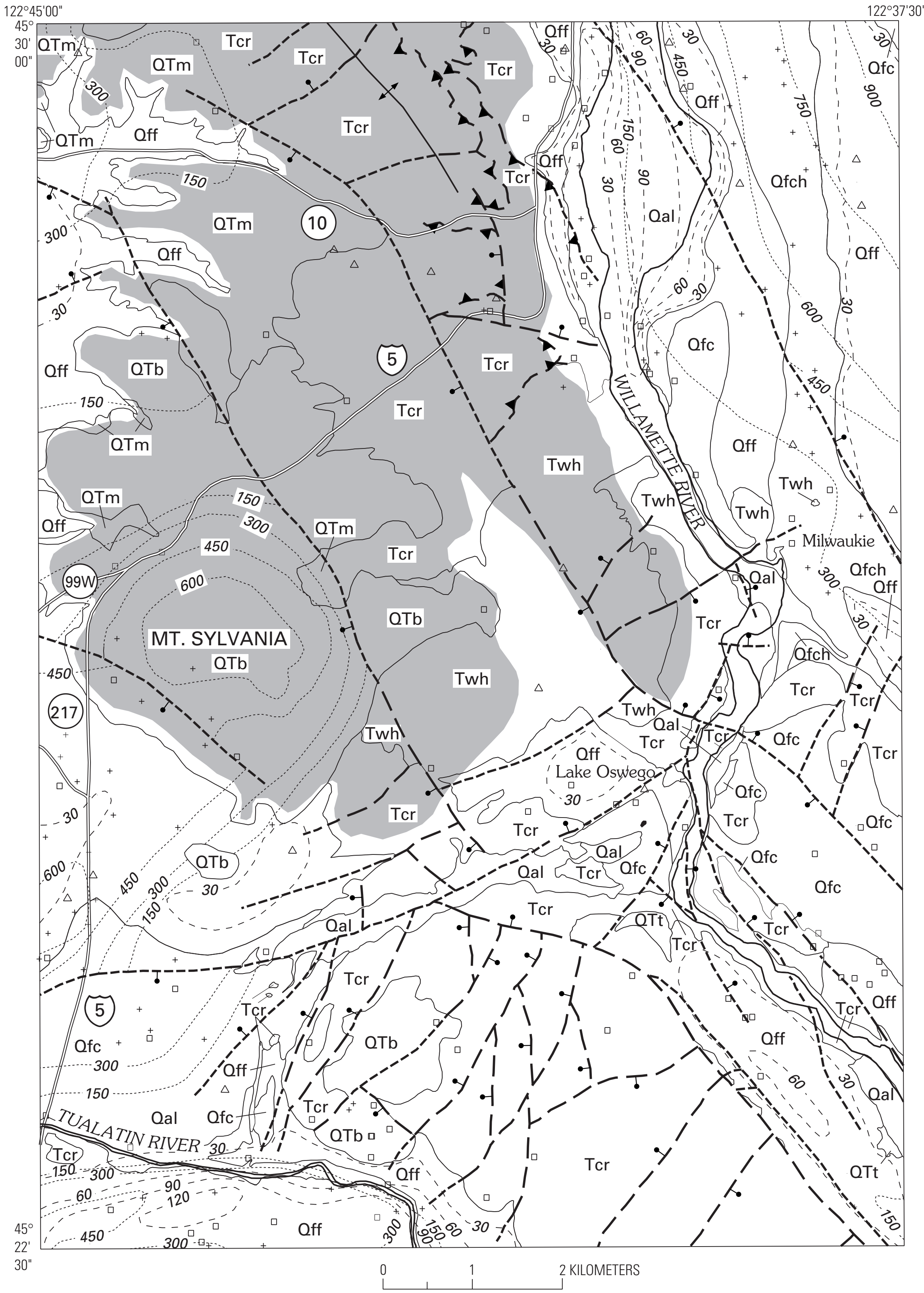


Figure 184. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Lake Oswego quadrangle. From Madin (1990).

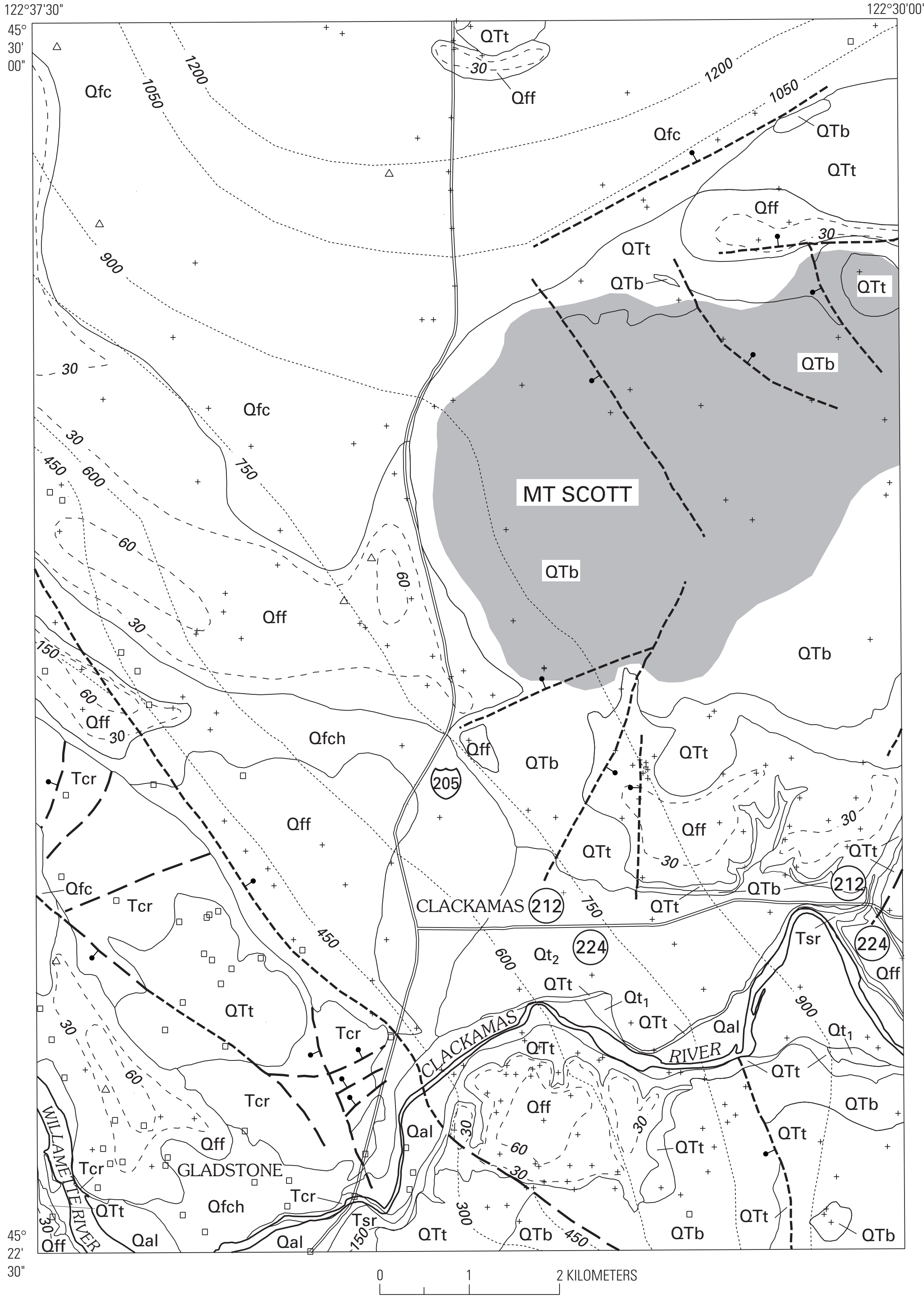


Figure 185. Geologic map of the U.S. Geological Survey's 1:24,000-series topographic Gladstone quadrangle. From Madin (1990).

Ground Failure

Preceding page. *Insert,* rescue of a motorist trapped by fallen bricks moments after the April 29, 1965, Seattle, Wash., earthquake. Photograph by Ken Harris of the Seattle Post-Intelligencer. *Background,* destruction caused by the fall of an unbraced masonry parapet in downtown Klamath Falls, Oreg., during the Sept. 20, 1993, *M* 5.9 and *M* 6.0 earthquakes. Photograph by Lou Sennick of the Herald and News, Klamath Falls, Oreg. (from Dewey, J.W., 1993, Damages from the 20 September earthquakes near Klamath Falls, Oregon: Earthquakes & Volcanoes, v. 24, no. 3, p. 121–128).

GROUND FAILURE ASSOCIATED WITH THE PUGET SOUND REGION EARTHQUAKES OF APRIL 13, 1949, AND APRIL 29, 1965

By Alan F. Chleborad[1] *and* Robert L. Schuster[1]

ABSTRACT

Landslides, ground settlement, and surface cracks generated during earthquakes have been a major cause of property damage and casualties in earthquake-prone regions of the world. The historical record suggests that during future large earthquakes, such ground failures will most likely occur at the same or geologically similar locations as those of previous earthquakes. At many of these locations, the potential for losses has increased due to rapid population growth and extensive urban development. Consequently, detailed information on historical earthquake-induced ground failures, including location, topography, hydrology, and geologic materials, is essential for understanding the nature and extent of the hazard and for responsible land-use planning.

The Puget Sound region earthquakes of April 13, 1949 (magnitude 7.1), and April 29, 1965 (magnitude 6.5), the two largest historical Puget Sound earthquakes, produced ground failures over a large area that includes most of western Washington and part of northwestern Oregon. Because information on the locations and nature of ground failures associated with earthquakes prior to the 1949 event is meager, the many reports on the 1949 and 1965 occurrences are an important source of data for predicting ground-failure hazards from future earthquakes. Our investigation of ground failures produced by the 1949 and 1965 earthquakes consisted of a review of published information, interviews with residents and local officials having information on the ground failures, and a field study of selected ground-failure sites. This collection of new data and the verification and refinement of reported data have resulted in a substantial increase in the quantity and quality of ground-failure information for the region.

Many of the 1949 and 1965 ground failures involved artificial fill underlain by alluvial, deltaic, lacustrine, or glacial deposits. Landslides, including slumps, slides, and flow failures, were common on bluffs overlooking Puget Sound, along roads and railroads, and along the banks of rivers and lakes. Rock falls, rock slides, and rock avalanches occurred almost exclusively in the Cascade Range and along the western Columbia River Valley. Reports of sand boils and other evidence that suggests liquefaction of sediments as the probable cause of ground failure are associated principally with failures in the lowlands involving Holocene fluvial deposits, deltaic deposits, beach deposits, tidal-flat muds, or artificial fill. In a few cases, evidence of possible liquefaction was reported for failures in poorly consolidated Pleistocene glacial deposits.

In this report, we provide topographic maps of the region showing the locations of all known landslides, ground cracks, liquefaction features, and miscellaneous effects related to ground failure from the 1949 and 1965 earthquakes. These maps allow quick visual comparison of the 1949 and 1965 data regarding types of ground failures and their distribution. In addition, we provide tables of information on selected ground failures keyed by number to locations on the maps. These tables include information on ground failure type, geographic location, estimates of location accuracy, and descriptive information from reports and field studies. Also included are numerous photos of ground failures, some published here for the first time.

INTRODUCTION

Many of the losses from a future large earthquake in the western Washington–northwestern Oregon region would likely be caused by ground failure. This prediction is supported by the local historical record and by studies of the effects of past earthquakes in other earthquake-prone regions of the world. The great Alaskan earthquake of 1964, for

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example, spawned major landslides and other ground failures that accounted for 48 deaths (more than one-third of the total fatalities) and 60 percent of the estimated $300 million in total damage (Youd, 1978; Keefer, 1984). Ground shaking during the Alaskan earthquake caused water-saturated sediment beneath roads, railroads, bridges, and port facilities to liquefy and lose strength; resulting ground failures destroyed waterfronts at three coastal communities and buckled or compressed more than 250 bridges (Committee on Earthquake Engineering, 1985). In the same year, a magnitude 7.5 earthquake in Niigata, Japan, produced spectacular ground-failure damage. During that earthquake, saturated sand liquefied beneath a large apartment complex, causing multistory buildings to sink and tilt as much as 60 degrees (Youd, 1978).

Occasionally, earthquakes generate ground failures that result in catastrophic loss of life. Since the year 1700, at least 250,000 people have been killed by earthquake-induced landslides in People's Republic of China (Li, 1990). In a single event in 1920 in Gansu Province, China, massive earthquake-triggered landslides in loess resulted in as many as 100,000 fatalities (Close and McCormick, 1922; Varnes, 1978). Yet another example is the devastating earthquake-induced rock and ice avalanche that occurred in 1970 on Nevados Huascaran, the highest mountain in Peru. In that disaster, the failed mass evolved into a high-velocity debris avalanche that swept downvalley, burying the town of Yungay and part of Ranrahirca and killing at least 18,000 people (Plafker and others, 1971).

Fortunately, ground failures generated by historical earthquakes in the western Washington–northwestern Oregon region have not resulted in catastrophic losses. The potential for greater losses in future earthquakes, however, has increased due to increased population and extensive urban development. About 2.6 million people and $93 billion in property are exposed to the earthquake hazard in the Seattle-Portland region alone (Hays and others, 1988). In addition, some studies suggest that an earthquake of magnitude 8 or greater, larger than any historical Washington or Oregon earthquake, is possible along the Cascadia subduction zone (Heaton and Hartzell, 1986). Such an earthquake would be expected to cause relatively strong shaking and numerous damaging ground failures over a large area that would probably include the heavily populated Puget Sound and Willamette Valley regions.

The historical record also suggests that ground failures caused by future large earthquakes will most likely occur at the same or geologically similar locations as those generated during previous earthquakes (Youd and Hoose, 1978). This was recently demonstrated by the magnitude 7.1 Loma Prieta, northern California earthquake of October 17, 1989 (Youd and Hoose, 1978; U.S. Geological Survey Staff, 1990; Benuska, 1990). In the area of San Francisco Bay, damaging ground failures occurred in zones of artificial fill located along the waterfront, just as in the 1906 San Francisco earthquake. In the Salinas–Santa Cruz area, many cataloged 1906 failures in flood-plain deposits were reactivated by the 1989 earthquake. In addition, some areas in the Santa Cruz Mountains that developed landslides during the 1906 earthquake were again hard hit by landslides triggered by the 1989 event. Thus, studies to determine the distribution, nature, and geologic environments of historical earthquake-induced ground failures are essential to efforts aimed at reducing earthquake hazards.

PURPOSE AND METHOD OF STUDY

The purpose of this study is to better define the distribution and characteristics of ground failures generated by two large Pacific Northwest earthquakes—the Puget Sound earthquakes of April 13, 1949, and April 29, 1965. This information is intended to further develop an understanding of the probable location and nature of future earthquake-induced ground failure, knowledge needed for earthquake-hazard reduction and effective land-use planning in the western Washington–northwestern Oregon region. In order to verify and refine reported data and to expand the existing fund of ground-failure information, a study was undertaken consisting of a review of published information (newspaper and technical journal articles, and governmental agency accounts), interviews with residents and local officials having information on ground failures related to the 1949 and 1965 earthquakes, and a field study of selected earthquake-induced ground-failure sites.

Locations of all known ground failures triggered by the 1949 and 1965 events are plotted on topographic base maps (pls. 4–8), allowing quick visual comparison of regional ground-failure distributions of the two earthquakes. Descriptions of selected ground failures are provided in tables 29–33. Estimates of the accuracy with which the selected ground-failure sites can be relocated, given the available information, are also provided in the tables.

ACKNOWLEDGMENTS

The authors thank Margaret Hopper of the U.S. Geological Survey for providing ground-failure data files compiled during her study of earthquake effects in the Puget Sound region, and Gerald Thorsen, Geological Consultant (formerly with the Washington Division of Geology and Earth Resources), who generously contributed much helpful information, including photographs, of ground failures that occurred in the vicinity of Olympia, Wash. Steve Palmer (Washington Division of Geology and Earth Resources) and Gerald Thorsen reviewed the manuscript and provided valuable suggestions and comments. We gratefully acknowledge the cooperation and technical assistance of personnel of the Washington Division of Geology and Earth Resources, the

Oregon Department of Geology and Mineral Industries, and the City and County governments in western Washington and northwestern Oregon that supplied helpful information on ground-failure locations. Newspaper organizations in the region were especially helpful in supplying photographs of ground failures. In addition, we thank the many individuals who supplied detailed information and photographs essential to the success of this study.

TYPES OF EARTHQUAKE-INDUCED GROUND FAILURE

Ground failure is movement of an earth mass (soil, rock, or debris) that results in permanent displacement or disruption of the ground surface. For the purpose of this report, earthquake-induced ground failure is defined as ground failure triggered by seismic shaking. Landslides, ground settlement, and ground cracks are the major types of earthquake-induced ground failure.

Landslides include rotational slides (slumps); translational slides; rock falls; soil falls; lateral spreads; mud, earth, and debris flows; and rock, soil, and debris avalanches (landslide nomenclature after Varnes, 1978). Three principal effects of earthquake wave propagation trigger landslides (Crozier, 1987): (1) the direct mechanical effect of horizontal acceleration that, at high shaking intensity, may exceed acceleration due to gravity; (2) cyclic loading (repeated events of compressive loading related to earthquake shaking) in clays, sands, and silts with weak interparticle bonding; and (3) reduction, by sudden shock, of intergranular bonding afforded by cohesion and internal friction, irrespective of the degree of saturation.

Ground settlement is defined as vertical displacement of the ground surface due to consolidation of sediments, subsurface sediment flow, landsliding, or a combination of those processes.

Ground cracks are fissures or openings in the ground produced by seismic shaking. Ground cracks are commonly associated with other forms of ground failure such as landsliding and ground settlement.

Sand boils or sand blows, though not technically a form of ground failure, are considered because of their relation to some occurrences of landsliding, settlement, and ground cracking. Sand boils are discussed in more detail in the following section on liquefaction and related ground failure.

Miscellaneous effects that often are related to earthquake-induced ground failure, but are not in themselves conclusive evidence of ground failure, include broken or damaged underground utility lines, permanent bridge and piling displacements, bent or broken well pipe, disruption or change in water-well or spring flow, and formation of dust clouds in areas susceptible to rockfalls, rockslides, or rock avalanches.

Types of earthquake-induced ground failure associated with earthquakes in other areas but not with the 1949 or 1965 Puget Sound earthquakes include ground cracking directly related to tectonic faulting, and regional tectonic subsidence or settlement. Although these forms of ground failure have not been identified among those produced by the 1949 and 1965 earthquakes and thus are not discussed in this report, they are possible hazards from future earthquakes.

LIQUEFACTION AND RELATED GROUND FAILURE

Damaging earthquake-induced ground failure is often the result of liquefaction within a deposit of loose, saturated sand or other granular material. Liquefaction is defined as "the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-pressures" (Youd, 1973). Ground shaking or cyclic loading during an earthquake initiates liquefaction in a loose, saturated granular soil by disrupting grain-to-grain contacts; ensuing soil consolidation and transfer of overlying load from the grains to the pore water between the grains results in increased pore pressure and nearly complete loss of shear strength. The strength loss can result in lateral displacement of large surficial blocks of soil on gently sloping or nearly level ground (lateral spreads), flow failures on moderate to steep slopes (mud, earth, and debris flows), ground settlement, loss of bearing capacity, and sand boils. The following descriptions of liquefaction-related ground failures are excerpted, in large part, from a report by the Committee on Earthquake Engineering (1985).

Lateral spreads generally develop on very gentle slopes (most commonly between 0.3° and 3°) and move toward a free face, such as an incised stream channel. Lateral displacements range up to a few meters and, in particularly susceptible conditions, to tens of meters, accompanied by ground cracking and differential vertical displacement (Youd, 1978). Lateral spreads often disrupt the foundations of buildings or other structures, rupture pipelines and other utilities within the failure mass, and compress engineering structures at the toe of the mass.

Flow failures develop in loose saturated sands or silts on natural or man-made slopes steeper than 3°. Flows may consist of completely liquefied soils or of blocks of intact material riding on layers of liquefied soil. They commonly displace large masses of material for tens of meters at velocities as great as tens of kilometers per hour.

Consolidation and settlement of saturated sediments is commonly associated with and enhanced by liquefaction. Settlement of the ground surface at Portage, Alaska, due to the 1964 earthquake was so great that houses and highway and railroad grades were inundated at high tide.

Loss of bearing capacity occurs when the soil supporting a building or other structure liquefies and loses strength.

This process results in large soil deformations under load, allowing buildings or other structures to founder and sink into the ground. The previously cited instance involving multistory apartment houses that tilted during the 1964 earthquake in Niigata, Japan, is a classic example of bearing-capacity failure due to liquefaction.

Sand boils are formed by water venting to the ground surface from zones of high pore pressure generated at shallow depth by the consolidation of saturated granular soils during seismic shaking. The ejected or vented water usually carries suspended sediment to the surface; this sediment is deposited in a conical shape around the vent. Sand boils are not strictly a form of ground failure because alone they do not cause ground deformation; they are, however, diagnostic evidence that liquefaction has occurred.

GROUND FAILURE CAUSED BY HISTORICAL EARTHQUAKES IN THE WESTERN WASHINGTON–NORTHWESTERN OREGON REGION

It is estimated that a magnitude 4 earthquake is the smallest event likely to cause landsliding (Keefer, 1984). Magnitude 5 earthquakes are considered the minimum for soil liquefaction and liquefaction-generated lateral spreads and flows (Kuribayashi and Tatsuoka, 1975, 1977; Youd, 1977; Keefer, 1984). The western Washington–northwestern Oregon region has experienced many historical earthquakes capable of causing ground failures. Noson and others (1988) listed the 23 known earthquakes felt in Washington having magnitudes greater than 4.7. Of those, 16 occurred in the Puget Sound region between Olympia and the Canadian border, in the Cascade Range, and along the Washington-Oregon border.

Noson and others (1988) noted 14 earthquakes from 1872 to 1980 that are known to have triggered landslides in Washington. However, information on the distribution and nature of landslides and other ground failures related to historical western Washington earthquakes prior to the 1949 Olympia earthquake is meager. For example, credible accounts of landslides generated by the 1872 North Cascades earthquake, the largest known seismic event in Washington or Oregon (magnitude 7.0–7.5), are limited to the few reports along the Columbia River east of the Cascades, along the shores of Lake Chelan north of Wenatchee, Wash., and in southern British Columbia in the vicinity of Fort Shepard and at Lake Okanagan (Coombs and others, 1977). An assertion, based on contemporaneous and later accounts, that the 13,000,000 m^3 Ribbon Cliffs rock slide along the Columbia River north of Wenatchee was triggered by the 1872 event (Coombs and others, 1977) is presently disputed. Kienle and others (1978) concluded, on the basis of tree and tree-stump dating, that the slide did not occur during the 1872 earthquake and that any significant movement of the landslide debris took place more than 215 years ago. In comparison to the few reports of ground failure due to the 1872 earthquake, several hundred to many thousands of landslides have been reported for earthquakes of similar magnitude in other areas of the world (Keefer, 1984), suggesting that few of the landslides triggered by the 1872 North Cascades earthquake were reported. Sparse population and difficult travel and communication at the time may account for the apparent lack of reported ground failures.

Landslides on Mount Rainier were attributed to earthquakes in 1894, 1903, and 1917 (Townley and Allen, 1939); however, few details are known about the extent and nature of those ground failures. A well-known and well-documented rock slide/debris avalanche, the world's largest historical landslide (volume of 2.7 km^3), was triggered by a magnitude 5 earthquake associated with the 1980 eruption of Mount St. Helens. The landslide swept about 22.5 km down the valley of the North Fork Toutle River, destroying public and private buildings, State Highway 504, U.S. Forest Service and logging company roads, and several bridges (Schuster, 1983).

During the period from 1872 to 1989, the greatest number of recorded earthquake-induced ground failures occurred as a result of the magnitude 7.1 Olympia earthquake of April 13, 1949, and the magnitude 6.5 Seattle-Tacoma earthquake of April 29, 1965. Consequently, ground failures associated with those two events were chosen for detailed study and are discussed in the following sections.

PREVIOUS STUDIES

Previous investigators (Hopper, 1981; Keefer, 1983) have identified types of ground failures associated with the 1949 and 1965 Puget Sound earthquakes, described their distribution, and defined geologic environments in the Puget Sound region that have high susceptibility to earthquake-induced ground failure. Their studies were based on published and unpublished data including extensive information derived from written responses to University of Washington intensity-survey questionnaires by local inhabitants of the damaged areas. Hopper (1981) noted that liquefaction phenomena were confined primarily to areas that experienced a Modified Mercalli intensity (MMI) of VIII (with a few occurrences in intensity VII areas) and that reports of landslides and settlement came from areas with shaking intensities as low as MMI V (isoseismal maps for the 1949 and 1965 earthquakes are shown in fig. 186). Keefer (1983) identified the following geologic environments in the Puget Sound region as having high susceptibility to earthquake-induced ground failure: areas of poorly compacted artificial fill; areas of Holocene alluvium, lacustrine sediments, and beach sediments; deltas of rivers emptying into Puget Sound; and rock or soil slopes steeper than 35° in the Puget Sound lowland or adjacent mountains.

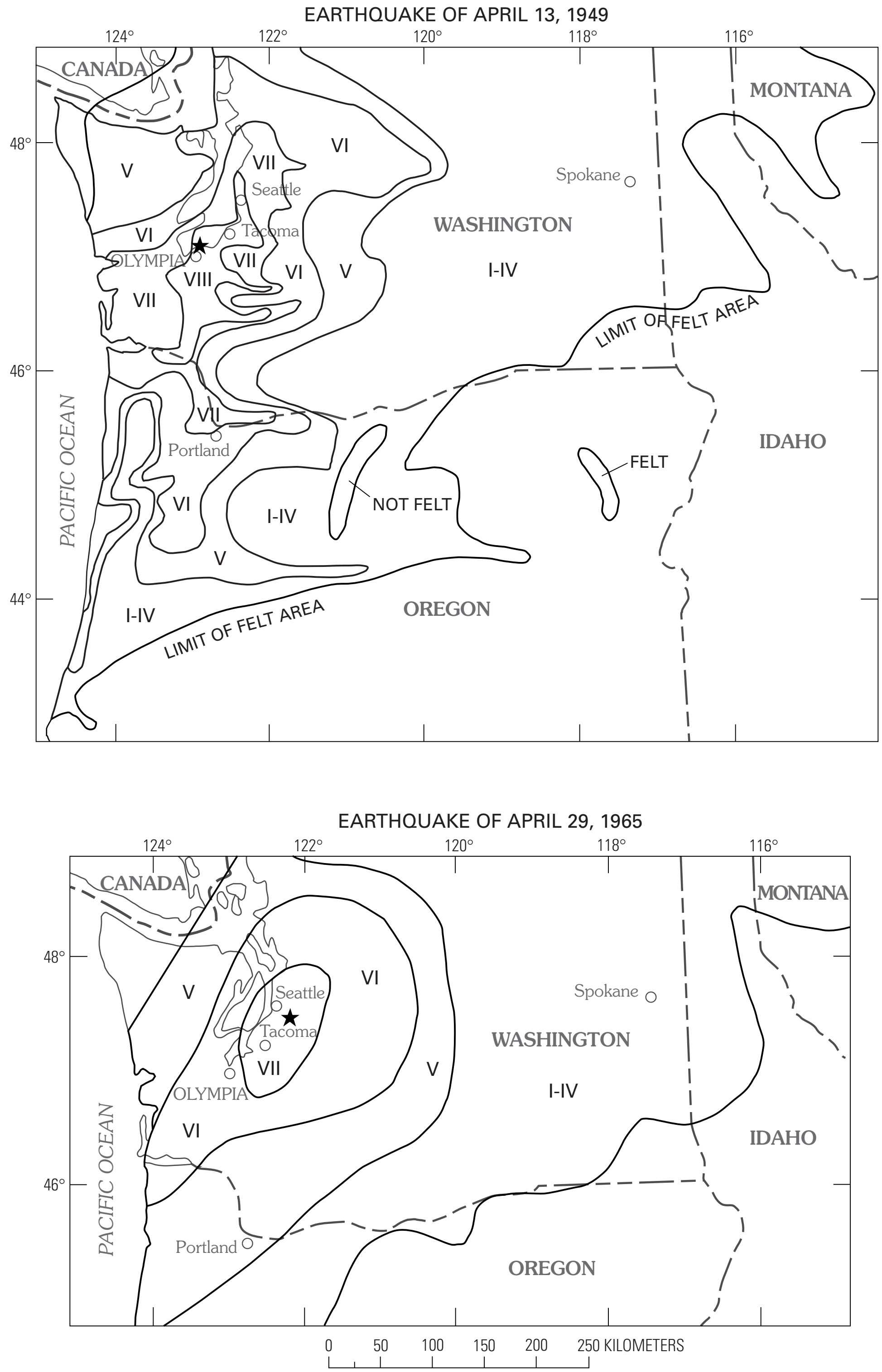


Figure 186. Modified Mercalli intensity maps for the Puget Sound earthquakes of April 13, 1949 (modified from Ulrich, 1949), and April 29, 1965 (modified from Algermissen and Harding, 1965). Stars indicate the earthquake epicenters.

DATA LIMITATIONS

The quality and completeness of available information on 1949 and 1965 ground failures are highly variable. Youd and Hoose (1978), in a similar study, cited several reasons for limited and incomplete data, two of which apply here: (1) most postearthquake investigations have been designed to assess the damage to structures; hence, ground failures not affecting constructed works often have been neglected; and (2) the areal coverage of postearthquake investigations has been uneven—areas in and near centers of population and along major transportation routes have received much more attention than less developed or remote areas. In addition, location information is sometimes vague or of questionable accuracy. In other cases, damage descriptions lack sufficient information to determine whether damage to structures resulted from ground failure or solely from some other cause such as ground shaking. An obvious disadvantage in a study such as this is the inability to examine reported ground failures immediately after their occurrence. Many years have passed since the 1949 and 1965 earthquakes, and field evidence of many of the ground failures is obscure or nonexistent. Despite these limitations, much reliable data on the location and characteristics of ground failures was obtained, which can be used to help delineate areas and geologic environments susceptible to earthquake-induced ground failure.

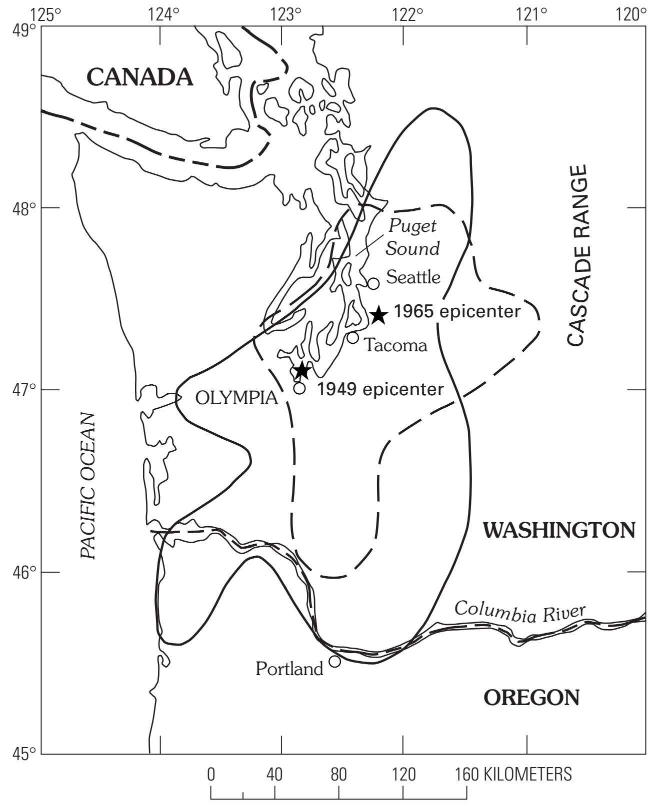


Figure 187. Areas of reported ground failures related to the Puget Sound earthquakes of April 13, 1949 (solid line), and April 29, 1965 (dashed line). Modified from Keefer (1983).

CHARACTERISTICS OF THE STUDY AREA

Ground failures associated with the 1949 earthquake were scattered over an area of about 28,500 km^2 and those of the 1965 earthquake over an area of about 20,700 km^2. The total area considered in this study encompasses these two areas from near the Canadian border on the north to just beyond Portland, Oreg., on the south and from the Cascade Range on the east to the Pacific Ocean on the west (fig. 187).

The physiography and geology of the total area affected by 1949 and 1965 ground failures are highly varied. A broad lowland, bordered on the east by the Cascade Range and on the west by the Coast Range, is underlain predominantly by Pleistocene glacial sediments associated with advances of the Puget Lobe of the Cordilleran ice sheet. These sediments include glacial till, outwash sand and gravel, and glacial lake deposits of sand, silt, and clay. Nonglacial sediments interbedded with the glacial deposits provide a record of repeated advances of the Puget Lobe into the Puget Sound region (Mullineaux, 1970). In some areas of the lowland, the thickness of unconsolidated sediments exceeds 900 m (Hall and Othberg, 1974). The Pleistocene sediments cover Tertiary sedimentary and volcanic bedrock in all but a few areas where the bedrock is covered by younger sediments or is exposed at the surface. Continental glacial sediments extend from north of the study area to a hilly area between Olympia and Centralia, Wash., on the south and from the Olympic Mountains on the west to the Cascade Range on the east. These glacial deposits are generally unconsolidated but vary in degree of compactness. Deposits overridden by the thick glacial ice are more highly consolidated than other glacial and postglacial sediments, resulting in varying physical properties. Compared to bedrock and postglacial deposits, glacial sediments overridden by glacial ice are intermediate in both density and water content (Mullineaux and others, 1967). The erosive action of rivers and glaciers has sculpted the glacial fill, leaving the troughs of Puget Sound, lake basins, broad valleys, and intervening land areas that stand as high as a few hundred meters above sea level. In many places, erosion of the glacial sediments has produced steep slopes that are susceptible to landsliding.

Numerous areas underlain by deltaic sediments, tidal-flat muds, or beach deposits border the many kilometers of Puget Sound shoreline. Also, local to fairly extensive deposits of artificial fill are common along transportation corridors and in residential, business, and industrial areas.

Valley floors in the lowland are underlain chiefly by postglacial alluvial deposits of unconsolidated sand, silt, clay, and gravel up to a few hundred meters thick. Prehistoric mud/debris flows that originated on the flanks of Mount Rainier deposited sediment beyond the mountain front onto nearby valley floors and other lowland areas. One of these, the Osceola "Mudflow," spread material over an area of about 170 km^2 to depths as great as 23 m (Crandell, 1963).

The rugged Cascade Range, in the eastern part of the study area, rises from about 200 m above sea level on its western border with lowland areas to as high as 4,389 m at the summit of Mount Rainier. In many areas, the terrain of the Cascade Range is characterized by steep slopes and sheer cliffs that are prone to various types of landsliding.

In northern Washington, the Cascade Range is composed of a variety of rock types including metamorphic rocks of Paleozoic age, Paleozoic and Mesozoic sedimentary and volcanic rocks of marine origin, and volcanic and plutonic rocks of various ages including those of the Mount Baker and Glacier Peak volcanoes. The northern Cascades were extensively glaciated during the Pleistocene; as a result, glacial till is ubiquitous, and outwash and glacial-margin deposits are common in the river valleys and along the mountain front (Fiksdal and Brunengo, 1981).

Most of the Cascades south of the Skykomish River, within the study area, are composed of Tertiary and Quaternary volcanic rocks. Smaller areas are underlain by intrusive rocks such as granodiorite, rhyolite, and granite, most of which are interspersed among widespread volcanic deposits (Walsh and others, 1987). In a few scattered areas, metamorphic rocks and marine and continental sedimentary rocks of various ages are present.

Towering, snowclad volcanoes such as Mount Rainier dominate the landscape with their steep rock faces and precipitous cliffs formed by the action of glaciers and other erosive agents. Jointed volcanic strata on the sides of the volcanoes typically dip downslope, which adds to other factors that can cause instability.

Alpine glaciers, fed by extensive ice fields, moved down major valleys in the Cascades at various times during the Pleistocene. Many valleys were glaciated in the central part of the Washington Cascades, including those of the Lewis, Kalama, Toutle, Cowlitz, Nisqually, Puyallup, White, Green, and Cedar Rivers. Alpine glacial drift, including till, and glaciofluvial and glaciolacustrine sediment are widespread in several of the mountain valleys occupied by those rivers. In some places on the west side of the range, the drift extends onto the adjoining lowland (Crandell, 1965; Fiksdal and Brunengo, 1981; Walsh and others, 1987). Artificial fill is present locally in developed areas, along transportation routes, and where it has been used in the construction of earthfill dams or other engineered structures.

Other lowlands within the study area are situated south or southwest of the Puget Sound lowlands in southwestern Washington and northwestern Oregon. These include the valleys of the Chehalis, Cowlitz, Columbia, and Willamette Rivers. Valley floors in these lowland areas are underlain chiefly by unconsolidated Quaternary alluvium composed of silt, sand, gravel, and clay (Trimble, 1963; Walsh and others, 1987). Local areas of artificial fill are common in some towns and urban areas, along railroads and highways, and at the sites of engineered structures such as earthfill dams.

Hills and mountains rise from valley bottoms and coastal areas in southwestern Washington and northwestern Oregon to form the upland areas of the remaining part of the study area. Most of the upland areas range in elevation from a few hundred to more than a thousand meters above sea level. The Coast Range of southwesternmost Washington and northwesternmost Oregon is composed predominantly of marine and nonmarine sedimentary rocks, various types of volcanic deposits, and basic intrusive rocks, all of Tertiary age (Warren and others, 1945; Walsh and others, 1987). Unlike many glaciated areas of the Cascades, the Coast Range of southwestern Washington and northwestern Oregon typically has a very thick weathering profile related to millions of years of exposure.

Upland areas between the Coast Range and the Cascades in southwestern Washington and northwestern Oregon are also underlain by a variety of rock types including volcanic rocks, continental sedimentary rocks, alpine glacial outwash deposits, and periglacial flood deposits. As in other parts of the study area, artificial fill is present locally in developed areas and along transportation corridors. Also, beach deposits that include fine to coarse beach sands and gravels, dune sands, and estuarine muds and sands are common in the coastal areas of the region.

The study region includes large areas that are particularly susceptible to landsliding due to a number of causes. The general character, distribution, and causes of landslides in the various physiographic regions of Washington and Oregon, including the area of this study, have been reviewed by the authors in a previous report (Schuster and Chleborad, 1989).

PRECIPITATION AND GROUND WATER

Precipitation is an important factor affecting the susceptibility of a given area to earthquake-induced ground failure. This is particularly true for areas underlain by sediment types susceptible to liquefaction because saturation or near saturation of sediments is required before liquefaction can occur. In addition, elevated pore pressures associated with saturated slope conditions can reduce slope stability, thus increasing the probability of slope failure during earthquakes.

Western Washington and northwestern Oregon are areas of relatively high precipitation (fig. 188), with the wet season extending from September through April. In the area of study, annual precipitation means range from approximately 122 cm/yr in the area of the Puget-Willamette lowland to more than 254 cm/yr in the high, snowy parts of the Cascade Range. Precipitation records for the Seattle-

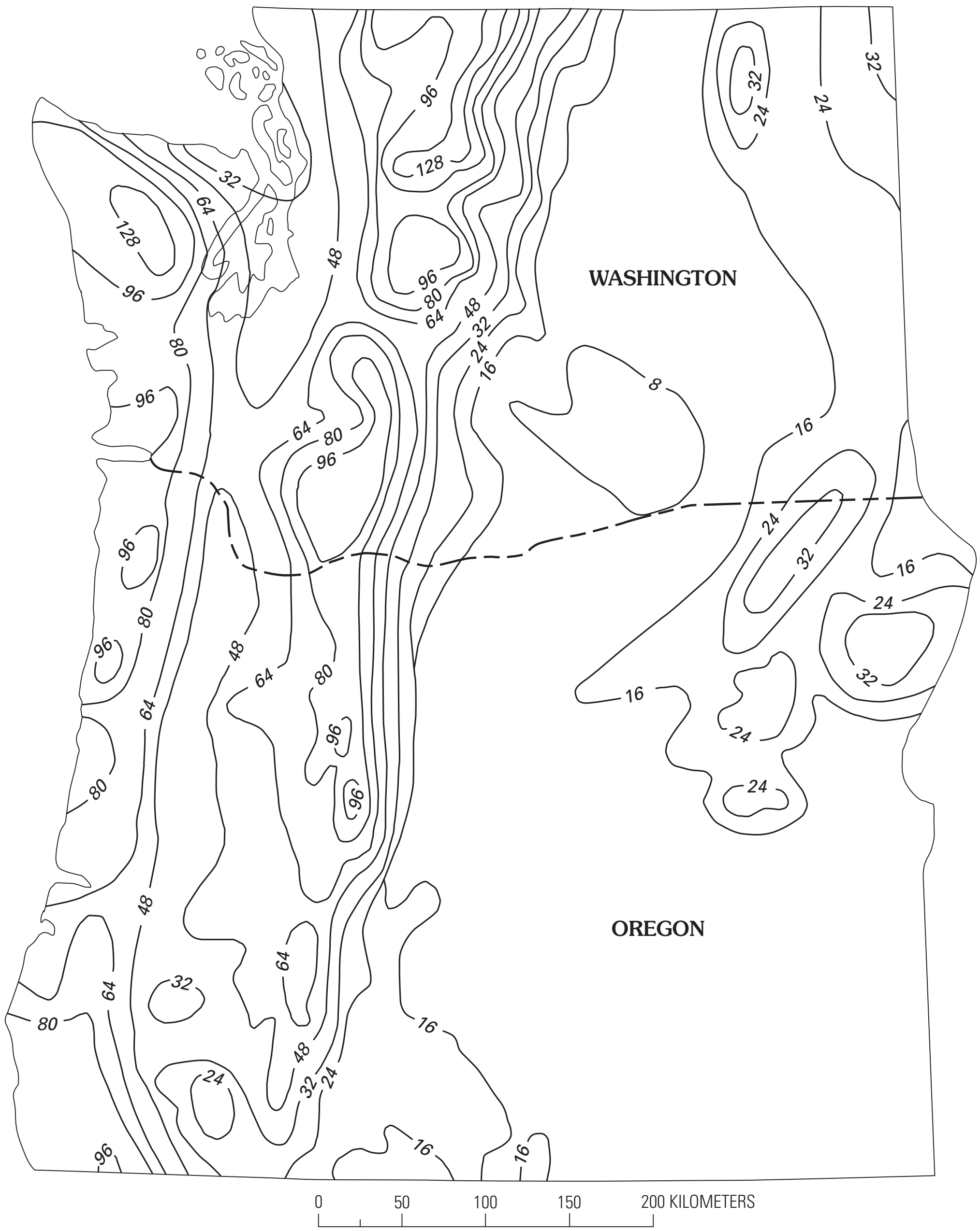


Figure 188. Contour map showing mean annual precipitation (1 inch equals 2.54 cm) in Washington and Oregon for the period 1931–1960 (modified from U.S. Geological Survey, 1970).

Tacoma area for the water years 1948–1949 and 1964–1965 (those associated with the 1949 and 1965 earthquakes) are shown in figure 189. These water years were slightly below normal; 8.66 cm below normal in 1948–1949 and 6.60 cm below normal in 1964–1965. For the purpose of comparison, precipitation records from the Seattle-Tacoma area for the water year 1971–1972 (an unusually wet year) are also shown in figure 189. Precipitation during that year was 40.6 cm above normal. High precipitation was a major cause of numerous damaging landslides that occurred in the Seattle area during the spring of 1972 (Tubbs, 1974). Because the 1949 and 1965 earthquakes occurred well into the wet seasons, water tables were probably at or near their yearly highs, increasing the probability of some types of ground failure; however, had amounts of precipitation been similar to those in the 1971–1972 water year, it is likely that many more ground failures would have have been triggered by the two earthquakes.

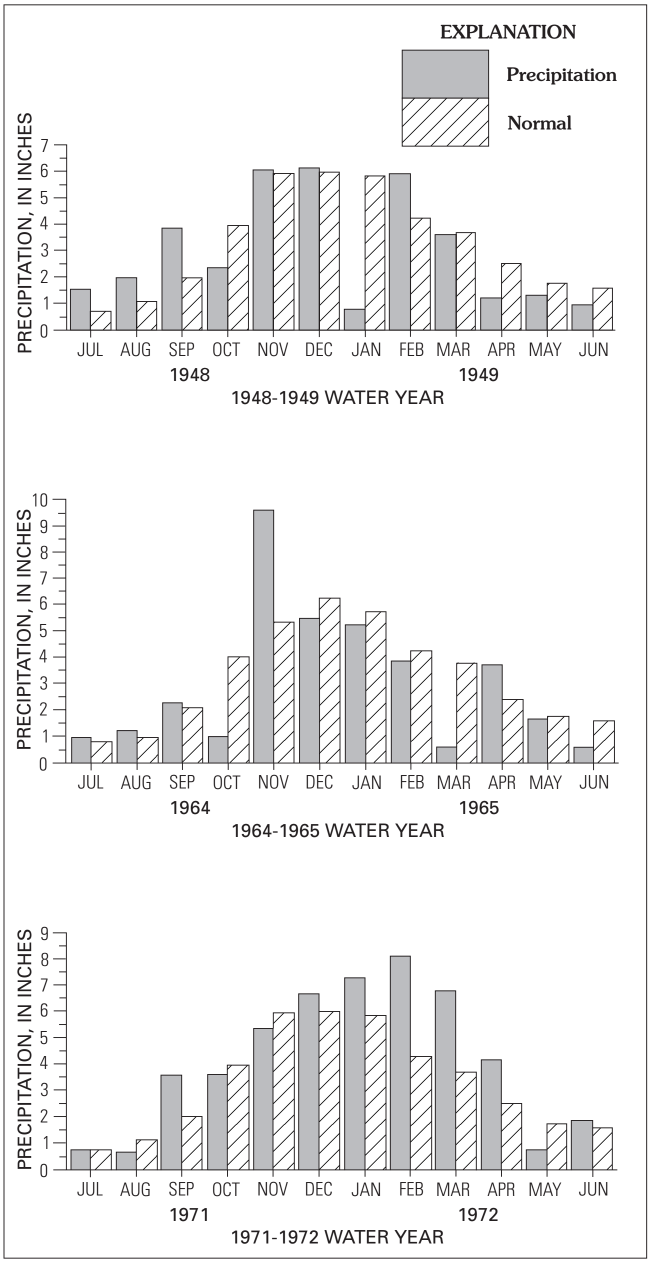


Figure 189. Graphs showing precipitation (1 inch equals 2.54 cm) in the Seattle-Tacoma area for the water years 1948–1949, 1964–1965, and 1971–1972 (U.S. Department of Commerce, 1948, 1949, 1964, 1965, 1971, and 1972).

DISTRIBUTION AND CHARACTER OF GROUND FAILURES TRIGGERED BY THE PUGET SOUND EARTHQUAKES

Data compiled on individual ground failures are presented in plates 4–8, which show ground-failure locations (1949, closed symbols; 1965, open symbols), and in tables 29–33, which provide descriptions of selected ground failures. Entries in the tables include the following: (1) relatively extensive ground failures and ground failures exhibiting relatively large displacements, (2) all known landslides, (3) all known sand boils and other ground failures that appear related to liquefaction of sediments, (4) significant ground failures at locations affected by both the 1949 and 1965 earthquakes, (5) significant ground failures at locations showing concentrations or trends of ground failure, and (6) ground failures that have affected engineered structures such as dams and bridges. Excluded from the tables are the numerous minor settlements and ground cracks that are not clearly related to landsliding or liquefaction phenomena. However, these smaller ground failures are included on the plates in order to show the overall distribution of ground effects and to help identify significant trends or concentrations of ground failures that may be present. Copies of published and unpublished information used in the development of tables 29–33 and plates 4–8 are on file in the offices of the U.S. Geological Survey in Golden, Colorado.

For the purpose of showing ground-failure distributions and for ease of discussion, the study area was divided into four regions. The regions were selected on the basis of the number or density of ground-failure locations in a given area, the availability of base maps at appropriate scales, and, as much as possible, on similarities in topography and geology. The following discussion considers the distribution and character of ground failures in each of the four regions.

CENTRAL AND SOUTHERN PUGET LOWLAND REGION

The central and southern Puget lowland region (pls. 4 and 5) includes much of the Puget Sound lowland. About 85 percent of the reported ground failures in the 1965 earthquake and 50 percent in the 1949 earthquake occurred in this region. Some areas experienced Modified Mercalli intensities as high as MMI VIII during both earthquakes (Ulrich, 1949; Algermissen and Harding, 1965; Hake and Cloud, 1967) (fig. 186). Ground cracks and settlement were the most numerous and widespread of the reported ground failures. Most were isolated occurrences of limited extent that caused only minor damage to roads, buildings, foundations, driveways, utilities, and so forth. Some, however, contributed to the considerable structural damage that occurred in areas of relatively intense ground shaking. Landslides in the region were most common on hillsides and coastal bluffs and along the banks of rivers, lakes, and other bodies of water. Many caused damage to roads, railroads, buildings, waterfront facilities, utility lines, and recreational facilities. One large debris avalanche, with an estimated volume of 500,000 m^3, occurred along the eastern bluff of the Tacoma Narrows 3 days after the April 13, 1949, earthquake. A few flow failures related to the 1965 event also occurred in the region. A significant number of ground failures developed in environments thought to be conducive to liquefaction failures, as suggested by the presence of sediment types susceptible to liquefaction, high water tables, and in some cases the occurrence of sand boils in the immediate vicinity.

NORTHERN HALF OF THE CENTRAL AND SOUTHERN PUGET LOWLAND REGION

The northern half of the central and southern Puget lowland region (pl. 4) includes the parts of King, Snohomish, Kitsap, Island, Jefferson, Mason, and Clallam Counties bounded by lat 48°00' N. and lat 47°30' N. and by long 122°00' W. and long 123°00' W.; this area includes Seattle. Plate 4 shows a conspicuous concentration of ground failures related to both the 1949 and 1965 earthquakes in West Seattle (locs. 7–13) and the adjacent Duwamish River–Harbor Island–Elliott Bay waterfront area (locs. 14–25, and 28).

In West Seattle, the number of reported ground failures for the 1965 earthquake far exceeded those of the 1949 event. One of the most destructive 1949 ground failures was a slump that occurred on moderately sloping ground in artificial fill overlying the Esperance Sand Member of the Vashon Drift (loc. 10; fig. 190). The failure reportedly damaged six homes, including four that were under construction (see damage description, table 29). Hillside residential property (loc. 13) in West Seattle was the site of minor ground cracking in 1949 and ground cracking and settlement in 1965. The proximity of that site to a steep bluff located near the head of a large mapped landslide (Waldron and others, 1962) suggests an incipient slope failure, apparently initiated by the 1949 quake and reactivated in 1965. Minor sliding also occurred in 1965 at a few other locations on steep to moderately sloping bluff areas on the east and west sides of West Seattle (locs. 8, 9, 11, and 12). Two of the 1965 slope failures were wholly or partly in artificial fill (locs. 8 and 11); the other three (locs. 9, 12, and 13) apparently involved the Esperance Sand Member and (or) overlying surficial debris. Most of the bluff areas that border West Seattle have been categorized as unstable with regard to slope stability (Washington Department of Ecology, 1979a). A common slope-failure process that occurs on the bluffs in West Seattle and in other parts of the city, especially during wet periods, involves the Esperance Sand Member and the underlying Lawton Clay Member of the Vashon Drift (Tubbs, 1974; Tubbs and Dunne, 1977). Ground water percolates downward through the Esperance Sand Member until it reaches relatively

Figure 190. Slumping and settlement in West Seattle (pl. 4, loc. 10) induced by the April 13, 1949, earthquake. The slumping exposed artificial fill (lower left) that underlies the site. Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.

impermeable alternating sand and clay layers at the top of the Lawton Clay Member; the water then changes direction and moves laterally until it reaches the hillside, where it saturates surface debris and seeps out onto the ground surface. Slumping of the Esperance Sand Member occurs near the Esperance-Lawton contact, usually due to the development of pore-water pressure in the sand (Tubbs, 1974). Other slides develop as slide debris accumulates and seepage undermines the toes of slopes (Tubbs and Dunne, 1977; fig. 191). Yount (1983) suggested that the water-saturated condition along the Esperance-Lawton contact may be a contributing factor to intensified ground shaking during earthquakes, particularly in the vicinity of Tertiary bedrock at Alki Point, a short distance from the bluffs (Waldron and others, 1962).

Ejection of ground water (a form of sand boil) in the Alki Point beach area (closed and open circles at loc. 7) that occurred during both the 1949 and 1965 earthquakes is a probable indication of liquefaction. The area is underlain chiefly by postglacial beach deposits (Waldron and others, 1962; Mullineaux and others, 1967). Similar deposits in other areas have been found to have moderate to high susceptibility to liquefaction and liquefaction ground failure (Youd and Perkins, 1978; Keefer, 1984). Closer to Alki Point, in the vicinity of Alki Monument (loc. 7, open-square symbol), about 15 cm of settlement occurred in the 1965 earthquake along an extensive stretch of promenade located behind a seawall. Many waterline breaks, some of which may have been caused by unreported or undetected ground failure, also occurred in the Alki Point area in 1965. According to Mullineaux and others (1967), waterline breaks were more numerous at Alki Point than anywhere else in Seattle.

Other 1965 reports of ground failures in the West Seattle area consist of numerous instances of minor ground cracking and settlement that often resulted in damage to foundations, basement floors, sidewalks, driveways, bulkheads, and so on, or jamming and sticking of windows and doors. Some of those failures probably were related to consolidation of sediments caused by vibration, although Hopper (1981) found little or no correlation between damage related to settling reports and reports of chimney damage caused by vibration. Hopper (1981) also noted that nearly the entire cluster of 1965 settling reports for West Seattle is located on the Esperance Sand Member (called the older sand by Waldron and others, 1962) but concluded that the relationship may be coincidental because the same geologic unit appears at other places in the city without any concentrations of reported ground settlement. In addition, a study of the distribution of chimney damage in the 1965 earthquake with respect to the various Pleistocene deposits in West Seattle demonstrated that the damage pattern is not related to recognizable differences in the underlying deposits (Mullineaux and others, 1967). Some incidents of minor settling and ground cracking may have been caused by incipient sliding, particularly those on the steep bluff areas that partly surround West Seattle. The occurrence of ground failures in West Seattle during both the 1965 and 1949 earthquakes indicates that the area is highly susceptible to ground failure caused by intense seismic shaking.

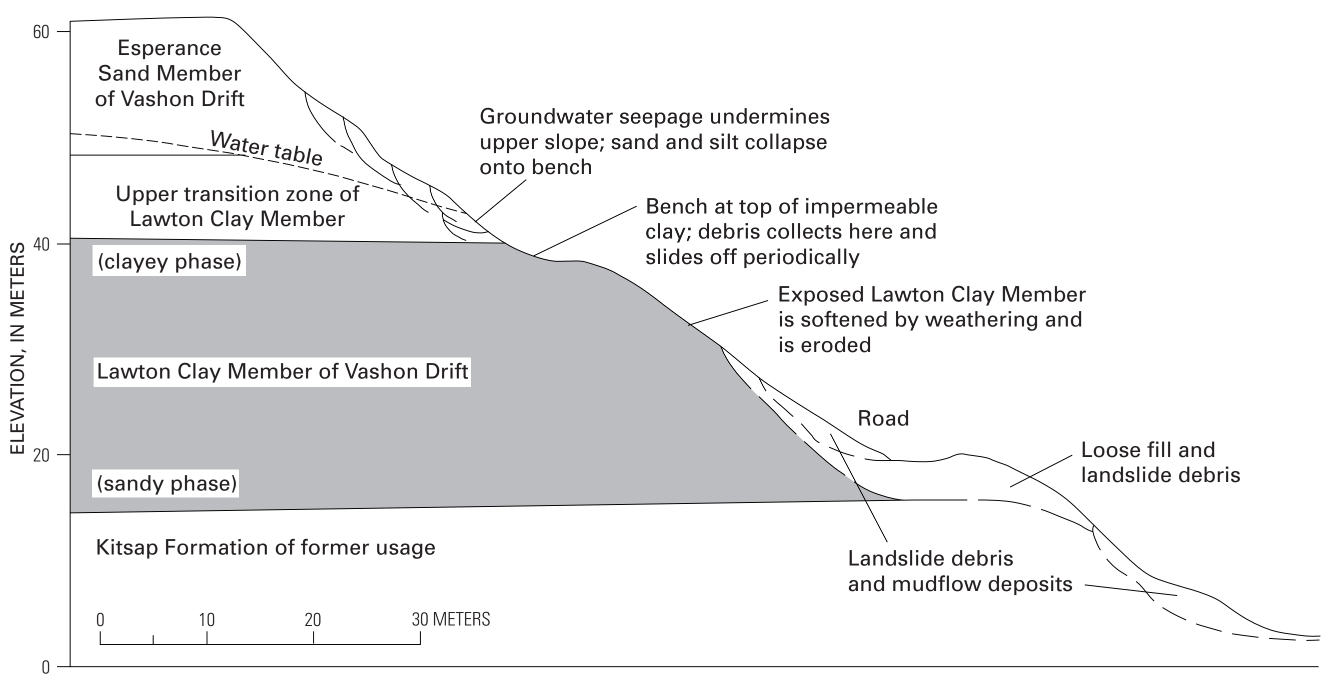
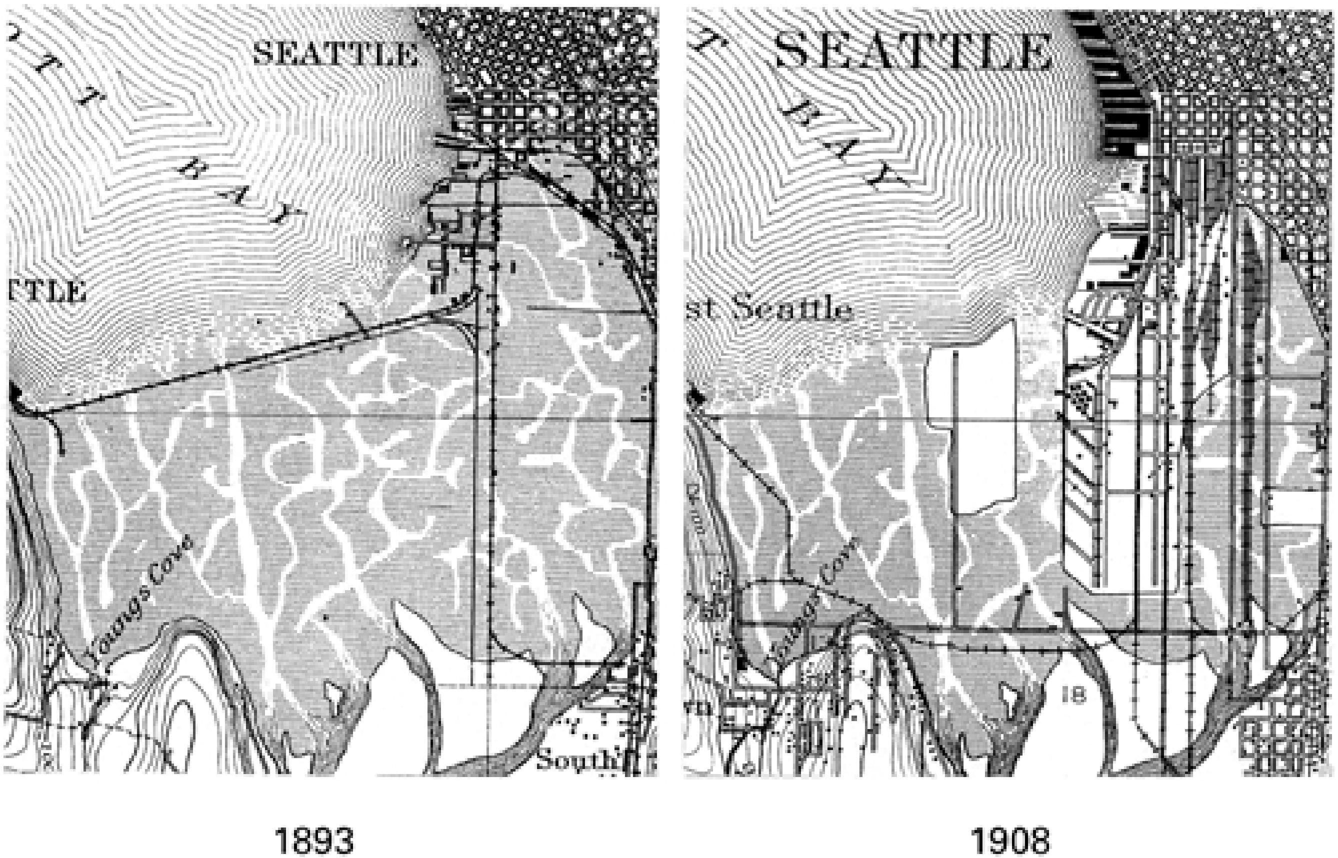


Figure 191. Cross section of a West Seattle bluff showing conditions associated with slope failure (from Tubbs and Dunne, 1977).



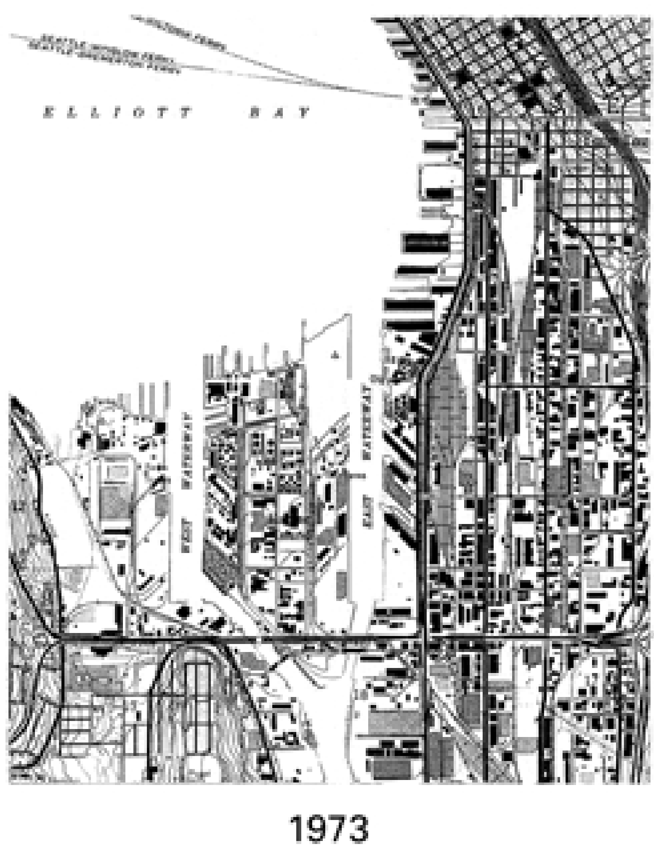


Figure 192. Maps showing the sequence of development of the former tidal flats area at the mouth of the Duwamish River, Seattle, between the years 1893 and 1973. Since 1893, the tidal flats have been extensively covered by artificial fill to allow waterfront development. The area was the site of many earthquake-induced ground failures and considerable property damage in both 1949 and 1965. From U.S. Geological Survey (1894, 1909, and 1949 (photorevised 1968, 1973)).

The Duwamish River–Harbor Island–Elliott Bay waterfront area lies just to the east of West Seattle (pl. 4). The area, much of which is a former tidal flat (fig. 192), was extensively artificially filled (Waldron and others, 1962) to provide real estate for industrial and commercial interests along the waterfront. Structural damage was substantial in this area in both the 1949 and 1965 earthquakes (Edwards, 1951; Mullineaux and others, 1967). The heaviest building damage in Seattle related to the 1965 earthquake occurred in this area, from the lower downtown business district south to about Spokane Street (Mullineaux and others, 1967). A considerable amount of the 1949 and 1965 damage was related to ground failure (table 29, locs. 14–25 and 28). Ground-failure displacements ranged from a few centimeters to about a meter, but most were less than 30 cm. Direct evidence of liquefaction of sediments is provided by reports of sand boils produced by the 1949 earthquake on the west side of the West Waterway (loc. 19), on Harbor Island (loc. 21), and adjacent to the Elliott Bay waterfront (loc. 25), and by the 1965 earthquake at locations 24 and 25 adjacent to Elliott Bay. Incipient lateral spreading or slumping, indicated by lateral as well as vertical displacements, occurred at locations 15–17 north and south of Spokane Street (fig. 193) in 1949 and north of Spokane Street (locs. 18 and 22) in 1965. There were many reports of settlement in the waterfront area in both 1949 and 1965 (pl. 4; table 29) that may have resulted from consolidation of sediments, incipient landsliding, or both. All this evidence indicates that many locations within the Duwamish River–Harbor Island–Elliott Bay waterfront area are highly susceptible to damaging ground failure during intense seismic shaking and that there is a high susceptibility to liquefaction of artificial fill and (or) underlying postglacial sediments in the former tidal flats area. Similar types of ground failure causing equal or greater damage can be expected in the event of future large earthquakes that cause intense ground shaking in the area.

Other locations in Seattle experiencing ground failure in both the 1949 and 1965 earthquakes include the University of Washington practice field area just west of Union Bay at Lake Washington (pl. 4, loc. 31), the area just south of Green Lake (loc. 33), and two locations along the west shore of Lake Washington (locs. 4 and 27). Similar to ground failures in the Duwamish River–Harbor Island–Elliott Bay waterfront area, locations 4, 31, and 33 are also in areas of artificial fill underlain by postglacial lacustrine or alluvial sediments (Waldron and others, 1962;

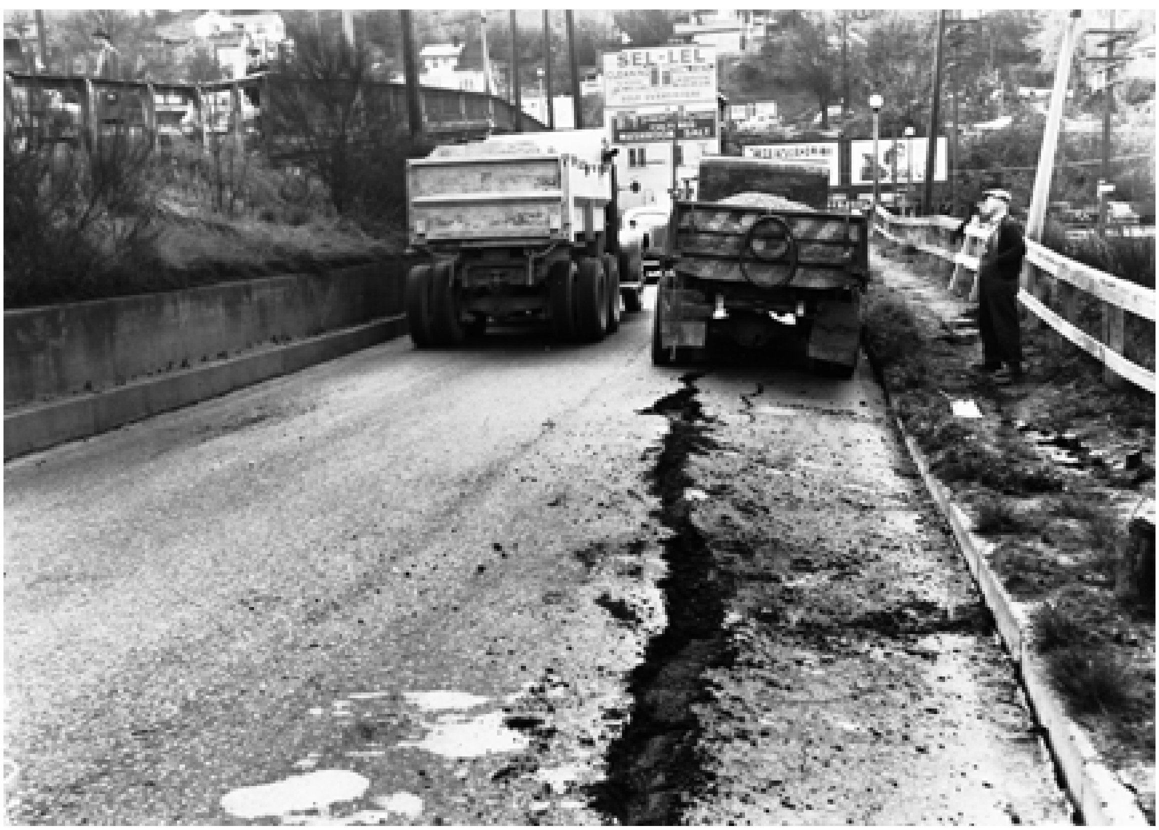


Figure 193. Ground failure along Spokane Street approach to West Seattle (pl. 4, loc. 16) triggered by the April 13, 1949, earthquake. Pavement cracks and slight slump are in a road embankment composed of artificial fill. Note arcuate scarp and tilted light pole at right. Photograph from the Seattle-Post Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.

Figure 194. Slump along the shore of Green Lake, north of downtown Seattle. This 1949 earthquake-induced ground failure occurred near the south end of the lake (pl. 4, loc. 33) in an area that subsequently experienced ground failure during the April 29, 1965, earthquake. Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.

Figure 195. Ground cracks on the southeast side of Green Lake in north Seattle (pl. 4, loc. 33). The cracks opened during or shortly after the April 13, 1949, earthquake and probably resulted from subsidence and lateral movement of ground downslope toward the lake (out of sight to the left of view). Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.

Mullineaux and others, 1967; Hale Lowry, oral commun., 1988). Ground-failure location 27 is locally underlain by artificial fill (Steele Lindsay, written commun., 1965).

In the Union Bay area of Lake Washington (locs. 31 and 32), vertical and horizontal displacements as great as 0.3 m were reported in both 1949 and 1965; damage caused by these ground failures was minor, however. As in the waterfront areas, the occurrence of sand boils and associated ground cracking during the1965 earthquake is evidence of the susceptibility of the artificial fill and (or) underlying alluvial and lacustrine sediments to liquefaction and liquefaction-related ground failure.

Slumping and possible lateral spreading along the south shore of Green Lake (loc. 33; figs. 194 and 195) in 1949 apparently did little damage. Ground failure in the same area in 1965 damaged a small building, fractured walks and paving, and broke utility lines (Mullineaux and others, 1967). Possible liquefaction of sediments at the south end of Green Lake is suggested by the presence of loose granular sediments, the probability of a high water table in sediments at or below lake level, and the characteristics of some of the 1949 and 1965 ground failures that suggest incipient lateral spreading.

A hillside failure in north Seattle, triggered by the 1965 earthquake, evolved into a debris flow that covered a road in Carkeek Park (loc. 36, fig. 196). The flow originated in a large ravine north of Piper Creek. The sides of the ravine are underlain by the Esperance Sand Member and undifferentiated nonglacial sediments (Washington Department of Ecology, 1979a). The Seattle Times (1965c) stated that the slide "opened a pool of ground water that roared down the creek," flooding the road with debris. Water from a small creek that flows down the ravine may also have mixed with the slide debris, adding to its mobility. The slide resulted in only minor damage to the park road.

Another 1965 flow failure occurred in the city of Edmonds, north of Seattle (loc. 40; fig. 197). The failure, which took place at the head of a small ravine on moderately sloping ground, left a cavity tens of meters across and 3–5 m deep. Slide debris flowed downslope for several hundred meters. The site of the failure is within an area underlain by advance outwash deposits of the Vashon Drift, mostly clean sand and gravel (Minard, 1983). According to local residents, the site is also directly underlain by artificial fill. An eyewitness to the event reported that the slide uncovered a stream that mixed with the slide material, transforming the slide "into a muck the consistency of wet cement." The earth flow destroyed an abandoned artesian well and watershed located on the property.

At Port Orchard, on the Kitsap Peninsula west of Seattle (loc. 1), ground failure triggered by the 1965 earthquake badly damaged an asphalt-covered parking lot in a business

Figure 196. Mudflow covering Carkeek Park Road in northwest Seattle (pl. 4, loc. 36). This mudflow developed as material from an earth slide triggered by the April 29, 1965, earthquake mixed with water and flowed down a Piper Creek tributary ravine. Photograph used by permission of the Seattle Times Co.

Figure 197. Earth flow in Edmonds, Wash. (pl. 4, loc. 40), induced by the April 29, 1965, earthquake. The landslide began at the head of a small ravine and flowed downslope about 180 m, destroying an abandoned city water-well shed in its path. Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.

Figure 198. Damage to Country Club Road, southwest of Port Orchard, Wash. (pl. 4, loc. 2), due to slumping induced by the April 29, 1965, earthquake. This slump occurred in granular fill underlain by glacial deposits of the Vashon Drift. Photograph used by permission of the Bremerton Sun.

area adjacent to Sinclair Inlet. The failure occurred in a waterfront area of artificial fill (Washington Department of Ecology, 1979b). Spatial relationships with adjacent geologic units (Washington Department of Ecology, 1979b) suggest that the artificial fill is underlain by the Esperance Sand Member. A newspaper photo of part of the damaged area (Bremerton Sun, 1965a) shows vertical displacements of the asphalt and underlying fill as great as 0.6 m. A slight lateral displacement was indicated in the direction of the inlet.

Another small slide in artificial fill during the1965 earthquake extensively damaged a paved road south of Port Orchard (loc. 2; fig. 198). Movement was downslope in the direction of a small ravine adjacent to the road embankment. Glacial deposits of the Vashon Drift underlie the artificial fill at this location.

Location 39 (pl. 4) at Suquamish was the site of a 1965 coastal-bluff landslide that badly damaged a house and uprooted trees. According to a press report, the shoreline heaved as much as 4.6 m in some places (Hake and Cloud, 1967). The 15-m-high bluff is underlain by the Vashon Drift (till and outwash sand and gravel) (Washington Department of Ecology, 1979b). Field studies in 1988 revealed zones of seepage near midslope in the reported area of sliding. The ground failure resulted in a 30-m-long cracked and raised area on the beach, parallel to the shoreline.

A 10 m section of highway fill, 5 km west of Kingston (loc. 41), slumped about 1 m as a result of the 1965 tremor. At that location, the highway crosses a low, wet area (a ravine and small creek). Geologic mapping by Garling and others (1965) indicates that the failure site is part of an area underlain by recessional outwash deposits of the Vashon Drift. Damage caused by the slide closed one lane to traffic until repairs could be made.

SOUTHERN HALF OF THE CENTRAL AND SOUTHERN PUGET LOWLAND REGION

The southern half of the central and southern Puget lowland region (pl. 5) includes parts of King, Pierce, Kitsap, Mason, and Thurston Counties bounded by lat 47°30' N. and lat 47°00' N., and by long 122°00' W. and long 123°00' W. In this area, reported landslides, ground cracks, and settlement related to the 1949 and 1965 earthquakes were numerous and widespread (pl. 5; table 30).

Sand boils and other ground-failure effects indicating liquefaction were common on broad valley floors extending from the former tidal flat area at Tacoma (area of locs. 77–79) southeast to Puyallup (locs. 60–71), and from Sumner (locs. 57–59) to just north of Kent (locs. 106 and 107). The valley floors are underlain generally by postglacial alluvial sediments and locally by artificial fill (Mullineaux, 1965a, 1965b; Walsh and others, 1987).

On the former Tacoma tidal flat (area of locs. 77–79), sand boils, ground cracks, and settlement occurred as a result of both the 1949 and 1965 earthquakes. Reported displacements were less than 0.3 m, but ground cracks developed that were as long as 300 m. In one instance in 1949, displacement (indicated by a ground crack) in the direction of the waterfront suggests incipient lateral spreading or slumping (loc. 77). Many waterline breaks occurred in the area in 1949, and streets and other paved areas were damaged by ground cracks and settlement in both 1949 and 1965. The area of the former tidal flat is underlain mostly by fine sand and silt that are extensively covered by artificial fill.

Reports of sand boils produced by the 1949 earthquake were most numerous in and near the city of Puyallup. Much of our data comes from Shulene (1990), who presented information on the location and nature of sand-boil occurrences in the Puyallup area. In northwest Puyallup, sand-boil activity was concentrated in areas north and south of Stewart Avenue (locs. 63–69), such as the 20-square-block area north of Stewart Avenue running west from 5th Street NW to 9th Street NW and from Stewart Avenue north to 8th Avenue NW (loc. 66). Sand boils reportedly pushed through the concrete basement floor of one home and forced timber foundation through the flooring of another, which caused considerable damage. Also, liquefied sand came up through a basement floor and floated a furnace that was apparently unsecured. In addition, city water mains were broken and ground cracks opened across some streets and walks. In one case, vertical displacement associated with a ground crack that crossed a street was great enough to cause a drop that was noticeable when driven over by a car. In general, reports of sand boils in this area did not include detailed descriptions of the amounts and types of sediment involved; however, at two of the sites, several small mounds (maximum dimension less than 0.6 m) of black sand were reported. Damage to the basements described above, however, suggests considerably larger volumes of ejected material at those locations.

Another concentration of sand-boil activity occurred in an area just south of Stewart Avenue and west of 12th Street NW (loc. 68). Ground cracks several meters long and several centimeters wide developed, and some reported "geysers" (sand boils) deposited many yards of sediment on the surface and caused flooding (figs. 199–201). At one location, as many as 20 sand boils appeared that left "cone shaped" piles of light-colored sand as much as 18 cm in diameter and 20 cm high; at another "sand pile," diameters were estimated as 0.6–0.9 m. At yet another location, sand boils producing a blue-gray sand were reported. The only sand-boil activity reported for the 1965 earthquake in or near Puyallup occurred within this same area (loc. 68). The 1965 occurrence took place on the Aylen Junior High School playfield and reportedly produced a "considerable amount of water."

Five or six "geysers" produced by the 1949 earthquake were reported to have deposited mounds as much as 0.3 m

Figure 199. Sand boil in Puyallup, Wash. (pl. 5, loc. 68), produced by the April 13, 1949, earthquake. The earthquake generated many sand boils in northwest Puyallup. Some, such as this one, deposited considerable volumes of sedinment on the surface; others were associated with damage to homes in the area. The sand boil vent (collapsed area in the center) is 2–3 m long. Photograph by Richard Six, Puyallup, Wash.

Figure 200. Ground crack and ejected sediment (sand boil) produced by the April 13, 1949, earthquake. This ground failure in northwest Puyallup, Wash. (pl. 5, loc. 68), may indicate incipient lateral spreading due to liquefaction of sediments. Shadow of individual (lower left) shows scale. Photograph by Richard Six, Puyallup, Wash.

Figure 201. Flooding in northwest Puyallup, Wash. (pl. 5, loc. 68), at the time of the April 13, 1949, earthquake. According to local residents, the flooding could not be attributed to broken water mains and may have resulted from the ejection of ground water from the many sand boils that occurred in the area. Photograph by Richard Six, Puyallup, Wash.

high at a location along West Main Street (loc. 63) presently occupied by the Puyallup High School Gymnasium. To the west (loc. 69), a basement was "pushed up" on one end so that the house teetered, and liquefied sand ejected into a basement attained a depth of approximately 1.2 m. Also at this location, 0.3-m-high sand mounds developed "all over" a cultivated field. In addition, a report of ground cracks and a "shift" in a road adjacent to the Puyallup River in Puyallup (loc. 67) suggests slumping or lateral spreading at that location.

Northwest of Puyallup, along the west side of Clarks Creek (loc. 71), a 60- to 100-m-long crack developed during the 1949 earthquake and exhibited as much as a few meters of horizontal and vertical displacement (fig. 202). Lateral movement was in the direction of the creek, indicating lateral spreading or slumping of the alluvial soil. The foundation of a nearby house on the east side of Clarks Creek was reportedly destroyed, probably as a result of ground failure.

Sand boils occurred at several locations north of the Puyallup River. Included among these were the reports of a sand-boil deposit as great as 5 m in diameter (loc. 72), "dozens" of sand boils composed of light-colored sand (loc. 74), and sand boils 0.3–0.5 m in diameter and 9–12 m apart made up of black, clean sand (loc. 75).

The 1949 earthquake generated many small sand boils with clean, black sand at one location just east of Sumner (loc. 58); detailed descriptions of sediment type were not reported for two other locations to the southeast (locs. 56 and 57).

Farther north, near the King-Pierce County line (loc. 100), sand boils in 1949 reportedly deposited fine sand at various points along a long fissure and at various locations in a cultivated field; in 1965, ejected sand formed many piles over two fields. In this same area in 1949, a fissure reported to be about 30 m long, 0.3 m wide, and as much as 2 m deep developed in a cultivated field. Immediately after the event, water was observed covering the bottom of the fissure. The

Figure 202. Ground crack along Clarks Creek, northwest of Puyallup, Wash., associated with slumping or lateral spreading of alluvial sediments (pl. 5, loc. 71). This 1949 earthquake-induced ground failure extended along 60–90 m of the west bank of Clarks Creek; lateral movement was in the direction of the creek (out of sight to the left of view). Photograph from the Richards Photographic Studio Photo Collection, courtesy of the Tacoma Public Library, Tacoma, Wash.

fissure was located near a swale immediately to the west, which suggests possible lateral movement in that direction. Drilling of a well in the area revealed a sequence of 3.0–3.5 m of clean sand overlying 30–35 cm of peat, followed by more clean sand (Richard Madole, U.S. Geological Survey, oral commun., 1989).

Two sand boils appeared in a cultivated field on the valley floor northwest of Kent near the Green River (loc. 107). A newspaper photograph of one of the sand boils (Kent News-Journal, 1965) shows an open vent, approximately 0.3 m in diameter, surrounded by a circular apron of ejected sediment several centimeters deep and a few meters in diameter.

Landslides were generated along the bluffs overlooking Puget Sound, on hillsides, in road embankments, and along the banks of rivers, lakes, and other bodies of water. Landslides were triggered on the bluffs overlooking Puget Sound at Tacoma (locs. 80–83), on the east and west sides of Vashon Island (locs. 92, 94, and 95), on Fox Island (loc. 84), and west of the Seattle-Tacoma Airport near Three Tree Point (loc. 109). The largest reported landslide triggered by either of the Puget Sound earthquakes occurred on a steep, 90-m-high bluff on the eastern shore of the Tacoma Narrows 3 days after the April 13, 1949, earthquake (loc. 81; fig. 203). The bluff failed catastrophically, sending about 500,000 m^3 of sand, gravel, trees, and other debris plunging into the waters of Puget Sound. The slide narrowly missed nearby beach homes and created a 2.5-m-high wave front that did minor damage to small docks and boats moored nearby. At the site, thick layers of unconsolidated sand and sand and gravel overlie a firm clayey silt base. Seepage occurs near the bottom of the slope at the gradational contact between the clayey silt base and overlying sand. Geologic mapping indicates that the bluff area is underlain (from top to bottom) by deposits of the Vashon Drift (glacial outwash), Esperance Sand Member, and undifferentiated Pleistocene sediments (Washington Department of Ecology, 1979c). A report of white sand boiling up through a deep crack a short distance from the cliff's edge (Vogel, 1949) suggests that liquefaction of sediments within the hillside may have weakened the slope at the time of the 1949 earthquake, 3 days prior to the failure (Chleborad and Schuster, 1989). Modeling and analysis of the landslide have been performed by Chleborad (1994). Also in 1949, in a similar geologic setting (pl. 5, loc. 84 on Fox Island), a 15- to 30-m-high bluff failed, dumping a small house into Puget Sound. The bluff at that location is composed of the Esperance Sand Member and underlying

Figure 203. Tacoma, Wash., landslide, April 16, 1949 (pl. 5, loc. 81). This landslide was probably initiated by the 1949 earthquake that occurred 3 days previously. The large mass narrowly missed homes to the south on Salmon Beach as it plunged into the waters of the Tacoma Narrows. The resulting 2.5 m tidal wave damaged small boats and nearby dock facilities. Photograph used by permission of the Associated Press.

undifferentiated Pleistocene sediments (Washington Department of Ecology, 1979c). Two slumps that caused minor damage along the bluffs in Tacoma (locs. 80 and 82) showed activity in 1949 and 1965; both are in areas underlain by a sequence of Pleistocene sediments that includes the Esperance Sand Member.

A landslide triggered by the 1965 earthquake on a steep bluff on the west side of Vashon Island near Sanford Point (pl. 5, loc. 92) reportedly involved "tons of sand." Pleistocene sand deposits older than the Vashon Drift (till) underlie the bluffs of that area (Washington Department of Ecology, 1979a). In 1965, at Klahanie on the east side of the island (loc. 94), slumping occurred along about 60 m of hillside underlain by Vashon advance outwash deposits and the Esperance Sand Member (of the Vashon). The slope failure resulted in minor damage to a waterfront cottage and retaining wall. Farther south on the island, near Burton (loc. 95), a slide that originated on a steep bluff covered the main highway between Burton and Tahlequah. Vashon till and the Esperance Sand Member are the mapped geologic units that underlie that area (Washington Department of Ecology, 1979a). East of Vashon Island, near Three Tree Point (loc. 109), an incipient slope failure related to the 1965 seismic event is suggested by the report of a ground crack 8–10 cm wide and at least 60 m long. The ground crack was located in the upper part of a steep 100-m-high bluff overlooking Puget Sound. The crack was oriented parallel to the strike of the slope. A short distance to the north, the 1965 earthquake triggered a slope failure that damaged a retaining wall. Both ground failures are in an area underlain by a large landslide deposit in Vashon glacial sediments (Waldron and others, 1962; Washington Department of Ecology, 1979a).

Hillside landslides involving glacial materials also occurred at locations inland from the bluffs of Puget Sound. East of Auburn, along the Big Soos Creek drainage (loc. 102), a hillside underlain by deposits of mass wasting, including relatively large block slides (Mullineaux, 1965a), showed evidence of earthquake-induced slope movement in 1949 and 1965. Several miles to the north along the Big Soos Creek drainage (loc. 105), about 30 m of hillside above a small reservoir slumped slightly during and immediately after the 1949 earthquake. Ejection of sediment and additional water from a spring on the hillside indicate possible liquefaction of sediments.

To the south, near Orting (pl. 5, loc. 54), a 1965 ground crack reported to be 120–150 m long and 15 cm wide and probably related to incipient sliding opened along the brow of a hill overlooking Kapowsin Creek. Geologic mapping by Crandell (1963) indicated that the hillside is underlain by proglacial lacustrine sand.

The 1949 and 1965 earthquakes generated a number of slumps in road embankments composed of artificial fill. A 1949 road failure south of Port Orchard (loc. 87) occurred at the same location as a previous ground failure triggered by an earlier seismic event, the magnitude 6.2 Puget Sound earthquake of November 12, 1939. The 1939 ground failure was described by Coombs and Barksdale (1942) as follows:

> Investigation of this crack showed it to be on the surface of a fill approximately 260 yards [240 m] in length and 4 yards [3.7 m] thick in the center. A bed of quicksand fed continuously by many springs a short distance away on the uphill side underlies the sand and gravel of the fill. So unstable a foundation might well be expected to give way under the effects of earthquake motion.

Geologic mapping by Garling and others (1965) indicated that the area is underlain by what they called the Colvos Sand (of the Vashon Drift). The upper part of the Colvos Sand is probably correlative with the Esperance Sand Member (of the Vashon) in some areas according to the Washington Department of Ecology (1979b).

A slump in a 6-m-high embankment of artificial fill adjacent to Case Inlet (loc. 86) in 1949 resulted in ground cracks and as much as 15 cm of vertical displacement along 30 m of highway; the slump was reactivated by the 1965 earthquake. The site is part of an area underlain by Pleistocene sand older than till of the Vashon Drift (Washington Department of Ecology, 1980a).

Failures involving artificial fill overlying postglacial alluvial sediments damaged roads in the Duwamish River valley in the vicinity of Kent (locs. 104 and 108) in 1965. Small slumps at those locations resulted in displacements of a few centimeters (loc. 104) to about a meter (loc. 108); damage was minor.

A 1965 failure (loc. 83) in artificial fill undermined the roadway on the mainland side of the approach to Day Island Bridge on the east side of the Tacoma Narrows. It was reported by the press that the slide sent trees and earth cascading into a gully.

As a result of the 1965 tremor, road-embankment failures in artificial fill overlying tidal-flat muds occurred at Gig Harbor (loc. 89), southwest of Grapeview at McLane Cove (loc. 85), and in Olympia (loc. 48). At location 85 southwest of Grapeview, a 9-m-high road embankment crossing a small arm of McClane Cove reportedly split down the middle and moved out along the cove as "a kind of flow." At Gig Harbor (loc. 89), a slump along 6.1 m of roadway caused fill material to move into a small creek and tidal pool.

Extensive slumping of artificial fill on tidal flat muds occurred along a 0.8 km stretch of the Deschutes Parkway on the west side of Capitol Lake in Olympia (pl. 5, loc. 48; fig. 204). Sand boils in the immediate vicinity (fig. 205) suggested that the ground failure was liquefaction induced.

The 1965 earthquake also generated a slump in artificial fill on a steep slope on the east side of Capitol Lake in Tumwater (loc. 45). The failure badly damaged 45.7 m of Union Pacific freight-line track (fig. 206) and broke Tumwater's main sewer line, causing sewage to spill into Capitol Lake. The hillside is underlain by outwash sand of the Vashon Drift (Walsh and others, 1987).

Figure 204. Damage to Deschutes Parkway, Olympia, Wash., resulting from a 1965 earthquake-induced ground failure (pl. 5, loc. 48). The parkway was constructed on granular fill placed on tidal flat muds that are now within the limits of Capitol Lake; failure was probably due to liquefaction. Photograph by Gerald W. Thorsen, Division of Geology and Earth Resources, Washington Department of Natural Resources, Olympia, Wash.

Figure 205. Sand boils near Capitol Lake in Olympia, Wash., related to the earthquake of April 29, 1965 (pl. 5, loc. 48). The sand boils are evidence of soil liquefaction at this ground failure location. Sidewalk slab in background shows scale. Photograph by Gerald W. Thorsen, Division of Geology and Earth Resources, Washington Department of Natural Resources, Olympia, Wash.

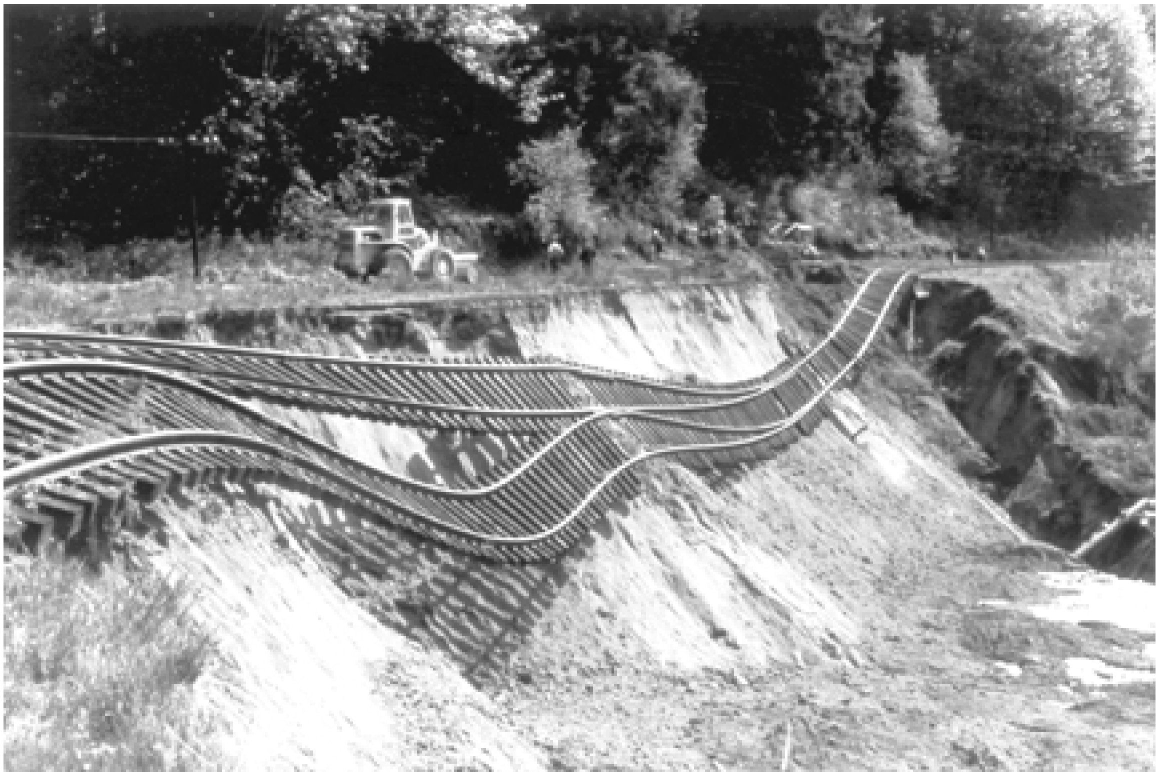


Figure 206. Damage to Union Pacific Railroad tracks near Tumwater, Wash. (pl. 5, loc. 45), due to a 1965 earthquake-induced slope failure in artificial fill. Photograph by Gerald W. Thorsen, Division of Geology and Earth Resources, Washington Department of Natural Resources, Olympia, Wash.

Figure 207. Damage to Black Lake Road south of Olympia, Wash. (pl. 5, loc. 44), caused by failure of a steep lake bank during the earthquake of April 13, 1949. Photograph used by permission of Jack Goldsby, Tumwater, Wash.

Figure 208. View of Cooper's Point, located 11 km north of Olympia, Wash. (pl. 5, loc. 51). About 45 m of the end of the sand spit failed and disappeared into Puget Sound during the April 13, 1949, earthquake. Photograph was taken in 1988.

Southwest of Olympia (pl. 5, loc. 44; fig. 207), about 30 m of one lane of Black Lake Road was damaged in 1949 by slumping. The failure occurred on a steep 8-m-high lake bank underlain by Vashon outwash sand and possibly some artificial fill.

About 45 m of the sandspit at Cooper's Point, north of Olympia (pl. 5, loc. 51, fig. 208), slid into Puget Sound during the 1949 earthquake. An eyewitness reported seeing the mass of land sinking beneath the waves. Soundings taken afterward at high tide indicated water depths of 15 m in an area where formerly the spit was 1.5 m above water at high tide. The sandspit is a Holocene beach deposit (Washington Department of Ecology, 1980b) that includes medium to coarse sand and minor gravel.

In Olympia, extensive settling was reported in 1949 in the Port of Olympia area (loc. 50) and in a residential area three to eight blocks east of the State Capitol (loc. 46). The entire port area, underlain by artificial fill, was reported to have settled 13 cm. Pipelines were broken and asphalt was bulged up over pilings. Settlement east of the State Capitol, which reportedly occurred in an area underlain by a peat soil, damaged several residences.

CASCADE RANGE, WASHINGTON, REGION

The Cascade Range of Washington (pl. 6) includes the area bounded by lat 49°00' N. and lat 46°00' N. and by long 121°00' W. and long 122°00' W. The region includes central and eastern parts of King, Skagit, Snohomish, and Whatcom Counties; eastern parts of Lewis and Pierce Counties; north-central and northeastern Skamania County; and far western parts of Chelan, Kittitas, and Yakima Counties. Nearly all of the reported 1949 and 1965 ground failures are located on the western side of the Cascade Range (pl. 6, table 31). Ground failures produced by the 1949 and 1965 earthquakes in this mostly mountainous region include (in order of abundance) rock falls and rock slides on steep cliffs and rock faces, slumps and other slides in alluvial valleys along roads and river banks, and minor ground cracks and (or) settlement in alluvial areas on valley floors and in embankment areas of dams.

A cluster of ground-failure activity was generated by the 1949 earthquake along the Cowlitz River Valley near Randle (locs. 117–122). Blocks of volcanic rocks fell from steep cliffs east of Randall onto Cline Road (locs. 120 and 121) and onto the old Randle-Packwood Highway (loc. 122). The blocks were reported to be as large as 6 m on a side. On the valley floor, southwest of Randle (loc. 117), a road embankment composed of artificial fill underlain by loose, liquefiable sand slumped into a nearby field. Road damage caused by the slump is shown in figure 209. Simultaneously on the same property (loc. 118), numerous sand boils erupted. To the east and closer to the Cowlitz River (loc. 119), small slumps were triggered along the bank of an abandoned river channel.

Figure 209. Slump in a 1- to 1.2-m-high road embankment in the Cowlitz River Valley, about 1.6 km southwest of Randle, Wash. (pl. 6, loc. 118). This April 13, 1949, earthquake-induced ground failure occurred in artificial fill underlain by loose liquefiable sand. The earthquake also produced sand boils in an adjacent field. Photograph by Alice Peters, Randle, Wash.

Rock slides on Mount Rainier were reported for both the 1949 and 1965 earthquakes. In 1949, a "major" rock slide occurred on the slopes above Nisqually Glacier and, in 1965, large amounts of rock and soil reportedly fell or slid in the vicinity of Kautz Glacier (pl. 6, loc. 126). Closer to the community of Longmire, the 1949 tremor induced rock falls and (or) rock slides of undetermined size on the cliffs of Eagle Peak (loc. 123) and Rampart Ridge (loc. 124). Also, incipient sliding of flood debris in the Kautz Creek drainage was reported (loc. 125). Numerous instances of ground failure on and near Mount Rainier, related to the 1949 and 1965 earthquakes and to several other historical earthquakes prior to the 1949 event (Noson and others, 1988), strongly indicate a high susceptibility to earthquake-induced landsliding. Jointing and layering of the volcanic rocks that underlie the steep slopes of Mount Rainier probably contribute to their seismic instability.

Mount Si (fig. 210; pl. 6, loc. 130) was the site of earthquake-triggered rock slides in 1945, 1949, and 1965. On April 29, 1945, an earthquake with a felt magnitude of 5.9 (Noson and others, 1988) triggered landsliding on Mount Si that was described by Bodle and Murphy (1947), as follows: "At the Mount Si Ranger Station, near North Bend, the earth buckled and heaved and tons of rock and earth cascaded down the 4,000 ft [1,220 m] cliffs of Mount Si." In 1949, a large dust cloud caused by a rock slide was observed rising from the west side of the mountain at about the 600 m level and, in 1965, a slide on the southwest slope of Mount Si was described as "extensive." The 1945, 1949, and 1965 ground failures demonstrate the high susceptibility of steep rock slopes on Mount Si to earthquake-induced rock falls, rock slides, and rock avalanches. Metavolcanic rocks (metamorphosed basic lavas), some of which are foliated, form the bedrock surface over much of the western part of Mount Si (Kremer, 1959). The rocks on the western part of the mountain dip very steeply to the west, and much of the rock is fractured. Fractures and bedding planes with unfavorable orientations commonly contribute to the instability of rock slopes. As stated by Piteau and Peckover (1978), "The stability of rock slopes depends largely on the presence and nature of defective planes or discontinuities within the rock mass."

Minor ground cracking was reported on Mud Mountain Dam (loc. 127) in 1949 and 1965 and on Howard Hanson Dam (loc. 128) in 1965. In both instances, the dams were not endangered. Small slides in the vicinity of Mud Mountain Dam were also reported for both the 1949 and 1965 earthquakes. In 1949, sliding occurred in an old slide area downstream from the dam and, in 1965, a slope near the Vista House was affected by small slides.

Figure 210. Mount Si near North Bend, Wash. (pl. 6, loc. 130). "Rockslides" on Mount Si were reported for the Puget Sound area earthquakes of April 29, 1945, April 13, 1949, and April 29, 1965. Photograph was taken in 1988.

CENTRAL-SOUTHWESTERN WASHINGTON REGION

The central-southwestern Washington region (pl. 7) extends from lat 47°30' N. to lat 46°22' N. and from long 122°00' W. to the Pacific Ocean (excluding the area of pl. 4). Included in the region is all of Lewis County west of long 122°00' W., the area of southwestern Pierce County south of lat 47°00' N. and west of long 122°00' W., all of Thurston County south of lat 47°00' N., Mason County south of lat 47°30' N. and west of long 123°00' W., all of Grays Harbor County south of lat 47°30' N., and all but the southwesternmost part of Pacific County. In this region, nearly all of the reported ground failures were produced by the 1949 earthquake; most occurred in lowlands, including the valley bottoms of major rivers and adjacent hillsides, and in glaciated areas bordering the southern terminus of Puget Sound. Ground-failure locations in this region are shown on plate 7; reports describing selected ground failures are listed in table 32.

Reports of sand boils and related ground cracking produced by the 1949 earthquake came from several locations in the central part of the region (locs. 141 and 146–149). As many as 12 sand boils deposited "patches" of sand in a swampy pasture near Deep Lake, east of Maytown (loc. 141). An eyewitness reported that mud was ejected first, followed by clean, white sand. The ejected sediment erupted along a north-south-trending line over a zone 3 m wide, forming "patches" on the ground as wide as 3 m. The area is underlain by glacial deposits of the Vashon Drift (Walsh and others, 1987); a gravel pit at the south end of the property, a short distance from the sand boils, exposes poorly sorted sand.

On a low terrace of the Chehalis River, just south of Centralia (loc. 146), about 20 ground cracks appeared in a farmer's field; from some of these (figs. 211 and 212), geysers of water and sediment spouted as much as 45 cm above the ground. It was reported that the geysers brought up what appeared to be "clean ocean sand." It was also reported that water continued to run slowly from the fissures for about a week.

On the flood plain of the Chehalis River northwest of Centralia (loc. 149), sand boils erupted from a ground crack approximately 2.5 cm wide and 5 m long. In the process, "several buckets full" of pure white sand were deposited on the ground. A 1949 sand boil south of Chehalis (loc. 147) is reported to have "heaved some ground" 0.6 m in the vicinity of a spring, forming a mound from which "muddy water" poured. Available information was not sufficient to determine the exact location of the sand boil or the type of sediment involved.

One other sand-boil occurrence in the region is suggested by the report of a fissure on a road near Ceres (loc. 148) that produced a "wet and soft spot in the roadbed where it was previously dry." Artificial fill underlies the road at that location.

Ground settlement related to the 1949 earthquake caused extensive damage to several buildings in Centralia (loc. 145), including a church that had to be condemned. Water mains in the city also were damaged. Foundation damage and broken water pipes in the Hanaford Valley area (loc. 142) were probably related to ground failure. Both

Figure 211. Alignment of sand boils in a field 1.6 km southwest of Centralia, Wash. (pl. 7, loc. 146), is related to linear ground crack from which the water and sand were emitted during a 1949 liquefaction incident. Photograph by Ted Dorn, Centralia, Wash.

areas are underlain by alluvial sediments that are locally covered by artificial fill.

In the areas adjoining the central Puget Sound lowland, landslides were triggered on hillsides, along roads and railroads, and on lake and river banks. In the LaGrande-Eatonville-Kapowsin area (locs. 136–139), landslides and ground cracks were associated with both the 1949 and 1965 earthquakes. Although little information is available regarding the exact locations and nature of ground failures in the vicinity of LaGrande (pl. 7, loc. 136), it was reported that the 1949 earthquake generated ground cracks on "side hills" in the area and, in 1965, that "slides went into rivers and onto roads."

A landslide triggered by the 1949 earthquake at Ohop Lake (loc. 138) is particularly interesting because, like the Tacoma Narrows landslide (pl. 5, loc. 81), it demonstrates the continuing hazard of some earthquake-induced ground failures beyond the time of the earthquake. At the time of the April 13, 1949, tremor, a 200-m-long and 8- to 10-cm-wide crack appeared on a county road located several feet above lake level on the northwest side of the lake. One month later, on May 13, complete failure occurred as the unstable mass suddenly slumped and (or) flowed about 30.5 m into the lake. The failure, which involved artificial fill underlain by alluvial sediments, left a scarp on the roadway about 1.5 m high (fig. 213). Summer cottages and supports for telephone and power lines were damaged by the slide.

In 1949, a smaller slide damaged about 30 m of an approach to a railroad overpass southeast of Eatonville (loc. 137). Artificial fill was also involved in that failure.

The 1949 earthquake induced a slump along about 30 m of county road adjacent to the Cowlitz River southeast of Morton (loc. 134). The slide material (glacial sand and gravel) dammed the river for a short time. Closer to Morton, the same event triggered a rock fall (loc. 135) from a near-vertical exposure of Tertiary-age sedimentary rocks. It was reported that a block of bedrock 8 m high fell from the cliff, frightening homeowners below.

Reported landslides in the vicinity of Centralia and Chehalis (locs. 143 and 144) were later determined to be small slumps with displacements of 0.6 m or less. One of the slides occurred on the side of an old gravel pit north of Centralia (loc. 143) in a glacial outwash deposit of sand and gravel; the other, located on the north shore of Plummer Lake (loc. 144), probably involved Quaternary alluvial sediments. Small slumps in 1949 also damaged roads near Rochester (loc. 150) and Oakville (loc. 151); both involved artificial fill on poor alluvial foundations. Horizontal and vertical displacements of 0.6 m or less were noted.

An 85-m-long section of a railroad embankment slumped into Patterson Lake south of Lacey (loc. 140) during or shortly after the 1949 earthquake. The slide is reported to have caused a wave surge that rose 25–30 cm over a nearby dock. About 19,000 m^3 of material was required to repair the damage (U.S. Army Corps of Engineers, 1949). The failure involved artificial fill over glacial sediments of the Vashon Drift.

Near Shelton (pl. 7, loc. 156), one lane of U.S. Highway 101 was damaged by a minor slump triggered by the 1965 earthquake. The slump, which was in artificial fill underlain by glacial sediments, dropped a part of the road approximately 0.3 m for a distance of about 46 m. Also, slides generated by the 1965 event were reported along the west side of Oakland Bay near Shelton (loc. 155). However, available information was insufficient to determine the exact locations and characteristics of those ground failures.

Numerous broken water mains and sidewalk cracks in Hoquiam and Aberdeen (locs. 152 and 153) associated with the 1949 earthquake may have resulted from minor settlement or incipient landsliding. Much of the Hoquiam-Aberdeen area adjacent to Grays Harbor is underlain by Quaternary alluvium (Walsh and others, 1987), and artificial fill is present locally. Ground failure induced by the 1949

Figure 212. Sand boils on the floodplain of the Chehalis River, about 1.6 km southwest of Centralia, Wash. (pl. 7, loc 146). Water and sand spouted from several ground cracks at this location at the time of the April 13, 1949, earthquake. Photograph by Ted Dorn, Centralia, Wash.

Figure 213. Scarp created by a landslide on the west side of Ohop Lake, Pierce County, Wash. (pl. 7, loc. 138). Incipient failure induced by the April 13, 1949, earthquake resulted in the development of a large ground crack. On May 13, complete failure occurred as the unstable mass suddenly slumped into the lake, damaging the roadway, utility lines, and cottages near the shore. Photograph used by permission of the Tacoma News Tribune.

and 1965 earthquakes has produced similar effects in other areas with similar geologic settings.

WESTERN COLUMBIA RIVER REGION, OREGON AND WASHINGTON

Included in the western Columbia River region (pl. 8) are the following Washington counties: Cowlitz and Wahkiakum Counties, western and southern parts of Skamania County west of long 121°00' W. and south of lat 46°00' N., part of western Klickitat County west of long 121°00' W. and south of lat 46°00' N, and southwestern Pacific County south of lat 46°23' N. Included in Oregon are Clatsop, Columbia, Washington, Multnomah, and Hood River Counties; the northwestern part of Wasco County west of long 121°00' W. and north of lat 45°14' N.; the northern parts of Clackamas and Yamhill Counties north of lat 45°14' N; and all of Tillamook County except the southwest corner south of lat 45°14' N.

In this region, the 1949 earthquake spawned numerous ground failures along and near the Columbia River; these included rock falls, rock slides, or rock falls/rock avalanches on steep cliffs and rock faces, and ground cracks, settlement, and sliding probably related to liquefaction in alluvial areas on the valley floor.

A landslide (probably a rock fall/rock avalanche) that originated on a steep head scarp of the 36 km^2 Bonneville landslide west of Stevenson, Wash. (loc. 160), reportedly created a dust cloud that was seen for miles along the Columbia Gorge. Rock falls on the steep scarps are a common, ongoing mass-wasting process that is probably easily accelerated by seismic activity. According to Palmer (1977), “The head scarps are actively raveling, with large blocks more than 15 ft [4.6 m] in diameter crashing down from time to time, so that it is unsafe at the base of the cliffs.” The head scarp of the Bonneville slide (fig. 214) exposes about 370 m of the Eagle Creek Formation (conglomerate, sandstone, and minor tuff) overlain by basalt (Korosec, 1987). It was reported that a “considerable” area of fresh surface on the rock cliff was exposed by the 1949 landslide and that abandoned buildings, including a small school house, were damaged or destroyed. Post-1949 airphotos reveal an area of slide debris, possibly related to the 1949 earthquake, as much as several tens of meters wide and a few hundred meters long at the base of a steep cliff on the south side of Table Mountain (loc. 160).

At Blue Lake, east of Portland, Oreg. (loc. 158), a 1949 rock fall from a near-vertical rockface on the south side of the lake reportedly endangered a boathouse. A 9- to 15-m-high cliff at that location exposes part of the Troutdale Formation (conglomerate and sandstone) (Trimble, 1963).

Rock falls involving highly jointed volcanic rocks occurred along the Spokane-Portland-Seattle railway about 1.6 km east of Mayger, Oreg. (loc. 166), and along the Ocean Beach Highway just west of Stella, Wash. (loc. 168). The rock fall east of Mayger damaged the railroad, but it was reported that only a few hours were required to clear the slide and repair the damage. The rock fall at location 168 originated on the near-vertical face of a 15- to 25-m-high bluff that extends for about 0.8 km along the highway west of Stella. Part of the rock fall reportedly crossed the highway and spilled into the Columbia River. According to an eyewitness, the Washington State Department of Highways had to “shoot” (use explosives) to remove a block of rock “as large as a house.”

Sand boils and associated ground cracks indicating liquefaction of sediments occurred at Longview, Wash., in 1949 near the junction of N.W. Nichols Street and Ocean Beach Highway (pl. 8, loc. 163) and near 40th Avenue (loc. 164). Geysers of water and sand 1–1.2 m high developed in a yard and, nearby, sand boils and settlement caused considerable structural damage to a local residence. The area is part of a flat, low-lying terrace or flood plain of the Columbia River underlain by Quaternary alluvium. Artificial fill is present locally. The 1949 ground failure near 40th Avenue took the form of a 6-m-long ground crack from which “black, fine sand bubbled.” The site is part of a sandy flood plain; Quaternary alluvial sediments underlie the area (Walsh and others, 1987). Local residents who lived in the vicinity in 1949 say the ground-water table was almost at the surface at the time of the earthquake.

Other effects of the 1949 earthquake, possibly related to liquefaction of Columbia River sediments, include the following: a slide involving artificial fill overlying alluvium that damaged 100 m of the Longview dike road (loc. 165); damage to a building at Mayger, Oreg. (loc. 167), related to shifting of pilings toward the Washington side of the river; sliding or flowing of sediments on Puget Island in the Columbia River (loc. 170), indicated by well pipes all bent in the same direction; and settling, ground cracks, and bent pipes in a flat-lying, swampy alluvial area at Skamokawa, Wash. (loc. 171).

OBSERVATIONS AND CONCLUSIONS

In this study, data on ground failures generated by the April 13, 1949, and April 29, 1965, Puget Sound earthquakes were obtained by (1) review of published and unpublished information, (2) interviews with local residents and State and local officials, and (3) field study of selected ground-failure sites. These data include new and previously unpublished ground-failure information, particularly on landslides, related to the 1949 and 1965 events. The data support conclusions by Hopper (1981) and Keefer (1984) regarding the general distribution and character of the 1949 and 1965 ground failures and the relative susceptibility of geologic environments in the Puget Sound region to earthquake-induced ground failure. The following observations and

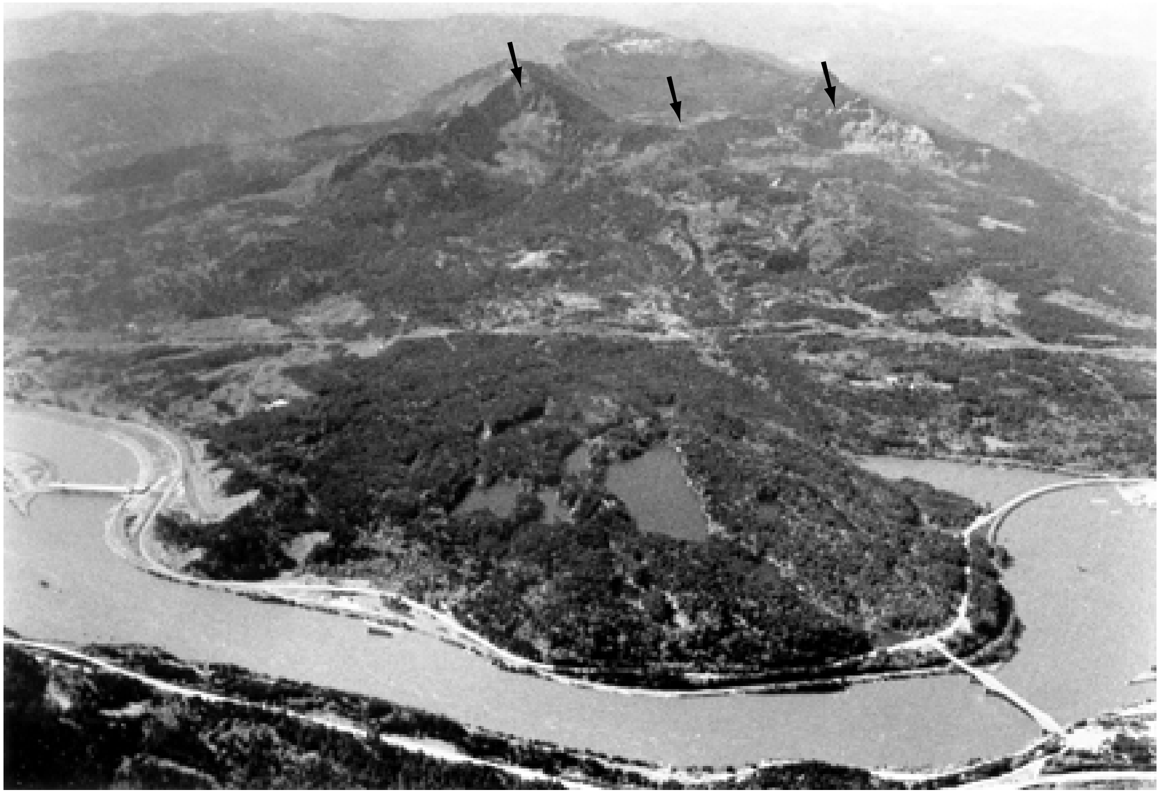


Figure 214. Bonneville landslide area along the Columbia River west of Stevenson, Wash. (pl. 8, loc. 160). Rock fall/rock avalanche activity triggered by the April 13, 1949, earthquake occurred along the steep head scarp (arrows), creating a dust cloud visible for many kilometers along the Columbia River Gorge. Photograph by Derek Cornforth, Landslide Technology, Portland, Oreg.

conclusions are based, in large part, on the perspective gained by the compilation of new and existing information on ground-failure characteristics and by study and comparison of ground-failure distributions made possible by the plotting of 1949 and 1965 ground failures on regional topographic maps (pls. 4–8).

Ground failures triggered by the 1949 and 1965 earthquakes were scattered over areas of about 28,500 km^2 and 20,700 km^2, respectively (fig. 187). Ground failures in areas affected by both earthquakes were similar, taking the form of landslides, settlement, and ground cracks. Although most of the reported ground failures were small settlements and ground cracks that resulted in only minor damage to roads, sidewalks, buildings, utility lines, and other structures, many caused significant damage in areas of intense ground shaking. Many damaging ground failures occurred in environments thought to be conducive to liquefaction failures, as suggested by the presence of sediment types susceptible to liquefaction, high water tables, and in some cases the occurrence of sand boils in the immediate vicinity.

Liquefaction of sediments, indicated by sand boils, was most common on flood plains or low terraces of valley floors extensively underlain by Quaternary alluvium and locally by artificial fill and at the mouths of rivers where deltaic sediments and tidal flat muds are extensively overlain by artificial fill. Many slides, mostly small slumps with estimated volumes of less than 1,500 m^3 (Chleborad and Schuster, 1989), involved artificial fill underlain by granular alluvial, deltaic, lacustrine, or glacial deposits. Most of these occurred in embankments along primary and secondary roads and railroads and along the banks of rivers, lakes, and other bodies of water. Also, slumps and other slides of undetermined type were common on steep bluffs along Puget Sound. Many of the slides along these bluffs occurred within a stratigraphic sequence composed of glacial sediments of the Vashon Drift that included its Esperance Sand Member or its lithologic equivalent underlain by impermeable silts and clays. Such conditions often give rise to naturally unstable slopes because of high groundwater conditions. The importance of local ground-water conditions in the development of earthquake-induced flows, slumps, and other slides is suggested by the proximity of many of the slope failures to rivers, lakes, streams, or other bodies of water and by reports of associated springs, swampy areas, and “opened pools of ground water,” all of which indicate a probable high water table and saturated ground conditions. Coupled with the presence of loose granular sediments, such conditions often indicate a high susceptibility to liquefaction-induced ground failure.

Rock falls, rock slides, and rock avalanches reported for the 1949 and 1965 earthquakes occurred almost exclusively in the mountainous terrain of the Cascade Range and along the western Columbia River valley. Typically, these failures originated on very steep slopes (slopes of 45° or more) in areas of highly jointed volcanic, metamorphic, or sedimentary rocks and in areas where such failures occur naturally even under nonseismic conditions.

Examination of ground-failure distributions in each of the four regions discussed reveals that a high percentage of the reported failures occurred in and near the more populated and heavily traveled areas, which suggests that many ground failures that occurred in less populated and inaccessible areas were not reported. This notion is supported, to some extent, by the paucity of reports of landsliding in several large areas of landslide-susceptible terrain in western Washington and northwestern Oregon, such as the Cascade and Coast Ranges (Radbruch-Hall and others, 1982; Schuster and Chleborad, 1989), where intense ground shaking (MMI V or greater) might be expected to generate such failures.

Future large earthquakes in the western Washington–northwestern Oregon region can be expected to generate similar types of ground failures in the same or geologically similar environments as those that occurred in the 1949 and 1965 earthquakes. The location and extent of losses caused by future earthquake-induced ground failures will depend on many factors, including the magnitude and location of the earthquake, ground-water conditions at the time of the earthquake, and the susceptibility of populated and developed areas to damaging ground failure during intense seismic shaking. Recognition of geologic environments susceptible to earthquake-induced ground failure is an important step in efforts to reduce the earthquake hazard faced by residents of the western Washington–northwestern Oregon region.

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TABLES 29–33

Descriptions of ground failures in the Puget Sound region caused by the April 13, 1949, and April 29, 1965, earthquakes

Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region.

[Location numbers correspond to ground-failure location numbers on plate 4. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
1	Slump or lateral spread (1965)	Port Orchard, Wash.; Kitsap County	A	[Photo caption] "HMM, HMM AND WOW!—Two people nonchalantly talk at the Thriftway Supermarket parking lot near the rumpled edge of the northeastern part of the lot. The store building itself suffered some damage but, as in the case of other locations in the county, blacktop on fill material was damaged the most by the temblor." (Bremerton Sun, 1965a). Photo shows part of a badly broken asphalt-covered parking area adjacent to Sinclair Inlet in Port Orchard. Vertical displacements of approximately 0.6 m are apparent in the photo.
2	Slump (1965)	Port Orchard, Wash.; Kitsap County	A	A slide caused by the 1965 earthquake damaged Country Club Road southeast of Port Orchard (Blair Seymour, Bremerton Sun, oral commun., 1988). Slump in artificial fill underlain by Vashon Drift damaged 15–30 m of pavement along Country Club Road. Movement was downslope in the direction of a small ravine adjacent to the road embankment (see fig. 198).
3	Settlement (1965)	Seattle, Wash. (Boeing Field); King County	B	"About a mile still farther south [of the Georgetown District], * * * property loss at the Boeing Company was reported to be high. Much destruction there resulted from subsidence" (Mullineaux and others, 1967).
4	Settlement (1949)	Seattle, Wash.; King County	A	"Quake opens 6 inch [15 cm] cracks in yard * * * house sank 4 inches [10 cm]." (Seattle Post-Intelligencer, 1949e).
	Settlement (1965)	do.	A	"Similar damage [to that in the 1949 earthquake] occurred as a result of the 1965 earthquake. Cracks appeared in the basement and the dock separated. House next door had settling and yard cracks in the 1949 and 1965 quakes. The area was once the site of the old Taylor Sawmill." (Hale Lowry, oral commun., 1988).
5	Slide(s) (1965)	Maple Valley, Wash. (Renton); King County	B	"Slides were reported in the * * * Devil's Elbow Road near Maple Valley." (Seattle Times, 1965a). The location of "Devil's Elbow Road" is believed to be a 0.8-km-long section of paved road that joins SE 95th Way and NE 27th Street just north of Renton (12.5 km northwest of Maple Valley). The road, which is presently abandoned due to extensive landsliding, is situated on the steep sides of a ravine in the May Creek drainage. Slumping has dropped parts of the paved road as much as 0.3 m vertically along sections 30 m in length on both sides of the ravine. The exact location of the earthquake-induced landsliding is undetermined.

6	Slump (1965)	Mercer Island, Wash.; King County	C	[Photo caption] "The shoulders of the road cracked along East Mercer Way." (Mercer Island Reporter, 1965). This Mercer Island photo shows arcuate crack, about 6 m long and 2.5–7.6 cm wide, along shoulder of road and steep embankment. Vertical and horizontal displacements appear slight.
7	Ejection of ground water (1949); ejection of ground water (1965)	Seattle, Wash. (West Seattle; Alki); King County	A	"Basement floor [damage] and fresh water came in [at the time of the 1965 earthquake] * * * after the 1949 earthquake the professor and some students came out and took samples of the water in our basement. It was fresh water and we are only about 100 feet [30 m] from the bay." (Mrs. J.W. Woodhouse, written commun., 1965).
	Settlement (1965)	do.	A	"Almost a third of the long promenade behind the seawall at Alki sank some 6 inches [15.2 cm] in the vicinity of the Alki Monument." (Seattle Times, 1965c).
	Miscellaneous effects (1965)	do.	B	"At Alki Point, * * * waterline breaks were more numerous than anywhere else in the city." (Mullineaux and others, 1967).
8	Slide (1965)	Seattle, Wash. (West Seattle); King County	A	"Cracks in swimming pool * * * shifting and sliding of dirt under pool." (John E. Smith, written commun., 1965).
9	Slide (1965)	Seattle, Wash. (West Seattle); King County	B	"There was some sliding on steep bluffs at the south end of Schmidt Park." (Harold Borden, oral commun., 1988).
10	Slump (1949)	Seattle, Wash (West Seattle); King County	A	"Six houses were ripped apart on the 5100 block of Admiral Way by Wednesday's earthquake. Two families were forced to move out of their shattered homes. The other four houses were new homes, under construction and nearly completed. All four were splintered. * * * Ground on the block shifted and pulled open in the quake. The home, * * * at 5127 Admiral Way, dropped three feet and slid a foot and a half off its foundation." (Seattle Post-Intelligencer, 1949g). [Photo caption] "A small residence on unconsolidated fill lost its foundation when settlement dropped the concrete wall and the horizontal movement added to the damage." (Edwards, 1950). [Photo caption] "LONG WAY DOWN—* * * deep crevasse * * * another graphic example of damage wrought by quake showed up at 5135 Admiral Way." (Seattle Post Intelligencer, 1949a). See figure 190.
11	Slump (1965)	Seattle, Wash. (West Seattle); King County	A	"Fill soil settled and cracked, 5 × 40 foot [1.5×12.3 m] concrete bulkhead twisted and dropped on north end. Fill area slid down hill." (E.J. Carlson, written commun., 1965).
12	Slump (1965)	Seattle, Wash. (West Seattle); King County	B	"Cracked cement steps. * * * Some breaking off of cliff." (A.R. Munson, written commun., 1965). "Slumping was observed along a steep slope adjacent to 36th Avenue S.W., near Admiral Way." (Hake and Cloud, 1967).

Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
13	Slump (1965)	Seattle, Wash. (West Seattle); King County	A	"In 1949 we had a * * * crack in the backyard along the same path as from this last quake, only less severe and no yard drop then like we have now * * * We live on a hillside." (G.F. Kok, written commun., 1965). Apparent slight slump triggered by the 1965 earthquake. Original, incipient sliding may have been triggered previously by the 1949 earthquake. The site is located at or near the head of a large landslide mapped by Waldron and others (1962).
14	Ground crack (1949)	Seattle, Wash. (Delridge Way); King County	A	"The Seattle Housing Authority will remove two buildings in the temporary Delridge Homes project, 4545 Delridge Way, as a result of Wednesday's earthquake, Charles W. Ross, executive director, said Thursday. Ross said no damage was done to the structures themselves, * * * but that a break in the earth underlying them might cause serious slippage later in case of heavy rainfall. [Ross also said] the area is partly a fill" (Seattle Post-Intelligencer, 1949c).
15	Lateral spread or slump (1965)	Seattle, Wash. (Spokane Street); King County	A	"The Bethlehem Steel Seattle Mill Depot No. 92, Spokane Street, Seattle, was observed by a competent engineer during the quake. The building is single story concrete posts with brick curtain walls on a concrete footing with a concrete floor resting on filled ground. The rear of the building is 9 feet [2.7 m] from the top of a 1 on 2 slope 7-1/2 feet [2.2 m] above adjacent tide land. After the perceptible ground motion of the quake had ceased, cracks started developing in the 20-foot [6 m] bay next to the tide land. A triangular section of the brick wall moved vertically downward from 1-3/16 inches to 1-3/4 inches [3.0–4.4 cm]. The ground at the rear of the building pulled away from the wall 2-1/2 inches [6.3 cm] and settled vertically 3 inches [7.6 cm] and 4 inches [10.2 cm] below the marks left on the wall by the soil surface." (U.S. Army Corps of Engineers, 1949).
16	Slump (1949)	Seattle, Wash. (Spokane Street); King County	A	[Photo caption] "QUAKE CRACKED STREET" (Seattle Post-Intelligencer, 1949d). Crack and slight slump on Spokane Street approach to West Seattle (see fig. 193). Failure occurred in embankment of artificial fill a few tens of meters high.
	Settlements (1949)	do.	B	[Spokane St. between 23d Ave. S.W. and Harbor Ave. S.W.] "Settlements of 1" to 4" [2.5–10.2 cm] at several points. Longitudinal joint separation." (City of Seattle earthquake damage report, 1949, unpublished, on file in the offices of the City of Seattle Engineering Department).
17	Lateral spread or slump (1949)	Seattle, Wash. (Duwamish Waterway); King County	C	"A concrete wall around a tank farm adjacent to the Duwamish waterway indicated considerable earth movement. One east-west wall about 100 feet [30 m] long and 12 feet [4 m] high reveals three vertical construction joints opened 1-5/8, 2, and 1-3/4 inches [4.1, 5.1, and 4.4 cm], or a total of 6 inches [15 cm] during or since the quake. The joint filler in a north-south wall was squeezed out a maximum of 3 inches [7.6 cm] at the bottom of one joint. The wall nearest to the Duwamish waterway and parallel to it has settled 2 inches [5.1 cm] below adjacent walls and is out of plumb. Lateral and vertical movement of the ground is evident." (U.S. Army Corps of Engineers, 1949).

18	Lateral spread or slump (1965)	Seattle, Wash. (Duwamish Waterway: West Waterway); King County	A	"Pier 5, where construction projects were underway, was hardest hit. The bulkhead and the fill behind it settled, the fill dropping 6 inches to 2 feet [0.15–0.61 m] for a width of 5 to 40 feet [7.6–12.2 m]. The bulkhead was reported to be 6 to 8 inches [15.2–20.3 cm] out of line." (Hake and Cloud, 1967). "* * * subsidence of the material along the west side of the pier [Pier 5]. * * * north end wall is exposed * * * wall has displaced downward from the dock a distance of 8 inches [20.3 cm]. The soil in this area for a 20-foot [6.1 m] width has subsided. The ground has displaced to approximately 1-1/2 feet [0.5 m] below the level of the existing dock. This subsidence decreases to approximately 8 inches [20.3 cm] at the southerly end of the pier."(Seattle Fire Department, 1965).
	Settlement (1965)	do.	A	"Pier 6, located directly south of Pier 5: This pier has had similar problems to those of Pier 5. There is subsidence of from 6" to 12" [15–30 cm] at the land face of the pier." (Seattle Fire Department, 1965).
19	Settlement (1949); sand boils (1949)	Seattle, Wash. (Duwamish Waterway); King County	A	"The KJR Radio transmitting tower suffered structural damage but the ground apparently settled around the footings 1 inch [2.5 cm] below the former level. Cracking of soil and sand boils occur in the area between the tower and the Duwamish waterway." (U.S. Army Corps of Engineers, 1949).
20	Settlement (1949)	Seattle, Wash. (Harbor Island); King County	A	"The Fisher Flouring Mills in Seattle constructed a new brick restaurant building adjoining an older brick office building. There is little evidence of movement on the exterior * * *. Inside the old office, the floor is badly out of level, in one place bulged up 7 inches [17.8 cm] above the adjacent floor of the new building" (U.S. Army Corps of Engineers, 1949).
	Miscellaneous effects (1965)	do.	A	"The Fisher Flouring Mills had extensive damage * * *. Underground piping around the plant also broke" (Hake and Cloud, 1967).
21	Sand boils (1949)	Seattle, Wash. (Harbor Island); King County	B	[Photo caption] "Water flowed and spurted from sand during the earthquake consolidation of ground on Harbor Island, Seattle." (Edwards, 1950).
22	Lateral spread or slump (1965)	Seattle, Wash. (Harbor Island); King County	A	"Piers 15 and 16 on Harbor Island shifted toward the water by about 1 foot [0.3 m] due to the soil losing much or all of its strength, or partially liquefying and pushing the dock toward the water. An exception was the northern extension of the pier which was under construction and did not yet have its soil backfill." (Hake and Cloud, 1967).
	Miscellaneous effects (1965)	do.	B	"Todd Shipyard Corporation: 3 breaks in underground mains" (Seattle Fire Department, 1965).
23	Miscellaneous effects (1949)	Seattle, Wash. (Duwamish Waterway); King County	B	"The Northern Pacific Railway Company's bridge (single bascule) crossing Duwamish Waterway near West Spokane Street was reported to have permanently shifted from 4 to 7 inches [10.2–17.8 cm]. The bridge was open at the time of the earthquake. * * * The city double bascule bridges * * * crossing Duwamish Waterway at Spokane Street were closed at the time of the quake. The main bridge piers shifted, reducing the horizontal distance between the piers several inches and jamming forward edges of the bascule leaves together." (U.S. Army Corps of Engineers, 1949).
	Miscellaneous effects (1965)	do.	B	"Both of the Southwest Spokane Street bridges were jammed shut when the shock threw them out of line." (Hake and Cloud, 1967).

Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
24	Settlement (1965); ejection of groundwater (1965)	Seattle, Wash. (Elliott Bay; 1st Ave. S.); King County	A	"The building [Millwork Supply, 2229 First Ave. S.] is located on dredged fill material and is believed to be on piling. During the earthquake approximately 8 inches [20 cm] maximum downward settlement of footings occurred. * * * basement floor slabs on grade were severely cracked and displaced due to the action of footing settlement combined with upward pressure of ground water against the bottom of the slabs." (Seattle Fire Department, 1965).
	Settlement (1949)	do.	B	[Road damage to 1st Ave. S. between Lander and Holgate Streets] "Settlements to extent of 3" [7.6 cm] vertically—2" [5 cm] horizontal separation." (City of Seattle Survey of Pavement Damage, etc.—Earthquake of April 13, 1949; unpublished report on file in the offices of the City of Seattle Engineering Department).
25	Sand boils (1949); settlement (1949)	Seattle, Wash. (Elliott Bay; 1st Ave. S. and Massachusetts Ave.); King County	A	"Examination of the ground around Albers Brothers Elevators shows no evidence of settlement except that a number of sand boils developed from 5 to 15 feet [1.5–4.5 m] away from the elevators on the northeast side. The ground around a large fuel tank has settled differentially from zero to 1/2 inch [1.3 cm] as evidenced by the soil contact mark." (U.S. Army Corps of Engineers, 1949).
	Settlement (1949); sand boils (1965)	do.	A	"The building [Queen City Sheet Metal Shop, 1730 1st Ave. S.] * * * is supported on posts and blocks. The building has settled very badly throughout the years. This settling has been exaggerated during the present earthquake. The floor has been shored up in different places during the recent years but all the old existing posts are leaning in various directions and the floor is very badly out of level. * * * During the winter months, the area has standing water and has to be pumped by means of a sump pump. During the present earthquake a considerable amount of water came in. This apparently was from consolidation of the earth below, which forced the water in this lower stratum into the area. This water was also followed by the characteristic fine silting which now covers most of the underneath area." (Seattle Fire Department, 1965). " 'We thought a sewer broke when water started coming in our basement but when the wooden floor down there splintered and a big bump of earth came up we didn't know what happened.' That's how Esther Kempton, bookkeeper at Washington Glass Co., 23 S. Massachusetts St., described early reactions to the earthquake at her place of work. Firemen were called when 'gasses and water continued to bubble from it' (the hump of earth), she said." (Seattle Post-Intelligencer, 1965b).
26	Slump (1949)	Seattle, Wash. (19th and Holgate); King County	A	"The April 13, 1949, earthquake caused a slide at 19th and Holgate that took out a driveway." (Jim Brazil, U.S. Forest Service, oral commun., 1988).
27	Settlement (1965); ground cracks (1949)	Seattle, Wash. (Mount Baker District); King County	A	"* * * we are on waterfront filled land * * * foundation cracked, also concrete * * * one arm of dock broken in two, fell into water; other parallel arm had second of five piles from shore settle, putting swayback in walkway. * * * Basement concrete floor cracked in 1949 [earthquake], opened wider and heaved to different levels." (Steele Lindsay, written commun., 1965).

28	Slide (1949)	Seattle, Wash. (4th Ave. S. at Dearborn St.); King County	A	"Lateral movement to west of west half of pavement." (City of Seattle earthquake damage report, 1949; unpublished report on file in the offices of the City of Seattle Engineering Department).
29	Slide (1965)	Seattle, Wash. (Queen Anne); King County	A	"Hillside backyard sank 2 ft [0.6 m]—seems to have settled on one side more" (Mrs. Jack A. Hanover, written commun., 1965).
30	Miscellaneous effects (1965)	Seattle, Wash. (Lake Washington Ship Canal); King County	C	"The gas distribution system was broken at about 60 different points. The major break was in a 16-inch [40 cm] main in a tunnel under the Lake Washington Ship Canal. All breaks were on filled ground. Many breaks were caused by lateral displacement of the mains pulling the service connections free" (U.S. Army Corps of Engineers, 1949).
31	Ground crack (1949)	Seattle, Wash. (Union Bay, University of Washington); King County	A	[Photo caption] "NEW 50-YARD LINE?—* * * The crack, about 100 yards [90 m] from the open end of Stadium, is about 50 feet [15 m] long by a foot [0.3 m] wide, and about 3 feet [1 m] deep." (Seattle Post-Intelligencer, 1949b).
	Sand boil (1965); ground crack (1965)	do.	A	"* * * a fissure opened in the practice field at the University. Underground pressure from the shock sent sand spurting in a 100-foot-long [30 m] zig-zag stretch on the lower football field." (Hake and Cloud, 1967).
	Settlement (1965)	do.	A	"Behind the men's pool, areas of the ground dropped as much as a foot [0.3 m]. Dirt floor sections in the Hec Edmondson Pavilion also sank slightly." (Hake and Cloud, 1967).
32	Settlement (1965); sand boils (1965)	Seattle, Wash. (Union Bay); King County	B	"North of Union Bay, a broad fill over alluvial and lacustrine sediments subsided and exhibited ground cracks and sand mounds. Subsidence caused minor damage to paving and walks, and an estimated 10 to 30 percent of shelf goods were shaken down in two stores in the shopping center there." (Mullineaux and others, 1967).
33	Slump (1949); slide (1949)	Seattle, Wash. (Green Lake); King County	A	"A 60-foot [18 m] section of the south shore of Green Lake dropped four feet into the lake during the earthquake Wednesday. Cracks three or four inches [8–10 cm] wide also appeared on the bicycle path a short distance from the slide. The ground was broken up and parts of the path appeared to have dropped from four to six inches [10–15 cm] into the lake." (Seattle Post-Intelligencer, 1949f). See figure 194. [Photo caption] "PAVEMENT CRACKED OPEN: These men * * * inspected the pavement in East Green Lake Way near North 63rd which split as a result of today's earthquake." (Seattle Times, 1949a). See figure 195.
	Settlement (1965); slide (1965); ground cracks (1965); miscellaneous effects (1965)	do.	A	"Just south of Green Lake * * * lacustrine sediments overlain by thin fill subsided, apparently as a result of both compaction and lateral movement downslope toward the lake. Here, ground cracks opened as much as 2 inches [5 cm] breaking the foundation of a small building, fracturing walks and paving, and breaking utility lines." (Mullineaux and others, 1967). "The earthquake [of 1965] produced bizarre results at Green Lake, John W. Sandusky, park-department engineer reported. [The earthquake] buckled blacktop paving around the Aqua Theater and opened large fissures in the ground on the south and west banks of the lake. * * * [the earthquake] put two waves in West Green Lake Way between the Aqua Theater and Lower Woodland Park. At the Lower Woodland baseball fields, water spurted 10 to 15 feet [3–5 m] high around the lighting standards. * * * A four inch [10 cm] water main serving Evans Pool at Green Lake was ruptured" (Seattle Times, 1965c).

Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
34	Slide (1965); settlement (1965)	Seattle, Wash. (Phinney Ridge); King County	A	"Bulkhead [slid] down. [Settling of] front yard by walk at stairs to front porch. * * * 35 feet [11 m] of west bulkhead fell. Doors jammed and would not close. Front door will not open—rubs on floor. Sewer pipe broken in middle from toilet outlet. Foundation shows open places and broken away from rockery." (Mrs. S.G. Tudor, written commun., 1965).
35	Slide (1949)	Kirkland, Wash. (Champaign Point); King County	B	"Point moved toward lake; * * * moved rail fence west; dock dropped * * * earthquake felt strongly over an area of 3 lots located on Champaign Point. Other residents in the neighborhood recorded no damage. * * * The cracks in cement have become wider since the shock, and we have noticed occasional creakings in the house * * *. In the front of the house deep cracks in the earth appeared next to the basement walls, and water pipes were broken in the sprinkler system from the lake. The basement floor was cracked and two small cement retaining walls dropped several inches." (B.J. Dalton, written commun., 1949).
36	Slide/mud flow (1965)	Seattle, Wash. (Carkeek Park); King County	B	"An earthslide opened a pool of ground water that roared down the creek in historic Carkeek Park. Debris flooded the road, blocking it until at least next week." (Seattle Times, 1965c). The mud flow (fig. 196) originated in a large ravine on the north side of Piper Creek in Carkeek Park. The exact point of origin of the ground failure is undetermined. Water in a small creek that flows down the ravine may have mixed with the slide debris, adding to its mobility.
37	Slide (1965)	Seattle, Wash. (Sheridan Beach); King County	A	"Rock bulkhead on Lake Washington lowered six (6) inches [15 cm]. Large rocks fell away—ground cracked in flower beds." (Mrs. K.J. Emery, written commun., 1965).
38	Slide (1965)	Seattle, Wash. (Lake City); King County	A	"Slide in lawn area where sand fill had been used for septic tank area (7 years ago). Area fell and slid about 8–12 inches [21–30 cm]." (Leon M. Pool, written commun., 1965).
39	Slump (1965)	Suquamish, Wash.; Kitsap County	A	"The press reported the shoreline of Suquamish, in northeast Kitsap County heaved up 15 feet [4.5 m] in places. A 2-story beach house was demolished and trees were uprooted." (Hake and Cloud, 1967). "A house was badly damaged and there was a crack about 100 ft [30 m] long on the beach parallel to the shoreline. The beach was uplifted as if by a hydraulic lift. The damage occurred along the bluff near the end of 8th Street." (Leroy Todd, oral commun., 1988). The slope failure is located within a 1.2-km-long coastal bluff area identified as "unstable" in the Coastal Zone Atlas of Washington (Washington Department of Ecology, 1979b). Seepage occurs near midslope on the 15.2-m-high bluff. A 1.0- to 1.5-m-high stone bulkhead, emplaced to prevent further erosion, extends about 100 m along the shoreline at the base of the slope.

40	Slide/earthflow (1965)	Edmonds, Wash.; Snohomish County	A	[Photo caption] "A CHURNING MASS of mud, rocks and other debris in Edmonds is investigated by curious visitors. The slide occurred during yesterday's quake, sucking in an abandoned shack and several trees and tapping an underground stream. First a big hole occurred, then earth and debris sloughed into it. The stream rapidly covered the bottom of the hole with the thick muck. The slide area was 50 feet [15 m] wide, 15 feet [5 m] deep, a block long." (Seattle Post-Intelligencer, 1965a). "A huge crack appeared in the earth. Then trees still standing up began to slide slowly down * * *. The slide uncovered a stream which is mixing the dirt into a muck the consistency of wet cement" (eyewitness account; Seattle Times, 1965b). See figure 197.
41	Slump (1965)	Kingston, Wash.; Kitsap County	A	[Photo caption] "NORTH END ROAD DAMAGE—A 30 ft [9 m] section of Highway 104, three miles [5 km] west of Kingston, was torn away by the force of this morning's earthquake. The crevice, estimated at three feet [0.9 m] deep, was being repaired." (Bremerton Sun, 1965b).
42	Ground cracks (1965)	Port Ludlow, Wash.; Jefferson County	C	"Beach at Port Ludlow cracked—then filled in by next day. Area 100×500 ft [30×150 m] on east side of bay (all sand)." (Mrs. John G. Jackowski, written commun., 1965).
43	Miscellaneous effects (1965)	Everett, Wash.; Snohomish County	C	"In Everett, two of the three 48-inch [1.2 m] main supply conduits to the city failed. These occurred where the lines are carried on trestles over Ebey Slough" (excerpt from a preliminary report by the Washington Surveying and Rating Bureau; Hake and Cloud, 1967).

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region.

[Location numbers correspond to ground-failure location numbers on plate 5. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
44	Slump (1949)	Olympia, Wash. (Black Lake); Thurston County	A	"* * * about 75 feet [23 m] of one lane of the Black Lake Road slipped into the lake about a half mile [0.8 km] north of Columbus Park." (Daily Olympian, 1949a). Failure involved steep lake bank and roadway on west side of Black Lake. Lake bank is about 8 m high. Cracks in pavement indicate continued instability at this location. Location on plate 5 is based on information given to Steve Palmer of the Washington Division of Geology and Earth Resources by local resident Jack Goldsby in 1992. See figure 207.
45	Slump (1965)	Tumwater, Wash. (Capitol Lake); Thurston County	A	"Thursday morning's seismic shock shook loose part of a Capitol Lake hillside snapping off 40 yards [37 m] of the City of Tumwater's main sewer line and diverting sewage into the lake. Tons of hillside opposite Wildwood Center in the 2800 block of Capitol Boulevard tumbled a hundred yards [91.4 m] downhill, covering a railroad spur and leaving behind another 50 yards [45 m] of Union Pacific freight line track dangling naked but unbroken." (Anderson, 1965). See figure 206.
46	Settlement (1949)	Olympia, Wash.; Thurston County	A	"A residential area three to eight blocks east of the capitol is founded on a peat soil and appears to be undergoing delayed settlement. The major portion of the residential damages are centered in this area." (U.S. Army Corps of Engineers, 1949).
47	Slide (1949)	Olympia, Wash.; Thurston County	B	[Northern Pacific Railway, Grays Harbor Line] "Mile Post 10-1/2—Embankment slipped out for 45 feet [14 m]." (U.S. Army Corps of Engineers, 1949).
48	Slump(s) (1965); sand boils (1965)	Olympia, Wash. (Capitol Lake, Deschutes Parkway); Thurston County	A	[Photo caption] "Shifting earth sent the edge of this highway at Olympia into Capitol Lake behind the state capitol. A half-mile [0.8 km] section was damaged." (Tacoma News Tribune, 1965c). See figure 204. [Photo caption] "Sand boils or 'mud volcanoes' along Capitol Lake in Olympia indicate local soil liquefaction during the 1965 quake. Such features are formed by geysers of muddy water escaping from saturated sediments." (Washington Division of Geology and Earth Resources, 1984). See figure 205.
49	Miscellaneous effects (1949)	Olympia, Wash.; Thurston County	B	"Breaks in water mains occurred during the 3 days following the earthquake. In all, 24 breaks were reported. The most serious drop in pressure (from 90 p.s.i. to 20 p.s.i.) resulted in the temporary closing of the business district" (U.S. Army Corps of Engineers, 1949). "* * * water and gas mains were broken [in Olympia]." (Murphy and Ulrich, 1951).

50	Settlement (1949)	Olympia, Wash. (port area); Thurston County	A	"The entire port area, a man-made fill, settled 5 inches [13 cm]. * * * Evidence of differential settlement around the Port of Olympia Cold Storage Warehouses of 2 inches [5 cm] was seen." (U.S. Army Corps of Engineers, 1949).
51	Slump (1949)	Olympia, Wash. (Coopers Point); Thurston County	A	"Clifford Kyllonen, Olympia tug boat skipper, reported that 150 feet [45 m] of the sandspit of Cooper's Point, seven miles [11 km] north of Olympia crumpled and disappeared into Puget Sound during the shock. Kyllonen said he was standing off the spit when the shock occurred, and took color pictures of the mass of land sinking beneath the waves. He said geodetic survey maps showed the spit being five feet [1.5 m] above water at high tide. At high tide yesterday, Kyllonen took soundings and found the spit was now 50 ft [15 m] below the surface." (Bremerton Sun, 1949). "It normally extends 300 yds [275 m] and at high tide is partially covered by water. After the quake the middle portion of the point no longer was visible at low tide. Between 100 and 150 feet [30–45 m] of the spit had sunk into the bay. About 25 feet [8 m] of the north end of the point remained as an island." (Daily Olympian, 1949c). See figure 208.
52	Slides (1965)	Hartstene Island, Wash.; Mason County	B	"We visited the hole in the wall settlement (Hartstene Estates) at the south end [of the island] * * *. Parts of the road had given way in that area, and the County Road crew was on the spot putting up barricades and making repairs." (Shelton-Mason County Journal, 1965).
53	Settlement (1949)	Lacey, Wash. (McAllister Springs); Thurston County	A	"The McAllister Springs project withstood the earthquake well. The only damage was done when the temblor caused an earth fill dam at the springs to drop." (Daily Olympian, 1949b).
54	Slump (1965)	Orting, Wash.; Pierce County	A	A crack 120–150 m long and 15 cm wide opened up along the brow of the hill and across the road (Emmett Chase, oral commun., 1988).
55	Sand boils (1949); ground crack (1949)	Orting, Wash.; Pierce County	B	Sand boils occurred on a farm about 3 km south of Orting. Fine, blue-gray sediment was ejected from a zigzag crack in the ground. It happened in a field on the west side of the [Orting-Electron] highway near a small creek. The sand was somewhat "oily" and the children got very dirty playing in it (Charlotte Rogich, oral commun., 1990).[1]
56	Sand boils (1949)	Sumner, Wash.; Pierce County	A	Two sand boils, about 0.9 m in diameter and 13–15 cm high, occurred at 8502 Riverside Road East in Sumner. Water from the sand boils had a salty taste (Francis Watson, oral commun., 1989).[1]
57	Sand boils (1949)	Sumner, Wash.; Pierce County	A	Blows of water and sand occurred on my property about 1.6 km east of Sumner (Herman Nix, oral commun., 1989).
58	Sand boils (1949)	Sumner, Wash.; Pierce County	A	The 1949 earthquake produced many sand boils, about 15 cm in diameter and 2.5–5.0 cm high, near the corner of Main and Van Tassle on the east side of Sumner. The sand was clean and black (Fred Weber, oral commun., 1989).[1]

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
59	Settlement (1965); miscellaneous effects (1965); miscellaneous effects (1949)	Sumner, Wash.; Pierce County	A	"Broken water mains * * * cement porch fell toward street * * * school gymnasium walk sunk in and cracked. [In the 1949 earthquake] springs disappeared, water lowered." (Mrs. L.R. Bariekman, written commun., 1965).
60	Miscellaneous effects (1949)	Puyallup, Wash.; Pierce County	B	"An opening in the earth, 1 foot [0.3 m] in diameter was reported just outside the East City limits towards Sumner on Linden Drive." (Puyallup Valley Tribune, 1949).
61	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Approximately 20 sand boils erupted as a result of the 1949 earthquake at 1100 7th Ave. SE. The spurts of water were about 15 cm high. The mounds of sediment were composed of clean, bluish sand and were less than 0.3 m in diameter. An artesian well is nearby (William McAlister, oral commun., 1989).[1]
62	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were six sand blows at 1224 5th St. SW. The sand was bluish gray and more water came from the holes after the earthquake. (Bill Morris, oral commun., 1989).[1]
63	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Five or six geysers spurted about 1.5 m high on West Main under where the Puyallup High School gym stands today. They came after the earthquake and lasted a few minutes. The mounds were less than 0.3 m wide and less than 0.3 m high. (Mrs. Hoganson, oral commun., 1989).[1]
64	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were sand blows at 811 2d Ave. NW in Puyallup. They came a little after the earthquake, were about 0.6 m high, and ejected black sand. (Erlyne Eklund, oral commun., 1989).[1]
65	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were many sand blows in the backyard at 113 16th St. SW and also across the alley from that location. (Mrs. Carstens, oral commun., 1989).[1]
66	Ground crack (1949); miscellaneous effects (1949)	Puyallup, Wash.; Pierce County	A	[716 7th Ave. N.W.] "* * * water pipe, from house to city main, running north and south was broken—also a crack opened running north and south across cement walk and across the street. Water was forced up out of the ground near the water main." (J. Stackhouse, written commun., 1949).
	Sand boils (1949)	do.	A	"Many of the geysers spurted up beneath homes. The Darrell Wilson home on 9th St. N.W. was damaged considerably when a geyser pushed up the basement's cement floor, leaving large chunks standing on end. Another home's timber foundation was pushed through the flooring on the first floor. * * * Residents at first believed the geysers were caused by breaks in the water mains * * * but the line of spurting water was far from any main." (Tacoma News Tribune, 1949c).
	Settlement (1949)	do.	A	At the time of the 1949 earthquake, a crack occurred across 9th St. and a car would drop when driven over it; the basement floor of the house at 407 N. 9th St. was pushed up to the ceiling, that is, to the floor joists (Warren Picha, oral commun., 1989).

	Sand boils (1949) miscellaneous effects (1949)	do.	A	Sand boils developed in the alley west of 7th St. NW and north of 5th Ave. NW and the basement floor buckled up at 714 7th St. NW. Also, liquefied sand came up through a basement floor and floated a furnace that was evidently not bolted to the floor at 407 8th St. NW (Merle McMullen, oral commun., 1989).[1]
	Sand boils (1949)	do.	A	Sand boils occurred at 702 5th Ave. NW, 616 5th Ave. NW, 609 7th Ave. NW, 802 5th Ave. NW, and at a brick house on the corner at 9th St. NW and 5th Ave. NW (Irwin Connell, oral commun., 1989).[1]
	Sand boils (1949)	do.	A	There were sand boils in the 800 block of 8th St. NW. There were maybe six black sand gushers. They came a little after the earthquake and were about 0.6 m high (Erlyne Eklund, oral commun., 1989).[1]
				There were sand boils at 5th Ave. NW and 6th St. NW, and the basement at 406 6th St. was pushed up (Earle Shoupe, oral commun., 1989).[1]
	Sand boils (1949)	do.	A	There were 8 to 10 "gushers" at 405 8th St. NW. The mounds were 5–8 cm high and about 5 cm wide. The sand was black. None appeared in 1965 (Helen Clingenpeel, oral commun., 1989).[1]
67	Ground cracks (1949); settlement (1949)	Puyallup, Wash.; Pierce County	A	"Breaks in the earth surface on the Zilke pasture, beyond 7th NW and River Road have been reported. A shift in the River Road is noticeable." (Puyallup Valley Tribune, 1949).
68	Sand boils (1949); ground cracks (1949)	Puyallup, Wash.; Pierce County	A	[1215 3d Ave. NW] "There were many openings in soil; some merely round holes, others were cracks several yards long through which water spouted—some reported five feet [1.5 m] high. Many of these were seen by me, however, none more than a few inches. This locality was badly flooded, but soon subsided, leaving many yards of silt on the surface." (F.J. Plattenberger, written commun., 1949).
	Sand boils (1949)	do.	A	There were possibly 20 sand boils at 1301 4th Ave. NW. These were rather cone shaped, 13–18 cm in diameter and 13–20 cm high. The sand was light colored and holes in the cones were maybe as much as 1.2 cm in diameter. This was the site of much water and sand all over the front lawn and driveway (Richard Six, oral commun., 1989).[1] See figures 199–201.
	Sand boils (1949)	do.	A	There were sand boils at 1515 4th Ave. NW (Mrs. Carstens, oral commun., 1989).[1]
	Sand boils (1949)	do.	A	A blue-gray sand came up in gushers among the daffodil rows between 12th St. NW and 13th St. NW and between 2d Ave. NW and 3d Ave. NW (unidentified respondent, oral commun., 1989).[1]
	Sand boils (1949)	do.	A	Sand piles, 0.6–0.9 m in diameter, appeared on the north side of Stewart Avenue between 11th St. NW and 13th St. NW (Fred Richen, oral commun., 1989).[1]
	Sand boils (1965)	do.	A	There was sand boil activity [related to the 1965 earthquake] on the Aylen Junior High School playfield. There was a considerable amount of water and the long jump pit had to be moved (Lloyd Freuderstein, oral commun., 1989; George Willfong, oral commun., 1989).[1]

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
69	Settlement (1949)	Puyallup, Wash.; Pierce County	A	Basement was pushed up on one end so house teetered [18th St. at 4th Ave.] (Warren Picha, oral commun., 1989).
	Sand boils (1949)	do.	A	The house on the NE corner of 4th Ave. NW and 18th St. NW had about 1.2 m of liquefied sand in the basement (Earle Shoupe, oral commun., 1989).[1]
				There were sand boils at 4th Ave. NW and 18th St. NW (Dorothy McCleary, oral commun., 1989).[1]
	Sand boils (1949)	do.	A	There were sand boils "all over" cultivated farm property at 2001 4th Ave. NW. The geysers were about 0.3 m high (Mr. and Mrs. Elmer Johnston, oral commun., 1989).[1]
70	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were sand boils at 2612 Tacoma Road [at the time of the 1949 earthquake] (Marie Biehn, oral commun., 1989).[1]
71	Slump or lateral spread (1949); ground crack (1949)	Puyallup, Wash.; Pierce County	A	"Cracks and destruction at the Pat Fox Farm." (anonymous, written commun., 1949). Crack along the west bank of Clarks Creek was 60–90 m long and about 0.9 m high. Photograph in 1949 issue of Life Magazine shows the ground crack.
	Settlement (1949)	do.	A	House across [Clarks] creek was tilted and concrete foundation destroyed (Warren Picha, oral commun., 1949). See figure 202.
	Miscellaneous effects (1949)	do.	A	At 5720 66th Ave. East, the basement floor came up and the well became cloudy but cleared up (Fred Richen, oral commun., 1989).[1]
	Ground crack (1949)	do.	A	There was an east-west crack down Stewart Avenue that extended past the Clarks Creek bridge (Richard Six, oral commun., 1989).[1]
72	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Sand boil activity just east of Freeman Road and about 2 blocks from the Puyallup River resulted in a deposit of sand as much as 4.6 m in diameter. The spurts of water and sand were 1.5–1.8 m high (Mrs. Eggiman, oral commun., 1989).[1]
73	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Sand boils occurred in back of the house and a little to the left of the driveway. The house is located north of the Puyallup River along Freeman Road and is between the railroad tracks and a small creek (Sylvia Veal, oral commun., 1989).[1]
74	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were dozens of sand boils from Freeman Road to the base of the North Hill. They were composed of light-colored sand (Ted Maloney, oral commun., 1989).[1]
75	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Sand boils at 5820 44th St. East ejected blackish, clean sand. The sand deposits were 0.3–0.5 m in diameter and 9–12 m apart. They looked like mole hills; the wider hills were flatter (George Richen, oral commun., 1989).[1]

76	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Sand boils appeared along the North Levee Road about 45 m from the river. The gushers were 2.4–3.0 m high (Marie Bingasser, oral commun., 1989).[1]
77	Settlement (1949); ground crack (1949)	Puyallup, Wash.; Pierce County	A	"Although survey data are not available, settlement in the tide flat area is known to have taken place. In one instance, a ground fissure approximately 1,000 feet [305 m] in length, opened along a line paralleling 11th Street. One black-topped side street entered 11th Street in this stretch. The black-top surface of this street was ruptured, the opening being approximately 4 inches [10 cm] wide and having a vertical displacement of 6 inches [15 cm], the low side was toward the waterfront." (U.S. Army Corps of Engineers, 1949).
	Sand boils (1965)	do.	A	"Sand boils appeared in the tide flats area at Alexander Avenue between 11th Street and Lincoln Avenue at the time of the 1965 earthquake." (R.M. Button, Chief, Building Department, Tacoma City Engineers Office, oral commun., 1988).
78	Settlement (1949); sand boils (1949)	Puyallup, Wash. (tidal flat area); Pierce County	B	"Settlement in the tide flats area was accompanied by boils of water, mud and debris at several points. The flow of material from these boils continued for about 20 minutes after the quake." (U.S. Army Corps of Engineers, 1949).
	Miscellaneous effects (1949)	do.	B	"The Superintendent of Water reports a total of 19 line breaks during the quake, the majority occurring in the tide flats area." (U.S. Army Corps of Engineers, 1949).
	Ground crack (1965)	do.	A	"City Public Works Director G.M. Schuster * * * said a crack a few inches wide and about 500 feet [152.4 m] long opened up alongside Thorne Road, in the port industrial area." (Tacoma News Tribune, 1965a).
79	Sand boils (1949); ground cracks (1949)	Tacoma, Wash. (tidal flat area); Pierce County	A	"Northern Pacific roundhouse and repair tracks crews gaped in astonishment just after the quake Wednesday. They saw an unadvertised "geyser" in their midst, apparently stemming from the long ago bed of the Puyallup River, near East 23rd and G Sts. Long jagged cracks, 60 to 70 feet [18.3–21.3 m] appeared at the edge of the repair track space where water shot upward, bringing with it deposits of fine, white sand. Quick investigation disclosed no water pipes or city mains were near the spot. The water spout, witnesses said, lasted a considerable time after the tremor subsided." (Tacoma News Tribune, 1949a).
80	Slide (1949)	Tacoma, Wash. (Mason Gulch); Pierce County	A	"Two of the 12-inch [0.3 m] diameter cast iron pipes were sheared by a landslide in Mason Gulch in the north end of the city." (U.S. Army Corps of Engineers, 1949).
	Slide (1965)	do.	A	"The 1949 quake caused sliding along Mason Gulch, and sliding occurred again at the same location due to the 1965 earthquake. The sidewalk and chainlink fence at top of slope have been moved back several times due to slide activity." (Unidentified resident, oral commun., 1988).

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
81	Slide (1949); ground cracks (1949)	Tacoma, Wash.; Pierce County	A	"The only major landslide known to have occurred as a result of the quake tremors was at Salmon Beach, 6 miles [10 km] northwest of downtown Tacoma at the Narrows. The slide occurred at 2:55 am on 16 April, 3 days after the quake. The top of the bluff is approximately 400 feet [120 m] above the waters of Puget Sound. Original estimates placed the quantity of earth moved at 11,000,000 cubic yards [8.4×10^6 m^3], although this is thought to be excessive. One million cubic yards [7.6×10^5 m^3] is believed to be a more reasonable figure. Geologists who have visited the site report the sand and gravel bluff to be resting on a clay base. Although the slide came within 20 yards [18.3 m] of the nearest of 108 beach residences, no property damage or loss of life was reported from the slide. However, a wave front estimated to be 8 feet [2.4 m] high was created by the slide. This wave did minor damage to small docks and boats moored nearby. Fissures are exposed along the bluff crest extending away from the present slide and paralleling the bluff brow for a distance of several hundred feet." (U.S. Army Corps of Engineers, 1949). See figure 203.
	Sand boil (1949)	do.	A	"The crack in the cliff could send more tons of earth plunging down. * * * Though the split is but two inches [5 cm] wide, it is deep. White sand boiled up through it to the surface during Wednesday's quake." (Vogel, 1949).
82	Slump (1949, 1965)	Tacoma, Wash.; Pierce County	A	"* * * there is a bank about twenty feet [6 m] high that drops down to the lower pasture, which slopes down the hill to the railroad tracks and the water. Part way down this bank the ground split and the whole lower area dropped about one and one-half feet [0.5 m]. This lower area is about 400 feet [120 m] east and west and 600 feet [183 m] north and south. This dropping also occurred during the 1949 earthquake." (Mr. and Mrs. Sydney Selden, Jr., written commun., 1965).
	Slide (1949)	do.	A	Failure occurred along same failure surface in both the 1949 and 1965 earthquakes, but was much worse in 1949. In 1949, the scarp developed for about 183 m and the slump dropped about 0.6 m. In 1965, movement along the scarp was probably somewhat shorter (maybe about 137–140 m), and slump dropped about 0.5 m in 1980 due to heavy rain (Sydney Selden, Sr., oral commun., 1988).
83	Slides (1965)	Tacoma, Wash. (Day Island Bridge); Pierce County	A	"City Public Works Director G.M. Schuster said * * * city crews Friday were placing fill in a portion of the road under the Day Island Bridge, where about 1,000 yards [900 m] of material slipped away." (Tacoma News Tribune, 1965a). "Slides reported on Lemons Beach Road and on a cliff near Day Island Bridge. Fill on mainland side of approach to Day Island Bridge gave way during the quake sending earth and trees cascading into a gully. The slide undermined the roadbed of the Lemons Beach Road under the bridge and that road was closed to traffic. Trees were uprooted and scattered like matchsticks by the slide." (Tacoma News Tribune, 1965b).

84	Slide (1949)	Fox Island, Wash. (west of Tacoma); Pierce County	A	[Photo caption] "QUAKE TOPPLES HOUSE INTO PUGET SOUND: This aerial photograph shows the roof of a house which the Coast Guard said toppled into Puget Sound from Fox Island, just south of Tacoma, during yesterday's earthquake. The Coast Guard did not learn whether anyone was in the house when the quake shook the small island." (Seattle Times, 1949b). "I visited the site a couple of months after the earthquake. The owner had excavated a small shelf 50 to 100 feet [15–30 m] above the beach, and the shelf and house had slid into the water. I saw wires, plastic pipe, etc., severed by the slide." (Jay Bower, oral commun., 1988).
85	Slump/debris flow (1965)	Grapeview, Wash.; Mason County	A	"* * * quake caused a slide in a section of the Grapeview road that necessitated closing the road the day of the quake." (Shelton-Mason County Journal, 1965). "Fill split down the middle and the slide material moved 150 yards [137.2 m] out along the cove as a kind of flow." (Kent Hansen, oral commun., 1988). Failure occurred in a 9.1-m-high road embankment where the road crosses a small arm of McLane Cove.
86	Slump (1949, 1965)	Allyn, Wash. (Rocky Point); Mason County	A	"The highway here was cracked in several places and portions of it settled about six inches [15 cm]." (G.H. Allyn, written commun., 1949). "The slide also moved in the quake of April 29, 1965." (Mrs. Gaetana, oral commun., 1988). The failure, which involved artificial fill, occurred along the highway adjacent to Case Inlet. The failed embankment is about 6 m high. Slumping caused a vertical displacement of approximately 15 cm along 30 m of highway.
87	Slump (1949)	Port Orchard, Wash. (south on old Gig Harbor highway); Kitsap County	A	"The road bed that went out [at the time of the April 13, 1949, earthquake] on the Gig Harbor highway about 1/2 mile [0.8 km] south of our place, also caved in the quake of '39 [November 13, 1939]." (Mrs. C.L. Wermer, written commun., 1949). [Photo caption] "Break in State Highway No. 14, near Port Orchard, Washington. SE 1/4 of SE 1/4 of Section 23, Township 23 N, Range 1 E, W.M." (Coombs and Barksdale, 1942). Ground failure at this location triggered by the Puget Sound earthquake of November 12, 1939 (M=6.2, Noson and others, 1988) is described by Coombs and Barksdale (1942) as follows: "Investigation of this crack showed it to be on the surface of a fill approximately 260 yards [237 m] in length and 4 yards [3.7 m] thick in the center. A bed of quicksand fed continuously by many springs a short distance away on the uphill side underlies the sand and gravel of the fill. So unstable a foundation might well be expected to give way under the effects of the earthquake motion."
88	Slump (1965)	Gig Harbor, Wash. (highway near Crescent Lake); Pierce County	A	[Photo caption] "A narrow but deep fissure opened up on the Purdy Road near its intersection with the Crescent Lake Road near Gig Harbor during Thursday's tremor. * * * [the crack] was more than a foot [0.3 m] wide and at least four feet [1.2 m] deep in spots." (Tacoma News Tribune, 1965a). The highway crosses a flat, swampy area at this location. The highway was less than 0.3 m above the lake originally, and underlying soil was probably saturated.

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
89	Slump (1965)	Gig Harbor, Wash. (north side of town); Pierce County	A	[Photo caption] "A 20-foot [6 m] section of the road by Gig Harbor's town park slid into a small creek and tidal pool Thursday during the quake." (Tacoma News Tribune, 1965a). Slump occurred in road embankment (artificial fill) founded on tidal-flat mud. Road embankment is about 2 m high.
90	Slide (1965); miscellaneous effects (1965)	Vashon Island, Wash. (west side); King County	A	"On road going down to the beach which is cut out of the side of a bank a crack approximately 1/2 to 3/4 inches [1–2 cm] wide and about 50 ft [15 m] long appeared. This road had been graded out in 1947 and has shown only very minor settling since then during heavy winter rains. The crack looked as though it developed along the line where the fill part of the road is. * * * Water in wells was murky for about 6 weeks afterward * * * they are only 10 ft [3 m] deep." (Norman A Benson, written commun., 1965).
91	Ground cracks (1965)	Vashon Island, Wash. (west side, Reddings Beach); King County	B	"Cracked foundation. Two hundred feet [60 m] of roadway blacktopped, opened up one inch [2.5 cm]." (Harold J. Raymond, written commun., 1965).
92	Slide (1965)	Vashon Island, Wash. (west side, Reddings Beach); King County	B	"Tons of sand broke off a 120 foot [37 m] bank north of us." (Harold J. Raymond, written commun., 1965).
93	Slide (1965)	Vashon Island, Wash. (west side, Jod Creek); King County	A	"50 feet [15 m] east of Jod Creek, crack in damp soil, 60 ft [18 m] long, 3 ft [0.9 m] deep × 1 ft [0.3 m] wide at center (crack runs N-S)." (M.C. Ball, written commun., 1965).
94	Slumps (1965)	Vashon Island, Wash. (east side, Klahanie Beach); King County	A	"Waterfront cottage sitting on wooden supports behind bulkhead, at bottom of hill, was pushed forward several inches. Concrete behind cottage cracked and buckled. Trail on hill behind community developed crack with some settling. Wood retaining wall behind cottage pushed forward." (Mark D. Hafermann, written commun., 1965). Crack on hill was about 60 m long. Downhill side dropped a few centimeters. There were also slides on side hill behind second and third houses from south end. Those slides moved about a meter but did no damage (Jan Weir, oral commun., 1988).
95	Slide (1965)	Vashon Island, Wash. (Shawnee Beach); King County	A	"Also there was a slide across the road about 1/2 mile [0.8 km] south from Burton." (Mrs. F.M. Urschel, written commun., 1965).

96	Settlement (1965)	Vashon Island, Wash. (Shawnee Beach); Mason County	A	"Two cracks formed in a small swimming pool in our yard. Cement patio around pool pulled away from pool—each section cracking away. Either the pool raised or the patio sunk because it sets up a little higher now." (Mrs. F.M. Urschel, written commun., 1965).
	Slide (1965)	do.	A	"* * * a large crack formed at the side of the road in the shoulder just behind our place—the main road between Burton and the Tahlequah Ferry. [The crack] was 2" [5.1 cm] wide in places with a drop about the same and was about 30' to 40' [9–12 m] long." (Mrs. F.M. Urschel, written commun., 1965).
97	Slide (1965)	Vashon Island, Wash. (Magnolia Beach); King County	A	Concrete bulkhead on beach settled. Bulkhead was built on fill that was placed on hard clay. There was approximately a 15 cm drop, and the bulkhead cracked (Robert Gordon, oral commun., 1988).
98	Ground crack (1965)	Maury Island, Wash. (south end); King County	A	"The private road into our property sustained a crack about 3 inches [8 cm] wide at the highest point of road and about 100 yards [90 m] down road crack continued." (Donald Boot, written commun., 1965).
99	Slide (1965)	Tacoma, Wash. (Palisades); King County	B	"30 ft [9 m] long crack in earth parallel to bank and running in north-south direction. Some sliding of bank." (J.C. Peaslie, written commun., 1965).
100	Ground crack (1949); sand boils (1949); miscellaneous effects (1965)	Pacific, Wash. (south, near county line); King and Pierce Counties	A	"Beginning in the south side of Pacific (Pacific City) and running almost straight south for a 1/2 mile [0.8 km] into Pierce County, a fissure opened up, out of which at various points water boiled out (according to one observer) * * * to a height of 2 feet [0.6 m]. Several inches of water were on the surface before the action stopped. The water carried with it a considerable amount of very fine sand." (Ralph Pommert, written commun., 1949). "The ground out here is peat and sand, and very pliable. The water bubbled in one place * * * approximately 1 ft [0.3 m] out of ground. Bubbled on all of our land out here and pushed up various types of soil. A very large crack on place next to ours * * * crack runs NW to SW. Imagine it was much deeper than it is now for soil and silt washed in. On next place to above a large crack * * * in berry patch. Their strawberries sank several inches. At trunks of trees fence posts, all bubbled and soil washed up. Water lines broke." (Margaret E. Farr, written commun., 1949).
	Sand boils (1965)	do.	A	"Among the strange things that came along with the earthquake Thursday was one out of Roy Road, on the way to Auburn, when a housewife saw a field near her home develop its own sprinkler irrigation system. * * * As it spouted out it brought with it a foamy sand which was in piles all over the two fields." (Sumner News-Index, 1965). The sand boils occurred just SW of the intersection of 2nd Street East and Valentine Road (Mrs. Palmer Johnson, oral commun., 1988).

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
101	Sand boils (1949)	Auburn, Wash.; King County	A	Coworkers reported seeing numerous water-sand geysers in fields adjacent to the shop at the north end of the Auburn General Depot [at the time of the 1949 earthquake] (Larry Lundberg, oral commun., 1988).
102	Slide (1949, 1965)	Auburn, Wash. (east of Auburn on Lake Holm Road); King County	A	"Slides were reported in the Lake Holm Road east of Auburn." (Seattle Times, 1965a). "In the 1949 quake, a crack about 3 inches [7.6 cm] wide and several feet deep opened between the house and the garage. I think it went down to the [Big Soos] creek and reappeared at about the Auburn-Black Diamond Road. In the 1965 quake the crack did not reopen on our place, but did cause a small slide on 148th St. where it comes down the hill." (Mr. and Mrs. Larry Lundberg, oral commun., 1988).
103	Ejection of ground water (1965)	Auburn, Wash. (north side); King County	B	[Photo caption] "GROUND SEEPAGE—Jerry Keesee, city sewage plant superintendent, * * * checks seriousness of seepage around manhole on line leading into plant in North Auburn. Keesee said later it appeared to be relief point for ground water—not sewage—and that there was no apparent break in the line." (Auburn Globe-News, 1965).
104	Slump (1965)	Kent, Wash. (Kent-Des Moines Road); King County	A	[Photo caption] "ROAD COLLAPSE—Damage caused when a water main broke alongside the Kent-Des Moines Highway just west of the Green River bridge during Thursday's earthquake * * *. The road shoulder collapsed as a result of the quake damage." (Kent News-Journal, 1965b).
105	Slump (1949); sand boils (1949); miscellaneous effects (1949)	Kent, Wash. (NE on Big Soos Creek); King County	A	"Water system is gravity line taken from springs east side of creek, 2 and 3 inch [5.1 and 7.6 cm] wooden pipe—about 950 feet [298.6 m]. Went to inspect pipelines 1 hour after quake, nearly all were leaking where line crosses creek and swamp, emitting white water (water mixed with clay). Water reservoir (earth constructed) all white and all springs giving more water. Above reservoir crack in earth about 100 feet [30.5 m] long north and south. At that time lower, or west side of crack, had slipped about 3 inches [8 cm] but after 24 hrs it was about 8 inches [20 cm] and appeared to be slowly settling. At one spot that was dry I could slip my hand into the crack. I went to inspect other springs, one on adjoining property about 1000 ft [300 m] north of my reservoir was emitting white water with about 4 times the volume as before the quake and brought up considerable fine sand and clay. Between this spring and mine there were numerous spots where seepage of new water occurred in spots that were dry." (John Haverinen, written commun., 1949). The reservoir mentioned in the letter above was located on hillside just east of Big Soos Creek and below the power lines that cross the upper part of the hillside. The reservoir was very small, not more than a few tens of feet across (John Haverinen, Jr., oral commun., 1988).

106	Sand boil (1965); ground crack (1965)	Kent, Wash. (208th St. near O'Brien); King County	A	"Cracked cement driveway * * * water and sand spurted through cement driveway—several ground cracks and erosions of water and sand." (Mrs. Milton Botts, written commun., 1965).
107	Sand boils (1965)	Kent, Wash. (212th St. just west of Green River); King County	A	[Photo caption] "BOIL AND BUBBLE—Thursday morning's earthquake created an odd phenomena in a field near O'Brien being worked by Albert Dreisow. * * * [Dreisow] found numerous 'mud pots' [sand boils] in the field, similar to the fissure he is examining here." (Kent News-Journal, 1965a). "Two sand boils appeared in the fields; one on each side of 212th Street." (Albert Dreisow, oral commun., 1988).
108	Slide (1965)	Kent, Wash. (42d Avenue S.); King County	B	[Photo caption] "ROAD DAMAGED—Last Thursday's earthquake caused the side of 42nd Avenue South, near St. Patrick's Cemetery, to cave in and county road crews placed one-way signs along the damaged roadway." (Kent News-Journal, 1965c).
109	Slide (1965)	Seattle, Wash. (Burien, Three Tree Point area, 172d Street S.W.); King County	A	"Home located above [Puget] sound water 300' [90 m] on hillside. Sandy soil, facing south. * * * cracks of 2" to 3" [5–8 cm] were discovered across bank running east to west. Concrete sidewalk along edge of bank, cracked and upheaved—sand shaken away from underneath the concrete. Place next door had same damage." (Larry Lemmel, written commun., 1965). "Buckled [concrete]; [cracks] approximately 4 inches [10 cm]; [settling] at hilltop." (Mrs. John Maass, written commun., 1965). Sketch map shows a continuous crack 8–10 cm wide on hillside overlooking Puget Sound. The crack (in the drawing) extends across the hillside parallel to 172d Street S.W. the length of 3 or 4 residential properties.
	Slide (1965)	do.	A	"Broken [concrete walkway]. The hill pushed down on the retaining walls and pushed them out about three inches [8 cm]." (Mrs. Henry A. Roche, written commun., 1965).
110	Slide (1965)	Seattle, Wash. (Tukwila); King County	B	The 1965 earthquake triggered a landslide on the Foster golf course along the Duwamish. The slide involved fluvial sands and silts and was probably induced by liquefaction (Seed, 1968).
111	Settlement (1965)	Renton, Wash. (Burnett Street and Seventh Avenue); King County	B	"Mayor Custer said filling and paving to repair settling of the entire length of Burnett Street and Seventh Avenue would cost an estimated $15,000 to $20,000. Custer said the settling was along the route of the Metro sewer line, but Robert Hillis of Metro reported there was no damage to the line. * * * City Engineer Jack Wilson said Burnett and Seventh had dropped as much as two feet [0.6 m] in some places." (The Record Chronicle, 1965).
	Settlement (1965)	Renton, Wash. (Shattuck Street between S. 6th and S. 7th Streets); King County	A	"Foundation cracked open under house. Cement walk from street to house cracked open. House settled about 2-1/2 inches [6 cm]. Front and backyard upheaved and sunken in spots." (A.F. Salisbury, written commun., 1965).

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
112	Slide (1965)	Renton, Wash. (Highlands); King County	C	"Cement block retaining wall holding back sand bank collapsed completely—wall was free standing, 5'×34' [1.5×10.4 m]. Wall runs north and south." (Edith Look, written commun., 1965).
113	Slides (1965)	Renton, Wash. (Jones Road); King County	C	"There was a lot of damage to Jones Road—slide, cracks, and settling (broke water pipes)." (Mrs. A.F. Savoya, written commun., 1965). "Slides were reported in the Lake Holm Road east of Auburn, the Jones Road near Maple Valley and the Devil's Elbow Road near Maple Valley." (Seattle Times, 1965a).
114	Ground crack (1965)	do.	A	"A narrow crack less than 2.5 cm wide and 45.7 m long opened up across Jones Road at the time of the 1965 quake. The crack ran across Jones Road from the south side of the street, and continued across our yard to the front of the house, where it damaged some brick-work" (Bill Niemi, oral commun., 1988). Crack developed on alluvial floodplain or low terrace of the Cedar River.

[1]Information originally gathered by Dr. John A. Shulene of Puyallup, Wash. This information is based on telephone conversations or personal interviews with residents who responded to a request for information on sand boils related to the April 13, 1949, or April 29, 1965, earthquakes. Dr. Shulene's request for information was placed in the Pierce County Herald in May of 1989.

Table 31. Descriptions of selected ground failures in the Cascade Range of Washington region.

[Location numbers correspond to ground-failure location numbers on plate 6. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers; D, information insufficient to locate accurately. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
115	Miscellaneous effects (1949)	Mount Adams, Wash.; Yakima County	C	"Clyde Sword and a passenger, 'Babe' Forsyth, flew over the mountain [Mount Adams] and reported that there was a large opening on the southeast side and steam was rising from it." (Chehalis Advocate, 1949). "* * * strange cloud formation which appeared from behind Mt. Adams after the quake and continued until darkness fell. This cloud formation looked stranger yet when viewed through high powered glasses. It looked like steam or smoke which rose from a certain point and drifted with the wind. No other clouds were in the clear sky and this one remained just like smoke would, except for its drifting with the wind * * *." (Chehalis Advocate Correspondence Service respondent [anonymous], written commun., 1949).
116	Slump (1949)	Randle, Wash. (just north of Cispus River bridge on old road); Lewis County	A	Slump of road on sidehill slope. Road slumped about 0.6 m vertically for a length of about 18 m (Lawrence E. Panco, oral commun., 1988).
117	Slump (1949)	Randle, Wash.; Lewis County	A	Road embankment failed about 1.6 km southwest of Randle during the 1949 earthquake (Hubert Derosett, oral commun., 1988). The slump occurred on a 0.9- to 1.2-m-high road embankment in artificial fill underlain by loose, liquefiable sand. The failure extensively damaged several meters of roadway (see fig. 209). Numerous sand boils simultaneously erupted in a nearby field (loc. 118).
118	Sand boils (1949)	Randle, Wash.; Lewis County	A	"Sand boils dumped wheelbarrow loads of sand in our pasture in the 1949 quake." (Lawrence Peters, oral commun., 1988).
119	Slumps (1949)	Randle, Wash.; Lewis County	A	"There were small slides along the west bank of the oxbow lake on my property southeast of Randle at the time of the 1949 quake." (Norm McMahon, oral commun., 1988).
120	Rockfall (1949)	Randle, Wash.; Lewis County	A	"Several blocks of rock 4–6 ft [1.2–1.8 m] across came down [during the 1949 earthquake] and blocked Cline Road about 1 mile [1.6 km] southeast of Randle." (Hubert Derosett, oral commun., 1988).

Table 31. Descriptions of selected ground failures in the Cascade Range of Washington region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
121	Rockfall (1949)	Randle, Wash.; Lewis County	A	"A large block about 20 ft [6 m] on a side dropped from a steep cliff onto Cline Road at a point about 2-1/2 miles [4 km] southeast of Randle. This happened as a result of the 1949 earthquake." (Hubert Derosett, oral commun., 1988).
122	Rockfall (1949)	Randle, Wash.; Lewis County	A	"A rockfall occurred along the old Randle-Packwood Highway, about 5 miles [8 km] east of Randle. Rocks up to 3 ft [0.9 m] in diameter came down and some trees toppled." (Hubert Derosett, oral commun., 1988).
123	Rockfall (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	C	"* * * rocks were observed falling from the cliffs of * * * Eagle Peak." (National Park Service, 1949).
124	Rockfall (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	B	"* * * rocks were observed falling from the cliffs of Rampart Ridge" (National Park Service, 1949).
125	Slide (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	C	"On the Kautz Creek drainage the 1947 flood debris showed an assortment of parallel cracks in the snow, indicating a shifting of the unconsolidated fill beneath." (National Park Service, 1949). "Of interest was the fact that the material deposited by the 1947 Kautz Creek flood shifted somewhat during the quake. In the snow overlying the flood deposits, a series of en echelon cracks showed up, with the direction of movement of the deposits downward toward lower elevations." (John C. Preston, National Park Service, written commun., 1949).
126	Rocklide (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	B	"One major rock slide on the slopes above the Nisqually Glacier was reported." (John C. Preston, National Park Service, written commun., 1949).
	Rockfall/rockslide (1965)	do.	B	"Some rock, snow and icefall occurred on the mountain. * * * A helicopter flying near the glacier observed large pieces of ice (glacier) breaking and falling away, and in turn creating avalanches. Large amounts of rock and soil adjacent to the Kautz Glacier were observed by Chief Park Ranger Ruben Hart from a helicopter, although none of this was large enough to form a barrier in the river." (National Park Service, 1965).

127	Ground cracks (1949)	Buckley, Wash. (Mud Mountain Dam); King and Pierce Counties	A	"At Mud Mountain Dam old longitudinal cracks in the fill in the zone of juncture between the core and the rock fill reopened to a width of about 1 inch [2.5 cm]. The dam is not endangered." (U.S. Army Corps of Engineers, 1949).
	Slide (1949)	do.	B	"Some additional material in an old slide area on the right bank downstream from the dam loosened and slid into the stream. A crack near the left side of the spillway was apparently unaffected." (U.S. Army Corps of Engineers, 1949).
	Ground cracks (1965); slides (1965)	do.	A	"Small cracks from 1/2 to 1-1/2 inches [1.3–2.8 cm] wide were found parallel to the axis of the dam between the impervious core and rockfill zones. These cracks are of an intermittent nature but extend generally along the entire length of the embankment. This cracking is similar to the cracking at Howard Hanson Dam. * * * The shock caused small earth slides adjacent to the Vista House and minor cracking of the concrete slab around the Vista House." (Steinborn, 1965).
128	Ground cracks (1965)	Palmer, Wash. (Howard Hanson Dam); King County	A	"Cracking was found along the crest of the embankment parallel to the axis of the dam and upstream of the centerline in the sand and gravel zone or between this zone and the drain. These cracks were intermittent but they extended in one line or two parallel lines throughout the length of the embankment. Where two lines of cracks occurred they were from 6 inches to 24 inches [15–61 cm] apart. The widest opening was 1/2 inch [1.3 cm]. Maximum differential settlement along the crack did not exceed 1/2 inch [1.3 cm]. There was no measurable settlement of the dam." (Steinborn, 1965).
129	Slide (1965)	Ronald, Wash. Kittitas County	C	"Large rock dump started to slide and cave." (Hake and Cloud, 1967).
130	Rockslides (1949)	North Bend, Wash. (Mount Si); King County	B	"Rockslides on Mt. Si [triggered by the 1949 earthquake]." (Murphy and Ulrich, 1951).
	Rockslides (1965)	do.	A	"Press reported an extensive slide occurred on the southwest slope of Mount Si near North Bend [at the time of the 1965 earthquake]." (Hake and Cloud, 1967). "Dust cloud rose from near the bottom of the rock face on the west side of Mt. Si during the 1965 earthquake [near the 670-m-elevation level]." (Jack Ferrell, U.S. Forest Service [retired], oral commun., 1988). Prior to 1949, the earthquake of April 1945 also triggered rockslides on Mount Si. According to Bodle and Murphy (1947), "At the Mount Si Ranger Station, near North Bend the earth buckled and heaved and tons of rock and earth cascaded down the 4,000-foot [1,200 m] cliffs of Mount Si." See figure 210.
131	Rockfall (1965)	Index, Wash. (Mount Persis); Snohomish County	C	"Mrs. Spencer White of the Mt. Index Service Station reported that the quake sent huge boulders rolling down the side of Mt. Persis, near the Stevens Pass Highway." (Everett Herald, 1965). "Boulders came rolling down onto the Stevens Pass Highway from Mt. Persis east of Everett, causing some damage." (Wenatchee Daily World, 1965).
132	Snow and rock avalanches (1949)	Darrington, Wash.; Snohomish County	D	"Snow and rock avalanches in the mountains [in the vicinity of Darrington]." (Murphy and Ulrich, 1951).

Table 32. Descriptions of selected ground failures in the central-southwestern Washington region.

[Location numbers correspond to ground-failure location numbers on plate 7. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
133	Slump (1949)	Mossyrock, Wash.; Lewis County	A	"Quake left a 25-foot [8 m] long crack in the ground in the backyard. * * *Crack runs north and south." (Mrs. V.C. Holsted, written commun., 1949). Crack resulted from a slight slump near the base of the slope adjacent to the Winston Creek flood plain.
134	Slump (1949)	Kosmos, Wash.; Lewis County	A	Road slumped into the Cowlitz River, damming it for a short time. Failure occurred along 90 m of river bank on the north side of the river. The failed slope was 15–21 m high and near vertical in its upper part. The material involved was sand and gravel, but mostly medium sand (Hubert Derosett, oral commun., 1988).
135	Rockfall (1949)	Morton, Wash.; Lewis County	A	"A rock cliff across the valley had huge boulders shaken down." (Mrs. Clifford Butts, written commun., 1965). A block of bedrock about 8 m high fell from the face of a near vertical cliff, frightening homeowners below (Ivy Beck and Lena Hall, oral commun., 1988).
136	Slides (1949)	La Grande, Wash.; Pierce County	C	"Ground cracks on side hills 1 inch [2.5 cm] wide 25–30 ft [8–9 m] long. Landslides [in the vicinity of La Grande]." (Murphy and Ulrich, 1951). "Earth cracks along canyon of the Nisqually River; slides into rivers and onto roads." (Hake and Cloud, 1967).
137	Slump (1949)	Eatonville, Wash.; Pierce County	A	"The quake opened a crack about 100 ft [30 m] in length on the Alder * * * cutoff, about 6 inches [15 cm] wide." (Eatonville Dispatch, 1949). About 1.6 km south of Eatonville, a 30-m-long road crack appeared as a result of a slump on an approach to a railway overpass. The slump, which occurred in an embankment of artificial fill, had a vertical displacement of approximately 0.6 m (Percy Williams, oral commun., 1987).
138	Slump (1949)	Eatonville, Wash. (Ohop Lake); Pierce County	A	"On the Lake road the crack is three to four inches [8–10 cm] wide and extends about 700 feet [210 m] from Point Ohop on towards Kapowsin." (Eatonville Dispatch, 1949). "Quake Slide Makes Isle—Reverberations from the April 13 earthquake continue to be felt throughout Pierce County. Witness the creation of a new island in Ohop Lake Friday noon when thousands of tons of earth from an 800-foot [250 m] stretch of the Ohop-Kapowsin road sheared off the hillside and plunged into the water. The road cave-in was a direct result of the quake occurring just a month ago. The quake had left a crack in the highway * * *. Efforts of county road crews to fill up the crevice had proved unavailing. * * * summer cottages were thrown off plumb as much as two feet [0.6 m] * * *. Communication lines, including telephone and power lines, were intact, but hanging on by slender threads." (Tacoma Sunday Ledger-News Tribune, 1949). The surface of the road along the west side of Ohop Lake originally developed a 215- to 250-m-long crack due to incipient slumping triggered by the 1949 earthquake. One month later, on May 13, complete failure occurred as the unstable mass slid and (or) flowed as far as 30.5 m into the lake, leaving a 1.5 m scarp along the roadway (see fig. 213). The slide involved artificial fill overlying well-consolidated alluvial sediments.

139	Soil fall (1965)	Electron, Wash.; Pierce County	A	Sand and gravel fell from a 15-m-high vertical face onto the road to the powerhouse. About 38 m^3 of material blocked the road (Emmett Chase, oral commun., 1988).
	Ground crack (1965)	do.	C	"Ground cracked [near Electron]." (Hake and Cloud, 1967).
140	Slump (1949)	Lacey, Wash. (Patterson Lake); Thurston County	A	"We really felt it bad on S.E. side of Lake Patterson. As I sat up after the shaking ground threw me, I saw the last cars of a freight train go over the trestle across the lake, then the land slid from under the tracks and at the same time the water rose over the dock (10 or 12 inches [25 or 30 cm])" (Mrs. Harry A. Esborg, written commun., 1949). "Bridge 31—East Approach: Embankment for 275 ft [84 m] slid into Patterson Lake. Repairs by contractor—25,000 CY [19.1×10^4 m^3] mtl" (U.S. Army Corps of Engineers, 1949).
141	Sand boils (1949)	Maytown, Wash. (just east of Deep Lake); Thurston County	A	"In one of our pastures we found a dozen patches of mud and sand which had apparently been forced up from under the ground. The largest patch was about ten feet [3 m] across; the smaller ones were only three to four feet [0.9–1.2 m]. The largest patch seemed to have come out of a crack in the earth; the others, from holes. Mud—quite liquid—came out first, and then sand flowed out to form a layer several inches thick. When we plowed the field recently we had to plow under a couple of these spots, but the rest are on swampy ground and can still be seen." (Mrs. W.N. Winslow, written commun., 1949). Ejected sand was clean and white and glistened like glass. It was extruded along a line spread over a zone about 3 m wide. The fissure was oriented north-south and lay east of Deep Lake (Mr. and Mrs. Conrad Newman, oral commun., 1988). Farming practices mixed sand with other soil, and features were obliterated in a relatively short time. For a year or so afterward, the sand boils were visible indirectly because they were drier and less fertile. The area is underlain by glacial drift; gravel exposed in gravel pit at the south end of the property has poorly sorted sand. The key control in the formation of the sand boils was probably a high water table and a lens of well sorted, sandy stratified drift in the glacial deposits.
142	Ground cracks (1949)	Centralia, Wash. (Hanaford Valley); Lewis County	C	"We are on a quicksand base, mostly at a depth of 7 ft [2.1 m] * * * most water pipes were broken and * * * 70 percent foundation damage." (Mrs. Paul Quay, written commun., 1949).
143	Slump (1949)	Centralia, Wash. (Pacific Sand and Gravel Pit); Lewis County	A	[Photo caption] "This fissure and others extended about 100 ft [30 m] in an old gravel pit near Centralia." (Edwards, 1951). Slight slump (vertical displacement of several centimeters) at edge of old gravel pit. Failure probably occurred in Vashon glacial outwash deposits (sand and gravel) present at the site.
144	Slump (1949)	Centralia, Wash. (north shore of Plummer Lake); Lewis County	A	Cracks 8–15 m long and several centimeters wide developed on the north shore of Plummer Lake during the 1949 earthquake (Don Swanson, oral commun., 1988).

Table 32. Descriptions of selected ground failures in the central-southwestern Washington region—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
145	Settlement (1949); miscellaneous effects (1949)	Centralia, Wash.; Lewis County	A	"* * * 1 church condemned, continued settling of ground caused extensive damage. Water mains broken, and 5,000 feet [1,520 m] of concrete pipe city intake water supply damaged." (Murphy and Ulrich, 1951). "In Centralia, Washington, the Field and Lease Building, constructed in 1890 of Tenino sandstone, is apparently settling after the quake. A plate glass window broke 5 days after the quake. Horizontal and diagonal lines drawn across plaster cracks show minute displacement after a week. * * * Dust and scratches on two adjoining masonry buildings, Warren Brothers Garage and the Pantorium Cleaners on West Main, Centralia, indicate differential vertical movement between the buildings." (U.S. Army Corps of Engineers, 1949).
146	Sand boils (1949); ground cracks (1949)	Centralia, Wash. (Chehalis River Valley); Lewis County	A	"Also reported yesterday was the opening of about 20 crevasses on the farm of Mrs. Ted Dorn on the old Military road between Centralia and Chehalis, some of them 25 feet [8 m] long. From some of them water spouted, followed by an upheaval of sand and mud." (Tacoma News Tribune, 1949b). "Clear water spouted 18 inches [45 cm] in the air and in a few moments brought up huge quantities of what appears to be clean ocean sand." (Daily Chronicle [Centralia], 1949). "Four miles [6.4 km] southwest of town, water spouted 18 inches [45 cm] high in middle of field, leaving a very fine sand formation for a considerable space around each hole, the holes varying from 1 to 3 inches [2.5–8.0 cm] in diameter. Water spouted from inch wide crack 8 or 10 feet [2.4 or 3.0 m] long." (Murphy and Ulrich, 1951). Water spouted about 3.0–3.7 m high and continued spouting (at lesser heights) for an hour or so. The water ran slowly for about a week (Ted Dorn, oral commun., 1988). See figures 211 and 212.
147	Sand boil (1949); miscellaneous effects (1949)	Chehalis, Wash.; Lewis County	B	"Our water supply is about half of what it was from a spring. It seems to have changed the spring some; heaved some ground near the spring up 2 feet [0.6 m] and poured muddy water out of top of mound." (Mrs. Frank O. Miller, written commun., 1949).
148	Ground crack (1949); ejection of ground water (1949)	Adna, Wash.; Lewis County	A	"* * * the carrier on Route 1 [Chehalis] observed that following the quake a fissure appeared in the county road on the hill above Ceres. This fissure appears to have produced a wet and soft spot in a roadbed which was previously dry." (Lloyd Sullivan, Postmaster, Chehalis, written commun., 1949). Apparently, this crack developed at the contact between artificial fill and the original slope. The road was cut from a steep slope, north of the railroad, about 6 m above the Chehalis River flood plain.
149	Sand boil (1949); ground crack (1949)	Rochester, Wash.; Thurston County	A	"Our farm borders on the Chehalis River nine miles [14.5 km] west of Centralia. Within one and one half blocks of the river bank the earth cracked about fifteen feet [4.5 m] in length and there was quite a deposit of pure white sand (several buckets full and moisture around it). The crack was about an inch [2.5 cm] wide." (Mrs. Wilbert Brewer, written commun., 1949).

150	Slump (1949)	Rochester, Wash.; Thurston County	A	A crack and slight slump occurred about 5 km northeast of Rochester on the Rochester Little Rock Road. The slump occurred along a section of road adjacent to a swampy alluvial flat near the Black River (Alan Schwiesow, City Engineer, Centralia, oral commun., 1988). Examination of a photograph of this 1949 ground failure (Hopper, 1981, p. 93) indicates that the shoulder of the road failed along several meters of roadway. Vertical and horizontal displacements appear to be less than 0.3 m and 0.6 m, respectively. The slide occurred in artificial fill on a very poor alluvial foundation.
151	Slump (1949)	Oakville, Wash.; Grays Harbor County	A	The 1949 earthquake caused a crack and slump on a county road along the Chehalis River, about 1.6 km southwest of Oakville. The crack was about 60 m long and there was about 0.3 m of vertical displacement (Alan Schwiesow, City Engineer, Centralia, oral commun., 1988). Failure probably occurred at the contact between the artificial fill and original ground surface. New cracks are apparent that indicate continued instability.
152	Miscellaneous effects (1949); ground cracks (1949)	Hoquiam, Wash.; Grays Harbor County	C	"At least a dozen water mains and pipes broken. Several sidewalks cracked." (Murphy and Ulrich, 1951).
153	Miscellaneous effects (1949)	Aberdeen, Wash.; Grays Harbor County	B	"Breaks and leaks in water mains were numerous and in widely scattered sections of the city * * *. A major break, with pipes broken in nearly a half-dozen places, occurred near Second and Grant Streets." (Aberdeen World, 1949).
154	Settlement (1949)	McCleary, Wash.; Grays Harbor County	B	"Simpson Logging Company in McCleary, Washington, reported a water reservoir, constructed originally in cut was enlarged later by 12 feet [3.7 m] of fill on about 1 on 1 slope and paved with reinforced concrete. The southeast and northwest corners opened about 2 inches [5 cm] at the top and about 6 feet [1.8 m] of water ran out rapidly. The fill was constructed by D8 caterpillar with no specified compaction. Settlement of the fill was clearly indicated." (U.S. Army Corps of Engineers, 1949).
155	Slides (1965)	Shelton, Wash. (west side of Oakland Bay); Mason County	C	"Some slides noticed along Oakland Bay closer to town." (Business Manager, Washington Corrections Center, written commun., 1965).
156	Slump (1965)	Shelton, Wash.; Mason County	B	"One lane of U.S. Highway 101, four miles [6.4 km] north of Shelton, sank about a foot [0.3 m] for a distance of about 150 feet [45 m]." (Washington Highways, 1965). Slump occurred on Highway 101 along the east side of Purdy Creek near Purdy Canyon. The failure took place wholly or partly in artificial fill underlain by granular sediments.

Table 33. Descriptions of selected ground failures in the western Columbia River region, Washington and Oregon.

[Location numbers correspond to ground-failure location numbers on plate 8. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers; D, information insufficient to locate accurately. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
157	Slump (1949)	Twin Rocks, Oreg.; Tillamook County	A	"Just south of the Twin Rocks Welding works several large cracks appeared in the earth causing part of the bank to drop and almost slide into the small lake. The cracks extend almost to the hard surface of the highway." (Headlight-Herald, 1949). Slight slump of highway embankment that crosses a low, wet area on the west side of Spring Lake in Twin Rocks. The existing embankment is about 1.2 m high and is composed of artificial fill founded on unconsolidated granular sediments.
158	Rockfall (1949)	Portland, Oreg.; Multnomah County	A	"Ray E. Wenger, 1283 SW Cardinell Drive, reported that a rock measuring 15 by 20 by 5 feet [4.6 m×6.1 m×1.5 m] had fallen within a few feet of his boathouse at Blue Lake. Wenger said the rock rolled to its present position during the earthquake, but now it is balancing on one end. He fears it may cause serious damage to the boathouse if not moved." (Oregon Journal, 1949b). The rockfall occurred along the south shore of Blue Lake where part of the Troutdale Formation (conglomerate and sandstone) (Trimble, 1963) is exposed in a near-vertical, 9- to 15-m-high cliff.
159	Miscellaneous effects (1949)	Government Camp, Oreg. (Mount Hood); Clackamas County	C	"This mountain village experienced a sharp earthquake just before noon today and startled residents, looking up at Mount Hood, saw several puffs of what appeared to be black smoke rise from behind Crater Rock. Crater Rock is below the summit on the south side. * * * The smoke—if smoke it was—subsided quickly, and experienced mountaineers believe it may have been dust clouds rising from a landslide that the temblor could have started. The steep area back of Crater Rock is an area of frequent slides, and often in the past great dust clouds have risen as the ice, snow and rock masses hurtled down the gullies." (Oregon Journal, 1949a).
160	Rockfall/rock avalanche (1949)	Stevenson, Wash.; Skamania County	B	"A two-mile [3.2 km] slide on the Washington side of the Columbia across from Cascade Locks swept away the face of a south cliff on Table Mountain. The avalanche of rocks and dirt threw up a cloud of dust that lasted more than 10 minutes and was observed for miles along the Columbia Gorge." (Oregonian, 1949a). "Hundreds of yards of Red Bluff, west of Stevenson, crashed to the bottom of a ravine along its base * * *. The most spectacular result of the quake was the collapse of Red Mountain. A heavy rumble from that direction focused hundreds of eyes on the sheer dirt and rock cliff above which a cloud of dust several hundred feet in height rose and swirled. The noise continued for two minutes or more and considerable fresh surface was exposed when the dust storm cleared. Smaller amounts of earth and rock continued to fall for several minutes after the quake had subsided." (Skamania County Pioneer, 1949).

				The rockfall-rock avalanche ground failure(s) originated along part of a 5-km-long, steep head scarp of the Cascades (Bonneville) landslide. The headscarp of the Cascades landslide exposes 370 m of the Eagle Creek Formation (conglomerate, sandstone, and minor tuff) overlain by basalt (Korosec, 1987). Air photo studies indicate that rockfalls and other slides are common along the scarp. Debris from slide activity, possibly related to the 1949 event, extends a few hundred meters downslope from the scarp on the south side of Table Mountain. See figure 214.
161	Slump (1949)	Castle Rock, Wash.; Cowlitz County	B	"C.H. Girardot, depot agent, said trainman told him there was a crack in the earth north of the Toutle River bridge; the crack opened about 4 inches [10 cm] wide and is 25 to 30 feet [8–9 m] long." (Cowlitz County Advocate, 1949). The "crack" apparently occurred on the flood plain of the Cowlitz River just north of its confluence with the Toutle River. The gently sloping to nearly flat terrain is underlain by a sandy alluvial soil. Probable slump or lateral spread.
162	Ground cracks (1949); slides (1949)	Castle Rock, Wash.; Cowlitz County	D	"Many cracks up to 6 inches [15 cm] wide in fields and on river dikes. Landslides." (Murphy and Ulrich, 1951).
163	Sand boils (1949); ground cracks (1949)	Longview, Wash.; Cowlitz County	A	"Here what appears to have been a subterranean eruption occurred and fissures or long splits over an extended area opened up. It was apparent that while the earth was in motion water and sand had erupted in the form of geysers. The severest damage was in the basement where the concrete floor literally bulged and cracked in every direction permitting water and sand to seep in. The force of the upheaval apparently lifted the house off its foundation and when it settled back its position was distorted as much plaster was cracked loose and hardly a door would close." (Longview Daily News, 1949b). "My brother said he saw 2 to 3 foot [0.6–0.9 m] high spurts of water and sand in the backyard." (Allen Windus, oral commun., 1988). The above quotations represent two separate ground-failure locations, about 180 m apart, near the junction of N.W. Nichols and Ocean Beach Highway in Longview. The area is part of a flat, low-lying terrace or flood plain of the Columbia River underlain by Quaternary alluvium (Walsh and others, 1987). Artificial fill may be present locally.
164	Sand boils (1949); ground crack (1949)	Longview, Wash.; Cowlitz County	A	"A crack about 20 feet [6 m] in length opened on the five acre farm of Charles Wilson, 2103 40th Avenue Longview, during the quake. Black, fine sand bubbled up out of the crack for a time it was reported." (Longview Daily News, 1949b). The ground-failure site was (in 1949) part of a swampy, sandy flood plain. The area is now a residential neighborhood. Local residents who lived in the vicinity at the time say the water table was almost at the surface. There is an open slough on the SW edge of the property. The area is underlain by Quaternary alluvium (Walsh and others, 1987). Artificial fill may be present locally.

Table 33. Descriptions of selected ground failures in the western Columbia River region, Washington and Oregon—Continued

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
165	Slump (1949)	Longview, Wash.; Cowlitz County	A	"Earthquake cracks * * * extend for more than 300 feet [90 m] along the Longview dike road near Willow Grove. * * * At another point along the road, the cracks extend in the soil at an angle to right of way, and cross through the dike." (Longview Daily News, 1949a). [Photo caption] "Earthquake cracks as deep as can be seen * * * range up to nine inches [22.9 cm] wide." (Longview Daily News, 1949a). Cracks and a slump in a dike road in a flat swampy area adjacent to the Columbia River. The cracks developed in an embankment of artificial fill underlain by alluvial sediments of the Columbia River. The road surface is 3.0–3.7 m above the river and approximately 1.8 m above a swamp on the opposite side.
166	Rockfall (1949)	Mayger, Oreg.; Columbia County	B	"The quake did start rock slides and bend rails on the Spokane, Portland and Seattle Railway that closed the line from Portland to Seaside at a point near Mayger, west of Rainier. Repairs were completed in a few hours, however." (Oregonian, 1949b). A steep face of the Wanapum Basalt and (or) Grays River volcanic rocks (Walsh and others, 1987), about 1.6 km east of Mayger, is the likely origin of the "rock slide" reported in the above newspaper quote. About 60 m of highly jointed volcanic rocks are exposed in the steep face.
167	Miscellaneous effects (1949)	Mayger, Oreg.; Columbia County	A	"Heaviest damage reported was at Mayger where the Point Adams Fish Co. station reports a loss of approximately $4,000 when several pilings were taken out by the quake and the building itself was moved about five feet [1.5 m] toward the Washington side of the river." (Clatskanie Chief, 1949b).
168	Rockfall (1949)	Stella, Wash.; Cowlitz County	B	"5 Narrowly Miss Highway Rock Slide—Five rural Longview residents narrowly escaped being in the path of a rock slide that came down across the Ocean Beach Highway, west of Stella, during Wednesday's earthquake. Traveling to Longview, Mr. and Mrs. Frank Jackson, Mr. and Mrs. Donald Jackson and their infant, stopped their car on the highway—without feeling the tremor—when they saw rocks suddenly start dropping from a towering bluff onto the highway. As they sat in their car, a large section of the bluff dropped across the highway, spilling over into the Columbia River." (Longview Daily News, 1949c). One block of rock that came down in the slide west of Stella was as big as a house. The Highway Department had to "shoot" it to get it off the road (Emmett Williams, oral commun., 1988). This rockfall originated on a 15- to 25-m-high face of highly jointed basalt (Wanapum Basalt, according to Walsh and others, 1987). The rock face is near vertical and extends from 0.4 to 1.2 km west of Stella on the north side of the Ocean Beach Highway.

169	Slide (1949)	Clatskanie, Oreg.; Columbia County	A	"Three were injured in Clatskanie Wednesday indirectly as a result of the earthquake. Andrew Rantala was buried in a slide at the new Clatskanie high school site * * *. After the workmen resumed work in the afternoon, Mr. Rantala was digging a footing for new forms next to a bank about eight feet [2.4 m] high when suddenly the bank gave way, covering him a foot or so. * * * It is surmised that the quake had loosened the dirt bank, causing the slide." (Clatskanie Chief, 1949a).
	Miscellaneous effects (1949)	do.	B	"Three or four water mains were broken in Clatskanie" (Clatskanie Chief, 1949b).
170	Miscellaneous effects (1949)	Cathlamet, Wash. (Puget Island, Columbia River); Wahkiakum County	B	"I understand from the commercial fisheries warden in this area, that on Puget Island in the Columbia near Cathlamet, a number of well pipes were all bent in the same direction, indicating a definite movement between strata there." (George C. Oldham, written commun., 1949).
171	Ground crack (1949); miscellaneous effects (1949)	Skamokawa, Wash.; Wahkiakum County	B	"The town of Skamokawa is situated partly on an island and partly on the mainland, connected by a bridge. The structures on the island are built on high underpinnings, or piling, because the tide of the Columbia River inundates the portion of the island outside the dike. Our Post Office is one of these. * * * The parsonage behind the Church [adjacent to the Post Office] divided by a six inch [15.2 cm] crack, and the underpinning split to the extent that it was unsafe for occupancy. The severest damage seems to have occurred to another dwelling a few hundred feet from our office. An outer storehouse crumpled and fell into the tide-land, and two women of the house who rushed to the sidewalk at the first tremor, were thrown through the air about ten feet [3 m], while the sidewalk collapsed. * * * oil and water lines were broken." (Barbara H. Eggman, written commun., 1949). Ground failure, probably caused by liquefaction of sandy alluvial sediments, occurred in a flat-lying swamp area on a point between Brooks Slough and Steamboat Slough. There were foundation failures of wooden buildings built on sand (and possibly on a surface layer of sawdust from sawmills that existed on the point at that time).
172	Miscellaneous effects (1949)	Astoria, Oreg.; Clatsop County	C	"Several water mains broke and flooded basements." (Murphy and Ulrich, 1949).

EVALUATION OF LIQUEFACTION POTENTIAL IN SEATTLE, WASHINGTON

By W. Paul Grant,[1] William J. Perkins,[2] *and* T. Leslie Youd[3]

ABSTRACT

Seattle has experienced significant damage related to liquefaction during historical earthquakes and may be subjected to even greater damage in the future due to increased development of the area and the potential occurrence of a subduction-zone earthquake. The methodologies and results of two research studies that evaluated the liquefaction hazard to Seattle are discussed and compiled in a single map indicating the local liquefaction-hazard potential. Delineation of the liquefaction hazard in the area will benefit land-use planning, future building development, and planning for disaster response.

All liquefaction evaluations were based upon existing data from more than 350 boring logs and an empirical procedure that relates Standard Penetration Test N-values to threshold ground accelerations needed to initiate liquefaction. A computerized database was developed to facilitate storage and retrieval of the boring data for subsequent analyses. The liquefaction potential was evaluated using two procedures. One procedure grouped similar geologic units and assigned relative rankings to the liquefaction potential based upon the percentage of Standard Penetration Test N-values that fell below a threshold N-value needed to resist liquefaction resulting from a 0.30*g* (where *g* is equal to 9.8 meters per second) ground acceleration. The second procedure assigned relative liquefaction-potential rankings based upon the computed thickness of material in individual borings that would liquefy for ground accelerations of 0.15*g* and 0.30*g*. A review of all major geologic units within the study area for liquefaction potential, using both criteria and assigned hazard ratings of high, moderate, low, or very low, showed that fills and Holocene alluvial deposits at the mouth of the Duwamish River have a high liquefaction potential; however, Holocene alluvium and beach deposits elsewhere were given a moderate liquefaction rating. Pleistocene alluvial sedimentary deposits were given a low liquefaction rating, and glacially consolidated Pleistocene sedimentary deposits were assigned a very low potential.

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INTRODUCTION

Earthquake-induced liquefaction and related ground failures have caused substantial casualties and major property losses in various parts of the world. Property losses in excess of $800 million have been attributed to liquefaction-related ground failures that occurred during the 1964 Niigata, Japan, earthquake (Keefer, 1983). Also, property losses related to liquefaction-induced ground failures were estimated to have exceeded $200 million in the March 27, 1964, Alaska earthquake (Keefer, 1983). During the Alaska earthquake, soil liquefaction induced lateral spreads that compressed or buckled more than 250 bridges, disrupting railroad and vehicular traffic. Liquefaction also generated subaqueous landslides that destroyed sections of the waterfronts of Valdez, Seward, and Whittier.

Earthquake-induced ground failures during the 1949 and 1965 Puget Sound, Washington, earthquakes resulted in substantial damage to buildings, bridges, highways, railroads, water distribution systems, and marine facilities. Property damage from the 1949 and 1965 events totaled $25 million and $12 million, respectively. Grant (1986) estimated that 25–50 percent of the total damage from these earthquakes may be attributed to earthquake-induced ground failures such as liquefaction. Whereas this amount of damage may seem relatively minor when compared with other major earthquakes, the damage is consistent with the relatively low levels of ground acceleration (typically less than 0.10*g*, where *g* is equal to 9.8 m/s) that were recorded in Seattle during these events. Should Puget Sound experience a major Cascadia subduction-zone earthquake of magnitude 8.0 or greater, as postulated by Heaton and Kanamori (1984), damage from earthquake-induced ground failures could easily be an order of magnitude higher than the damage experienced in past events.

This report summarizes the results of two research studies (Grant, 1990; Perkins, 1991) that evaluated the liquefaction-hazard potential in Seattle (fig. 215). Grant (1990) was a U.S. Geological Survey (USGS) sponsored study in which a computer database of existing borings in Seattle was developed and used to evaluate liquefaction potential based on empirical procedures by Seed and Idriss (1971), Seed and others (1983), and Seed and others (1984). Liquefaction-hazard categories were differentiated on the basis of comparing SPT (Standard Penetration Test) N values for a geologic unit with the N values required to resist liquefaction during an earthquake with a 0.30*g* ground acceleration. Perkins

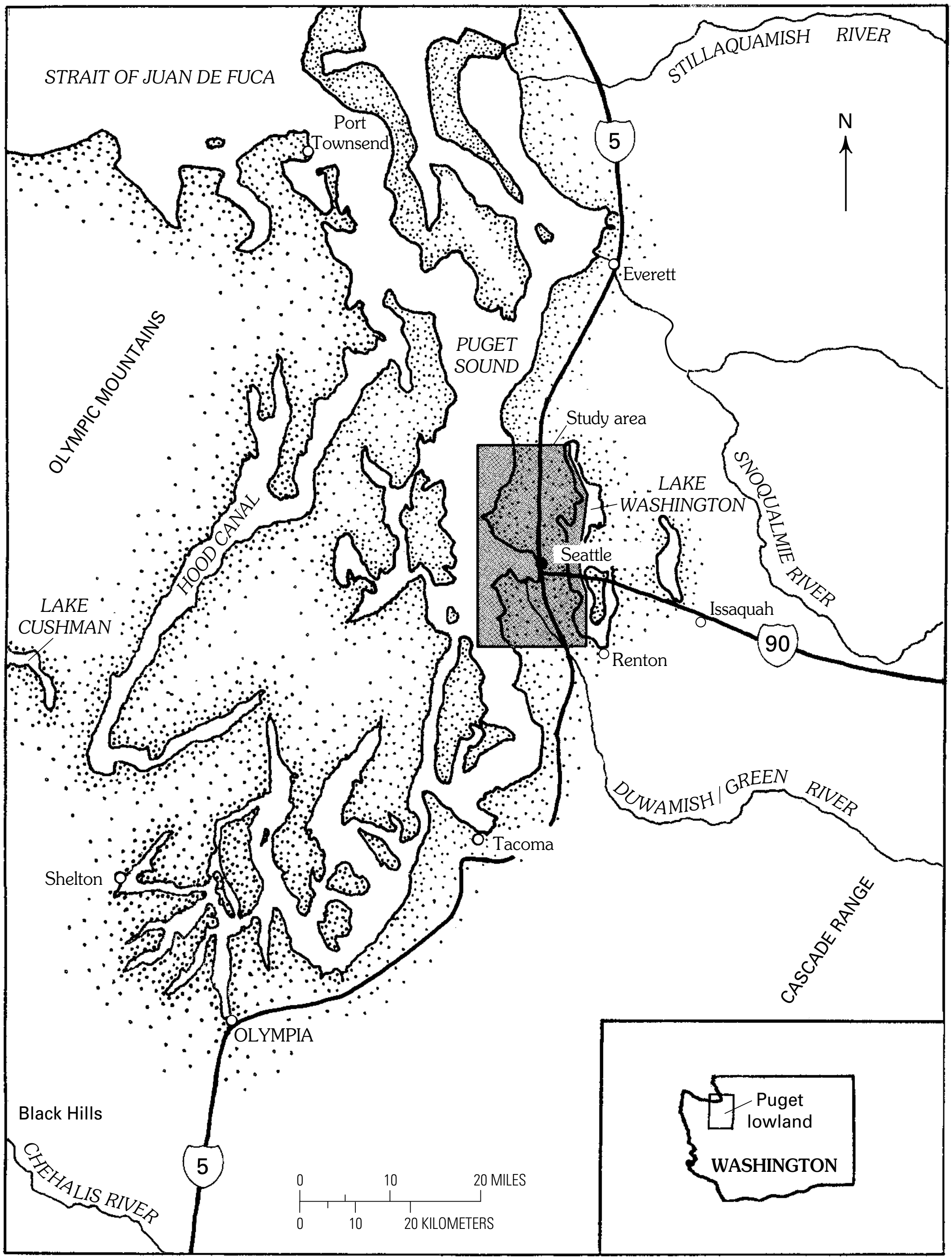


Figure 215. The Puget lowland and location of the study area, Washington.

(1991) used the same database but established liquefaction-hazard categories based upon the cumulative thickness of material liquefying from either 0.15*g* or 0.30*g* ground accelerations. The results from both of these studies were combined, resulting in the single liquefaction-hazard map contained on plate 9.

Identifying areas where liquefaction may potentially occur within Seattle provides a tool to aid government agencies in land-use planning, building development, and planning for disaster response. The liquefaction-potential map developed as a result of this study may be used by engineers, city officials, and planners to assess the need for changes in zoning ordinances or building codes to mitigate the hazard. For example, building codes could be modified to require site-specific liquefaction assessments and appropriate foundation designs for structures located in high-risk areas. The map also could be used by engineering departments within various governmental agencies and the insurance industry to estimate the damage potential to existing buildings during a future earthquake, information that may be used to prioritize structures for seismic retrofitting. Finally, the liquefaction-hazard map could be used by emergency-response planners to anticipate areas within the city that may sustain high damage and casualties or where the infrastructure (for example, roads, bridges and water-supply lines) may be particularly vulnerable, affecting emergency response efforts.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support and sponsorship of this project by the USGS under the Earthquake Hazards Reduction Program. The support provided by Ms. Deborah Walsh, the contracting officer with the USGS, is greatly appreciated. We also wish to acknowledge the efforts of Ms. Joanmarie Gorans-Eggert of Shannon & Wilson, Inc., in creating the computerized database for subsurface boring data and the help of Mr. Steven Bartlett, a research assistant at Brigham Young University, in providing the computer software to evaluate the thickness of liquefied sediments. Finally, we appreciate the valuable technical review of this paper by Dr. Steve Obermeier of the USGS and Dr. Steve Palmer of the Washington State Department of Natural Resources.

THE LIQUEFACTION PHENOMENON

Liquefaction is a phenomenon in which saturated, cohesionless soils are temporarily transformed into a liquid state, most commonly as a result of earthquake-induced ground shaking. Liquefaction occurs as a result of the buildup of excess pore-water pressures during the shaking. When the pore-water pressure exceeds the grain-to-grain (effective) contact pressure of the soil, the soil particles lose contact with each other and the soil essentially behaves as a liquid. Pore-water pressure in a liquefied soil may become so great as to result in small geysers from which water is ejected, leaving sedimentary features commonly termed sand boils.

The development of liquefaction is controlled by a number of complex and interrelated factors. These factors can be generally related to the following parameters: (1) the strength of the underlying soil deposit, (2) the location of the water table, and (3) the severity of earthquake ground shaking. Historically, clean sands and silty sands are the materials most susceptible to liquefaction. In addition, the liquefaction resistance of any particular soil is affected by its density, fabric, prior earthquake history, and in-place stress conditions. The depth of the water table is a controlling factor because a soil must be saturated or located below the water table for liquefaction to occur. Within any given soil deposit, liquefaction is more likely to occur where the water table is shallow as opposed to conditions where the water table is depressed. Finally, development of liquefaction is dependent upon the magnitude of the earthquake stresses induced in the soil deposit and also the duration of ground shaking. The stresses and duration of ground shaking are, in turn, affected by the size and location of the earthquake, the travel path of the earthquake motions to the site, and any local amplification of ground motions that may occur within the soil column.

Depending on site-specific factors, liquefied soil can cause various types of ground failures that may damage overlying structures. A common result is loss of bearing capacity for shallow foundations located over the liquefied soil. Other adverse effects include flow failures, buoyant rise of buried structures, ground settlement, failure of retaining walls due to an increase of lateral pressures, and lateral spreading.

HISTORICAL LIQUEFACTION IN SEATTLE

Historical records provide valuable information for assessing earthquake-induced liquefaction potential. Specifically, areas that have experienced liquefaction during past earthquakes may liquefy again during a future event. For example, reconnaissance reports from the 1989 Loma Prieta earthquake (U.S. Geological Survey, 1989) indicate that many of the areas that experienced liquefaction and unusually severe ground shaking during the 1906 San Francisco earthquake experienced similar damage patterns in the recent event. In both of these earthquakes, locations of uncontrolled, random fills significantly correlated with severely damaged areas. Therefore, in our study of the liquefaction potential of soils in Seattle, we first reviewed accounts of historical liquefaction in the area and then correlated these accounts with historical maps that show tideland reclamation along shoreline areas. This information would likely identify the soil conditions having the highest relative liquefaction potential.

Table 34 provides accounts of liquefaction occurrences in Seattle during the 1949 and 1965 Puget Sound earthquakes. The April 13, 1949, event was located about 63 km south-southwest of Seattle, near Olympia, and had a surface-wave magnitude (M_s) of 7.1 (Weaver and Baker, 1988). The body-wave magnitude (m_b) 6.5 earthquake of April 29, 1965, occurred about 23 km south of Seattle (Weaver and Baker, 1988). As indicated in table 34, liquefaction during these earthquakes typically resulted in differential settlement of buildings, lateral movement of bulkheads, and cracking of basement walls.

Because uncontrolled fills have been particularly susceptible to earthquake-induced liquefaction during historical time, old topographic maps of Seattle were reviewed to delineate fill areas. The changes to Seattle shorelines and their associated fills are shown in figure 216. Additionally, the figure shows the locations of sites that liquefied during the 1949 and 1965 earthquakes, the majority of which coincide with shoreline areas that were filled during the early development of Seattle. Experience from earthquakes in other regions also suggests that areas of uncontrolled fill may be particularly vulnerable to liquefaction during a future event.

A final factor that is needed in understanding the historical accounts of liquefaction in Seattle is the level of ground shaking, or peak ground acceleration, that occurred locally during the 1949 and 1965 earthquakes. Fortunately, both events were locally recorded on strong-ground-motion accelerographs (Shannon & Wilson, Inc., and Agbabian Associates, 1980), which were located close to areas that experienced liquefaction (fig. 216). These accelerographs recorded peak ground accelerations of about 0.10*g* during both the 1949 and 1965 earthquakes (California Institute of Technology , 1976; Shannon & Wilson, Inc., and Agbabian Associates, 1980). Based upon seismicity studies conducted by Shannon & Wilson, Inc. (1980) for various sites within the Puget Sound region, it is estimated that this level of ground acceleration may have a 20- to 40-year recurrence interval.

GEOLOGIC FRAMEWORK

Because liquefaction resistance can generally be correlated with the age of a geologic deposit, understanding the origins and ages of the different geologic units in the study area helps establish a framework for categorizing potentially liquefiable soils. In the following discussion, primary emphasis is given to the glacial deposits in the region.

REGIONAL GEOLOGY

Seattle is located in the Puget lowland, which is a slightly arcuate, convex-eastward basin lying between the Cascade Range on the east and the Olympic Mountains on the west (fig. 215). The basin is open on the north to the Georgia depression and the Strait of Juan de Fuca, the latter connecting Puget Sound with the Pacific Ocean. Beneath the Puget lowland, nonlithified Quaternary sedimentary deposits of varying thickness generally unconformably overlie Tertiary bedrock. These sedimentary deposits are both glacial and nonglacial in origin.

The incursion of Pleistocene continental ice into the basin is well documented (Willis, 1898; Bretz, 1913; Mackin, 1941; Crandell and others, 1958; Armstrong and others, 1965; Crandell, 1965; Easterbrook and others, 1967; Mullineaux, 1970; Crandell and Miller, 1974; Blunt and others, 1987). Ice originating in the coast and insular mountains of western British Columbia, Canada, coalesced in the Georgia depression and moved south across the 49th parallel to the south end of the Puget lowland, about 80 km south of Seattle. At least four major advances and several partial advances have been identified. Although highly complex, each advance left a sequence of lacustrine, advance outwash, glaciomarine drift, till, and recessional outwash deposits. The nonglacial intervals generated combinations of fine-grained deposits of fluvial and lacustrine origin and also some organic deposits, except along the basin margins, where coarse fluvial deposits and mudflows predominate. The trend of the existing ridges, valleys, and deep inlets of Puget Sound is north-south, with the valleys being scoured to great depths. The thickness of the total unconsolidated basin fill varies from trace amounts in scattered locations throughout the lowland to over 1,100 m in the central part of the basin near downtown Seattle (Hall and Othberg, 1974; Yount and others, 1985) (fig. 217).

The bedrock underlying the Puget lowland is not well understood because of the thick and pervasive mantle of Pleistocene deposits. The sparse knowledge of the configuration of the bedrock surface has been interpreted from geophysical data, a few deep borings, projection of surface exposures along the basin flanks, and several bedrock ridges that partly cross the basin along northwest trends. The rocks are mostly folded, faulted, and deeply eroded Tertiary marine and estuarine sedimentary materials; volcanic materials consisting of basalt, andesite, and volcaniclastic rocks; and terrigenous deposits such as sandstone, shale, and conglomerate, including extensive interbedded coal seams that lie along the Cascade Range flank east and south of Seattle. Gravity- and magnetic-survey data show high differentials in the bedrock elevations, a result most likely related to major faulting. In fact, some of the steepest gravity gradients in the United States have been measured in Seattle (Danes and others, 1965; Rogers, 1970). One of these steep gravity gradients coincides with the Olympic-Wallowa lineament, a

Table 34. Descriptions of liquefaction occurrences in Seattle during the 1949 and 1965 Puget Sound earthquakes.

[Location numbers correspond to those used in figure 216]

Location no.	Location	Quotation and (or) comment	Source
		Earthquake of April 13, 1949	
1	Near south end of Green Lake (NE¼ sec. 22, T. 25 N., R. 4 E., Seattle North 7½' quadrangle)	A 60-foot [18 m] section of the south shore of Green Lake dropped four feet [1.2 m] into the lake during the earthquake Wednesday. Cracks three or four inches [8–10 cm] wide also appeared on the bicycle path a short distance from the slide. The ground was broken up and parts of the path appeared to have dropped from four to six inches [10–15 cm] into the lake.	Seattle Post-Intelligencer (1949)
2	Pier 66	The 1949 earthquake resulted in displacement of the transit shed in a seaward direction. The column displacement amount to a maximum of about 9 inches [23 cm] in a lesser displacement at the north end of the north portion.	Olsen (1978)
3	Pier 36 area; exact location not determined	A concrete wall around a tank farm adjacent to the Duwamish waterway indicated considerable earth movement. One east-west wall about 100 feet [30 m] long and 12 feet [4 m] high reveals three vertical construction joints opened 1-5/8, 2, 1-3/4 inches [4.1, 5.1, and 4.4 cm], or a total of 6 inches [15.2 cm] during or since the quake. The joint filler in a north-south wall was squeezed out a maximum of 3 inches [7.6 cm] at the bottom of one joint. The wall nearest to the Duwamish waterway and parallel to it has settled 2 inches [5.1 cm] below adjacent walls and is out of plumb. Lateral and vertical movement of ground is evident.	U.S. Army Corps of Engineers (1949)
4	Pier 30	At the front of the building which faces on Alaskan Way severe cracking of brickwork appears. The cracks are arranged in such a way as to indicate a downward movement of the building relative to the front wall or the corner pier * * *. In this instance the bearing and nonbearing piers moved differentially.	U.S. Army Corps of Engineers (1949)
5	Harbor Island (Fisher Flouring Mills)	Inside the old office, the floor is badly out of level, in one place bulged up 7 inches [18 cm] above the adjacent floor of the new building.	U.S. Army Corps of Engineers (1949)
6	W. Spokane St.	The Northern Pacific Railway Company's bridge (single bascule) crossing Duwamish Waterway near West Spokane Street was reported to have permanently shifted from 4 to 7 inches [10–18 cm]. The bridge was open at the time of the earthquake. Repairs consisted of realigning the tracks * * *. The city double bascule bridges Nos. 1 and 2, crossing Duwamish Waterway at Spokane Street, were closed at the time of the quake. The main piers shifted, reducing the horizontal distance between the piers several inches and jamming the forward edges * * *.	U.S. Army Corps of Engineers (1949)
7	Spokane St.	The Bethlehem Steel Seattle Mill Depot No. 92, Spokane Street, Seattle, was observed by a competent engineer during the quake. The building is a single story concrete [frame] with brick curtain walls on a concrete footing with a concrete floor resting on filled ground. The rear of the building is 9 feet [2.7 m] from the top of a 1 on 2 slope 7½ feet [2.3 m] above adjacent tide land. After the perceptible ground motion of the quake had ceased, cracks started developing in the	U.S. Army Corps of Engineers (1949)

Table 34. Descriptions of liquefaction occurrences in Seattle during the 1949 and 1965 Puget Sound earthquakes—Continued.

Location no.	Location	Quotation and (or) comment	Source
		20-foot [6 m] bay next to the tide land. A triangular section of the brick wall moved vertically downward from 1-13/16 inches to 1-3/4 inches [3.0–4.4 cm]. The ground at the rear of the building pulled away from the wall 2½ inches [6.4 cm] and settled vertically 3 inches and 4 inches [7.6 cm and 10.2 cm] below the marks left on the wall by the soil surface * * *. This failure resulted from downward and lateral movement of the ground after perceptible motion of the ground had ceased, indicating an incipient slide * * *. Later examination all around the building revealed that the end bay on the opposite side had moved in a similar manner but a large door in the bay eliminated the possibility of as clear evidence developing. Several other bays in the building developed cracks which indicate less severe settlement elsewhere. The end wall, facing the tide land reveals cracks in the concrete footings under each bay.	
8	177 S.W. Massachusetts (Albers Brothers Elevators)	Examination of ground around the Albers Brothers Elevators shows no evidence of settlement except that a number of sand boils developed from 5 feet to 15 feet [1.5–4.6 m] away from the elevators on the northeast side. The ground around a large fuel tank has settled differentially from zero to ½ inch [1.3 cm] as evidenced by the soil contact mark.	U.S. Army Corps of Engineers (1949)
9	2600 26th Ave. S.W. (KJR radio tower)	The KJR Radio transmitting tower suffered structural damage but the ground apparently settled around the footing 1 inch [2.5 cm] below the former level. Cracking of the soil and sand boils occur in the area between the tower and the Duwamish waterway.	U.S. Army Corps of Engineers (1949)
10	2613 Marine Ave. S.W.	After the 1949 earthquake the professor and some students came out and took samples of the water in our basement. It was fresh water and we are only about 100 feet from the bay (Mrs. J. Woodhouse, written commun., 1965).	University of Washington, unpub data (1965)
11	1st Ave. S. and S. Lander (Sears)	* * * geysers of water and mud which spurted from the ground reportedly as high as 3 feet [0.9 m], which flowed continuously for as long as 24 hours, and which filled basements * * *	Edwards (1950)
		Earthquake of April 29, 1965	
12	Green Lake (NE¼ sec. 7, T. 25 N., R. 4 E., Seattle North 7½' quadrangle)	Green Lake, sloshing back and forth like soup in a shallow bowl, buckled blacktop paving around Aqua Theater and opened large fissures in the ground on the south and west banks of the lake. Water pressure from the lake put two waves in West Green Lake Way between Aqua Theater and Lower Woodland Park. The concrete-block junior crew house at the Aqua Theater was damaged, possibly beyond repair. A wall buckled. [Probable slight slumping along shoreline of Green Lake at or near the same location at the southwest end of the lake as that reported for the April 13, 1949, earthquake. These, like the 1949 ground failures, were probably liquefaction induced].	Seattle Times (1965)

13	University of Washington	A fissure opened in the practice field at the University. Underground pressure from the shock sent sand spurting in a 100-foot-long [30 m] zigzag stretch on the lower football field. Behind the men's pool, areas of the ground dropped as much as a foot [30 cm]. Dirt floor sections in the Hec Edmondson Pavilion also sank slightly.	Hake and Cloud (1967)
		North of Union Bay, broad fill over alluvial and lacustrine sediments subsided and exhibited scattered ground cracks and sand mounds.	Mullineaux and others (1967)
14	2422 Elliott Ave. (Perfection Smokery)	The building has suffered damage throughout the years from settlement and cracking due to this settlement of the building. Presently the building appears to have suffered additional damage due to the earthquake in that the front wall has bulged at the northwest corner.	MacPherson (1965)
15	Pier 66	Break in underground supply mains.	MacPherson (1965)
16	Piers 64 and 65	Fire protection * * * supply main break.	MacPherson (1965)
17	410 5th Ave. S. (Apex Automotive and Garage)	Whole front footing for the building has settled from a few inches to eight to ten inches [20–25 cm]. The beams are generally cracked and sheared. Apparently this has been going on for many years.	MacPherson (1965)
18	1730 1st Ave. S. (Queen City Sheet Metal Shop)	The building is supported on posts and blocks. The building has settled very badly throughout the years. This settling has been exaggerated during the present earthquake. The floor has been shored up in different places during the recent years, but all the old existing posts are leaning in various directions and the floor is very badly out of level. The area underneath the building is very damp. During the winter months, the area has standing water * * *. During the present earthquake a considerable amount of water came in. This apparently was from consolidation of the earth below which forced the water in this lower stratum up into the area. This water was also followed by the characteristic fine silting which now covers most of the underneath area * * *. In past years, the lower floor * * * was used as part of the shop * * *. At the present time it is not possible to walk upright.	MacPherson (1965)
19	2228 1st Ave. S. (Millwork Supply)	The building is located on dredged fill material and is believed to be on piling * * *. Approximately 8" [20 cm] maximum downward settlement of footings * * *. An upward movement of some footings of 1" to 2" [2.5–5 cm] * * *. The basement floor slabs on grade were severely cracked and displaced due to the action of footing settlement combined with upward pressure of ground water against the bottom of the slabs.	MacPherson (1965)
20	Various piers	Port of Seattle Engineering Department letter describes ground settlement along bulkhead lines at Piers 5, 20, 28, and 42; broken underground firemains at Piers 20, 42, and 66.	MacPherson (1965)
21	Pier 25	Breaks in underground piping.	MacPherson (1965)
22	Duwamish River	The low-lying filled areas along the Duwamish River and its mouth settled and were the locations of considerable building damage * * *. A number of bridges were closed temporarily due to slight damage * * *. The 14th Avenue South drawbridge across the Duwamish River had some pier damage * * *. Both of the Southwest Spokane Street bridges were jammed shut when the shock threw them out of line * * *. East-bound lanes of a drawbridge across the Duwamish Waterway were closed * * * because of a drop in the road level * * *. Pier 20 at the East Waterway Terminal settled.	Hake and Cloud (1967)

Table 34. Descriptions of liquefaction occurrences in Seattle during the 1949 and 1965 Puget Sound earthquakes—Continued.

Location no.	Location	Quotation and (or) comment	Source
23	Harbor Island Piers 15 and 16 and Fisher Flouring Mills	"The Seattle Water Department had one break in a 12-inch [30 cm] main in the Harbor Island area * * *. Harbor Island, at the mouth of the Duwamish River, was a special high-damage location * * *.The Fisher Flouring Mills had extensive damage * * *. Underground piping around the plant * * * broke * * *. Piers 15 and 16 on Harbor Island shifted toward the water by about 1 foot [30 cm] due to the soil losing much or all of its strength, or partially liquefying and pushing the dock toward the water. An exception was the northern extension of the pier which was under construction and did not yet have its soil backfill.	Algermissen and others (1965)
24	Pier 5	Pier 5, where construction projects were underway, was hardest hit. The bulkhead and the fill behind it settled, the fill dropping 6 inches to 2 feet [15–61 cm] for a width of 25 to 40 feet [7–12 m]. The bulkhead was reported to be 6 to 8 inches [15–20 cm] out of line. Several Port piers suffered similar damage.	Hake and Cloud (1967)
		Subsidence of the material along the west side of the pier. The area at the north end wall is exposed; the sheet pile wall has displaced downward from the reinforced concrete dock a distance of 8 inches [20 cm]. The soil in this area for a 20-foot [6 m] width has subsided. The ground has displaced to approximately 1½ feet [0.5 m] below the level of existing dock. This subsidence decreases to approximately 8 inches [20 cm] at the southerly end of pier.	MacPherson (1965)
25	Pier 6	Similar problems to * * * Pier 5. There is subsidence of 6" to 12" [15–30 cm] at the land face of the pier.	MacPherson (1965)
26	2613 Marine Ave. S.W.	Damage to "basement floor and fresh water came in." (Mrs. J. Woodhouse, written commun., 1965)	University of Washington, unpub. data (1965)

major west-northwest-trending structural zone that cuts through the Cascade Range and Columbia Plateau to the east. South of this lineament, bedrock is exposed in scattered outcrops in southeast Seattle, at Alki Point, and in a series of prominent ridges to the east, collectively called the Newcastle Hills, that trend eastward to the Cascade Range.

LOCAL GEOLOGY

Seattle consists of several north-south-trending elongated ridges and drift uplands. The hills and uplands are separated by large Pleistocene glacial troughs and outwash channels that are now occupied by tidal waters and large lakes or alluviated by streams that occupied the troughs about 13,500 years ago following the retreat of the last glaciation. Major troughs lie beneath the main body of Puget Sound, the Duwamish River valley, and Lake Washington. The symbols used to identify the geologic units in the following discussion correspond to those used on plate 9 and those used by Waldron and others (1962), who originally mapped the surficial geology of the area.

BEDROCK

A broad band of Tertiary sedimentary and volcanic-intrusive rocks forms the Newcastle Hills promontory between Renton and Issaquah, east of Seattle. This west-northwest-plunging promontory crosses the southern part of the city, with bedrock exposed or subcropping in the southern part of Beacon Hill, locally in the southern Duwamish River valley, and at Alki Point in West Seattle. These rocks are folded into northwest to west-northwest-trending anticlines and synclines that are broken by northeast-trending left-lateral faults (Weaver, 1937; Mullineaux, 1970). The faults were most recently active in early to middle Tertiary time (Gower and others, 1985).

Two Tertiary bedrock units lie beneath and sporadically crop out within the study area. Waldron and others (1962) identified the oldest unit as middle Eocene sedimentary conglomerate, sandstone, siltstone, and shale chiefly with volcanic clasts (Td). This older unit crops out along the southern edge of the study area, along the sides and below the Duwamish River valley. The younger bedrock unit (Tb) contains Oligocene marine to estuarine sandstone and shale with subordinate amounts of conglomerate, mostly of volcanic origin. The unit is part of the Blakely Formation (Weaver, 1937; Waldron, 1962; and Livingston, 1971). This unit crops out across the southern part of Seattle and at Alki Point.

Immediately north of this band of Tertiary rocks, the bedrock surface drops abruptly to depths of more than 1,100 m below sea level in a horizontal distance of less than 1.6 km, as shown in figure 217. Present data suggest that the bedrock surface rises from its lowest point in downtown Seattle gradually to the northeast to about 400 m below sea level at the north end of Lake Washington (Hall and Othberg, 1974; Yount and others, 1985).

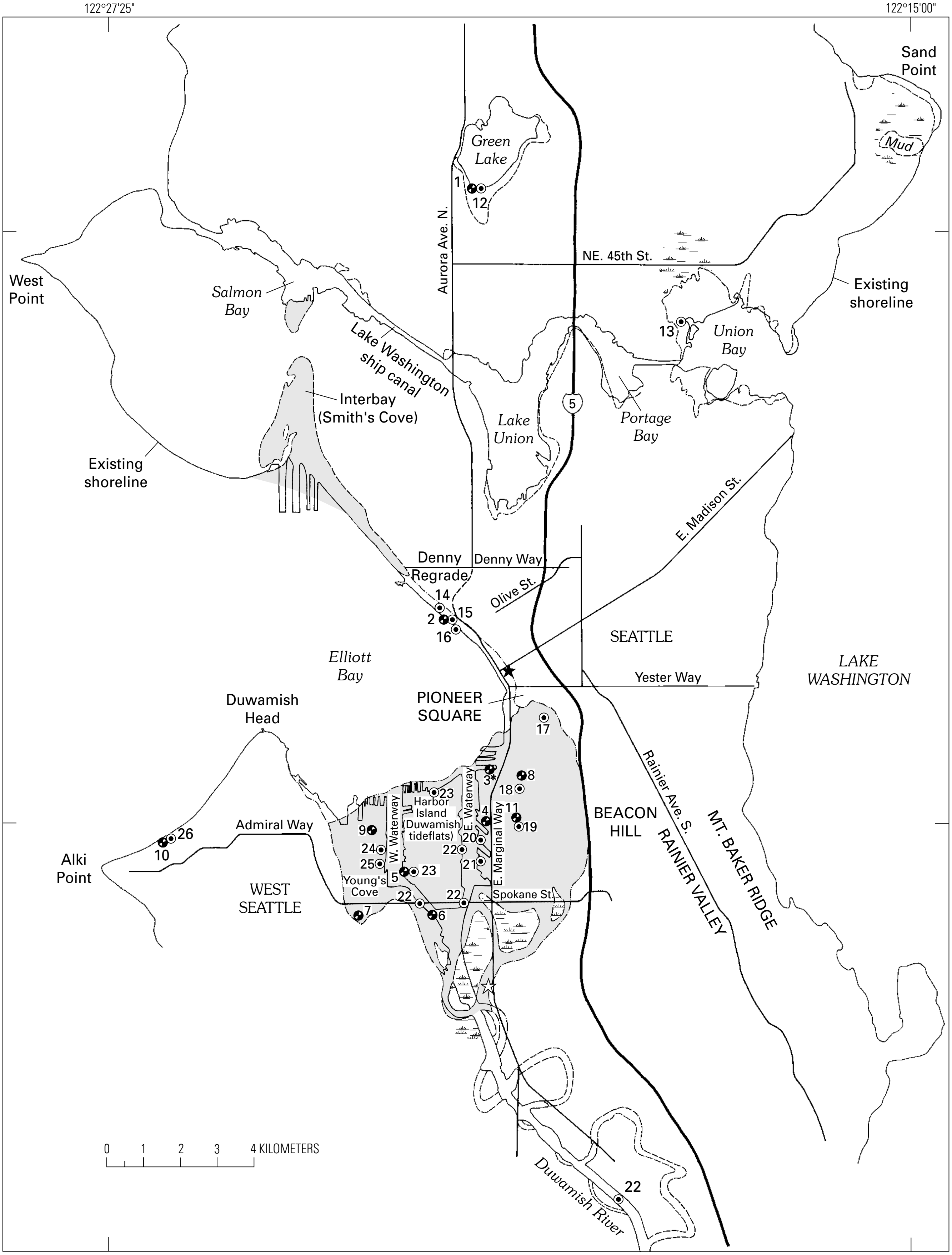
PLEISTOCENE DEPOSITS

Nonlithified, glacially overridden sedimentary deposits generally lie unconformably above the Tertiary bedrock (pl. 9). This sedimentary material is both glacial and nonglacial in origin. The youngest of these sedimentary deposits, the lower parts of the Vashon Drift, were deposited as the Vashon ice lobe advanced southward during the Vashon stade of the Frasier glaciation, about 15,000 yr B.P. (Mullineaux and others, 1965). At its greatest extent, the lobe advanced to a position about 80 km south of Seattle (Booth, 1987). Covering Seattle with an estimated 900-m-thick layer of ice, the weight of the glacier greatly overconsolidated the underlying sediment to various degrees, including the lower parts of the Vashon Drift. In the Seattle area, these very dense sedimentary materials underlie most upland areas, including major hills and ridges.

As the Vashon ice lobe retreated northward, it left behind recessional outwash deposits (Qys, Qyg) largely consisting of mixtures of gravel and sand. The outwash was generally confined to the major glacial troughs but was also irregularly distributed on the drift uplands. Recessional deposits also include coarse-grained outwash deltas, kame terraces and other ice-contact deposits along certain ridge flanks, local fine sand and silt deposited in ephemeral ice-marginal lakes, and sands and gravels in local outwash channels. Locally, recessional deposits attain thicknesses of 30 m or more in major outwash deltas. The younger sands (Qys) are fine to medium grained and generally less than 3 m thick in the upland channels. The younger gravels (Qyg) are composed of sand and pebble-size gravel and are also about 30 m thick.

HOLOCENE DEPOSITS

Holocene deposits in the Seattle area include alluvium (Qa) in the Duwamish River, Rainier, and Interbay valleys; beach and adjacent marine deposits (Qb) along shorelines; colluvial and landslide deposits (Ql); and peat (Qp) and lacustrine deposits (Qsc) in upland depressions and along low-lying lakes. Alluvial deposits (Qa) consist of fine sand, silty fine sand, fine sandy silt, and nonplastic silt, with local pockets or stringers of organic materials. Owing to shifting of depositional channels, individual beds of uniform grain size are rarely laterally continuous over large areas, and interfingering of different soil units is common. Typically, the Holocene deposits consist of very loose to loose granular soils within about 10 m of the ground surface. Subsurface


122°27'25"
122°15'00"
47° 37' 40"
47° 37' 20"
Sand Point
Mud
Green Lake
Aurora Ave. N.
NE. 45th St.
West Point
Salmon Bay
Existing shoreline
Union Bay
Lake Washington ship canal
Interbay (Smith's Cove)
Lake Union
Portage Bay
Existing shoreline
E. Madison St.
Denny Regrade
Denny Way
Olive St.
SEATTLE
Elliott Bay
LAKE WASHINGTON
Yester Way
PIONEER SQUARE
Duwamish Head
Rainier Ave. S.
MT. BAKER RIDGE
BEACON HILL
RAINIER VALLEY
Harbor Island (Duwamish tideflats)
W. Waterway
E. Waterway
E. Marginal Way
Admiral Way
Alki Point
WEST SEATTLE
Young's Cove
Spokane St.
0 1 2 3 4 KILOMETERS
Duwamish River

EXPLANATION

ACCELEROGRAPH STATIONS AND LOCATIONS

★ USGS accelerograph station 2170 (discontinued) that recorded the April 13, 1949 earthquake; 4735 E. Marginal Way (≈ 47.55 N.; 122.34 W.)

☆ USGS accelerograph station 2102 (existing) that recorded the April 29, 1965 earthquake; 909 1st Ave. (≈ 47.604 N.; 122.335 W.)

SITES OF HISTORICAL LIQUEFACTION

- 1949 earthquake
- 1965 earthquake
- * Approximate location of liquefaction site

HISTORICAL SHORELINES

- U.S. Coast Survey (1879)
- U.S. Geological Survey (1897)

Tidal flat

Marsh or swamp

Figure 216 (facing page and above). Sites of historical liquefaction in Seattle. The numbers correspond to the location numbers used in table 34 for descriptions of liquefaction. Base map from Waldron and others (1962).

explorations for the West Seattle Bridge indicated that the alluvium near the mouth of the Duwamish River generally extends to a depth of about 55 m and locally extends to depths of 75 m.

Lacustrine deposits (Qsc) and very soft to soft peat (Qp) also occur in numerous closed depressions on the surface of the drift uplands and along the shorelines of lakes. Lacustrine sedimentary deposits are composed of silt, clay, and fine sand and are usually less than 3 m thick. The peat ranges from fibrous to peaty silt (muck). Both the upland and lowland peats contain a pervasive 2.5- to 5.0-cm-thick layer of ash related to the eruption of Mount Mazama (Crater Lake, Oreg.) 6,800 years ago (Wilcox and Power, 1964; Curran, 1965).

Colluvium is the veneer of loose to medium-dense soil that drapes the sides and toes of slopes throughout the city and its environs. The deposits consist of mixtures of the materials composing the slopes and, hence, the grain size of these colluvial deposits can range from fine-grained clay and silt to boulder-size clasts. Processes forming colluvium range from very slow creep (the imperceptible movement of only fractions of a centimeter per year) to catastrophic landslides. The areal extent of landslide deposits (Ql) is relatively small; these deposits lie near the base of steep hills, ridges, and uplands. Slide material is especially common at or below the contact of the Esperance Sand and Lawton Clay Members of the Vashon Drift (Tubbs, 1974). On steep slopes (greater than 40°), the colluvial veneer is generally very thin (1 m or less), whereas near the toe of the hillside, where slope angles are 10°–20°, thicknesses of colluvium generally range from 5 to 10 m.

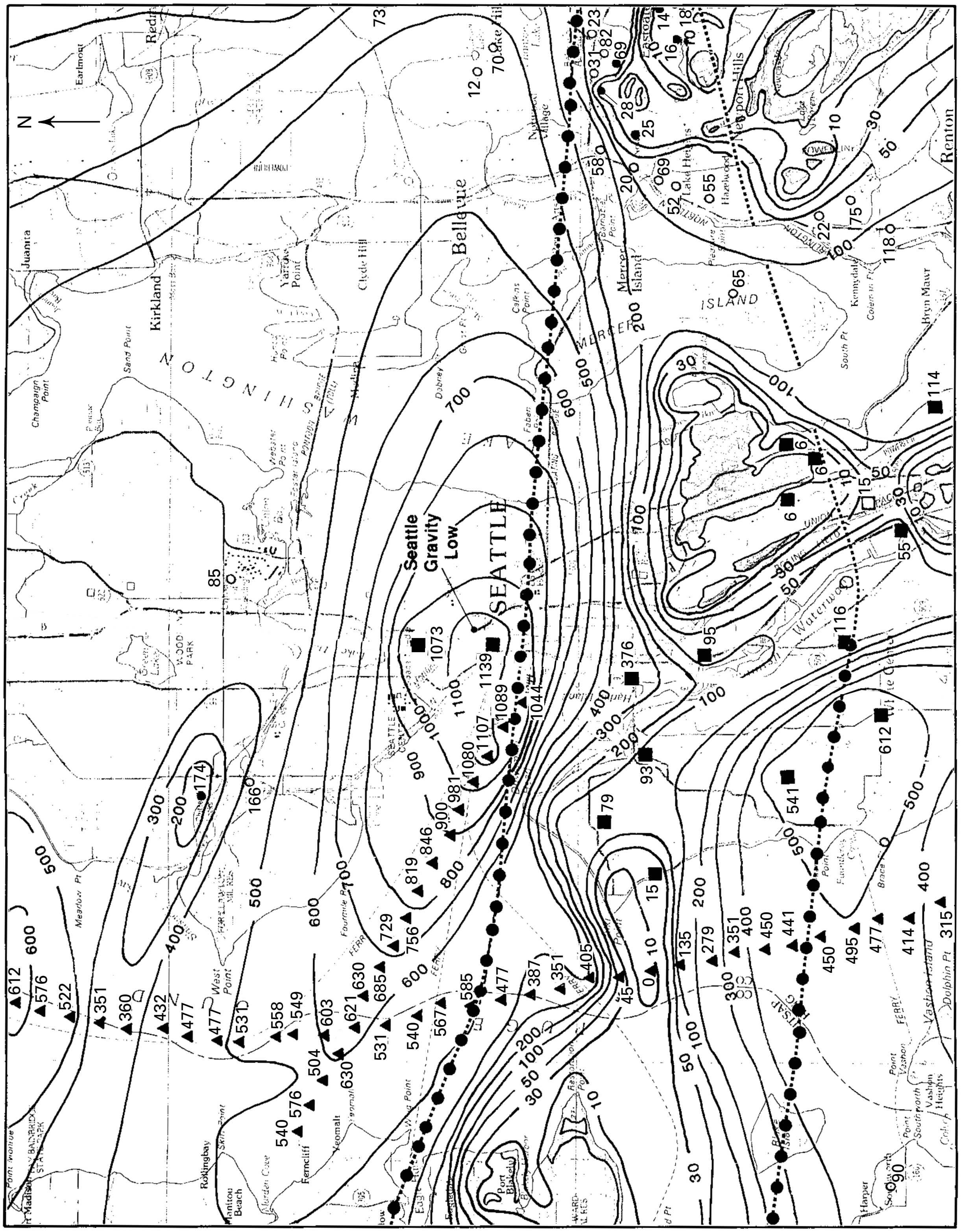
FILLS AND LAND MODIFICATIONS

Major fills (f) and drainage modifications (m) in the city have resulted from engineering projects during the first two decades of the 20th century (Phelps, 1978). Areas of major tideland reclamation are shown in figure 216. In the early 1900's, shallow tidal areas of the Duwamish River delta were filled with material that was largely sluiced from adjacent drift uplands to improve the usability of the seaport and obtain an area for industrial development. As a result of these operations, the mouth of the Duwamish River was extended about 0.80 km northwest to its present location. Also during this period, the sinuous, meandering course of the lower Duwamish River was straightened and deepened to what is now the Duwamish Waterway. Additionally, Harbor Island was built of hydraulic fill placed on tidelands at the river mouth when the East and West Waterways were dredged. A tidal marsh in the Pioneer Square area was filled with soil and with organic debris from nearby lumber mills. Glacial soils from the Jackson and Dearborn Regrades were sluiced via flumes and pipes to the Duwamish tidal flats south of the Pioneer Square area, where it accumulated to depths up to 12 m in the period between 1909 and 1910. The water-laden soil was washed into a series of diked ponds so that the fine particles could settle out of the slurry (Phelps, 1978). The tidal marsh at Smith's Cove (Interbay) was filled, as was the delta of Longfellow Creek (Young's Cove) in West Seattle. These projects provided extensive areas for seaport facilities and industrial expansion.

Logs of geotechnical borings show that these fills are highly variable in composition, ranging from sand to silt to clay and often containing sawdust, bricks, logs, wood fragments, cinders, and other debris. Yount (1983) reported that later fills are generally of better quality (more compact material consisting of medium to coarse sand) than the older fills. The fills are typically 3–5 m thick but can be as much as 10 m thick.

Regrading of the downtown Seattle hillsides was accomplished in two major phases between 1903 and 1928 to facilitate expansion and ease access within the central business district. This included removing Denny Hill entirely, which resulted in an excavation that was locally in excess of 30 m and covered a 62-city-block area (Sale, 1976; Morse, 1989). Glacial soils removed from Denny Hill were either sluiced or dumped by barge into shallow areas of Elliott Bay.

Between 1911 and 1916, the Lake Washington Ship Canal was constructed, linking Lake Washington to Puget Sound. This construction resulted in lowering of the surface of Lake Washington a nominal 3 m to the level of Lake Union. Additionally, the canal construction, which also includes a set of locks, resulted in raising the water surface in Salmon Bay to the level of Lake Union. The lowering of the water surface in Lake Washington eliminated the Black River, which drained from the south end of Lake


N
Seattle Gravity Low
SEATTLE
Bellevue
Kirkland
Mercer Island
Renton
West Point

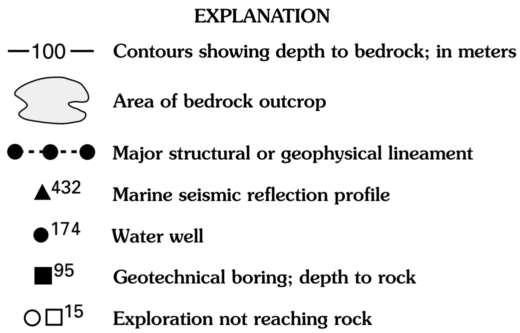


Figure 217 (facing page and above). Map showing depth to bedrock in the Seattle area. From Yount and others (1985).

Washington to the Duwamish River at Tukwila. Also as part of the canal construction, the Cedar River was diverted into Lake Washington (Chrzastowski, 1983).

The lowering of Lake Washington left a gently sloping terrace underlain by loose sedimentary materials around the lake's periphery, part of which has been retained as park land and part of which has been privately developed (Galster, 1989). The northern portion of Union Bay was filled subsequent to the lowering of Lake Washington. Originally, the site was a landfill that was later capped with fill material. A peat bog to the north of N.E. 45th Street was partially removed for peat and then filled with granular materials.

During construction of the Sand Point Naval Air Station, the site was extensively graded. Glacial soils from the central portion of the site were excavated and used to fill a small embayment on the north side and at Mud Lake.

Smaller areas of fill, as shown in figure 216, are located at the south end and northwest corner of Green Lake, the south and west sides of Lake Union, and the southern portion of Salmon Bay. Smaller fills were also placed in oxbow features along the Duwamish and Green Rivers.

GROUND WATER

Most of the normally consolidated soil units in the Seattle area lie in alluvial valleys or along lakes and bays where ground-water levels are relatively high. Static water levels recorded or estimated from borings in various areas of the city are summarized in table 35. As shown in the table, the average depth to ground water generally ranges from 0.6 to 3 m except in the upland outwash gravels. Although available boring data for the upland gravels suggest the absence of near-surface ground water, the near-surface presence of water cannot be precluded because of the paucity of data. High ground-water levels are likely where this gravel lies adjacent to lakes or ponds in the upland areas. Additionally, perched ground-water conditions may locally occur.

REGIONAL SEISMICITY

Examining the historical record concerning seismicity, earthquake source mechanisms, and postulated levels of peak ground motion for the Puget Sound region is essential to defining the liquefaction hazard of the Seattle area because the strength of the earthquake and the duration of the ground shaking directly affect the development of liquefaction.

HISTORICAL SEISMICITY

Seattle is located in a moderately active tectonic province that has been subjected to earthquakes of low to moderate strength and occasionally to strong shocks during the 160-year historical record of the Pacific Northwest. The largest historical earthquakes in the region are believed to be associated with deep-seated plate-tectonic activity (U.S. Geological Survey, 1975). Major mapped faults in the region (within 88 km of Seattle) have not been active in the Holocene and, consequently, none are known to be associated with historical seismicity. The nearest faults known to be active are small faults on the Olympic Peninsula, about 65 km west of Seattle.

The more significant historical earthquakes (those of Modified Mercalli intensity VI or greater) that have occurred in the Seattle area are listed in table 36. Of the 18 events listed, 5 had intensities of VII or greater. The largest of these were the April 13, 1949, M_s 7.1 intensity VIII shock and the April 29, 1965, m_b 6.5 intensity VII–VIII event. These earthquakes, which were respectively centered 63 km and 23 km from Seattle, caused considerable property damage in the city.

Other large historical earthquakes that have affected Seattle include one in the North Cascades of Washington and two in western British Columbia. The North Cascades earthquake of December 15, 1872, appears to have been one of the largest in the Pacific Northwest, as it was felt over an area of about 1,295,000 km^2. It has been estimated that this major shock had a magnitude of about 7 and an MMI of VIII. Although the epicenter of this event is uncertain owing to the sparse population of the area at that time, it apparently occurred somewhere in the northern Cascade Range.

In Canada, major earthquakes occurred on Vancouver Island on June 23, 1946, and in the Queen Charlotte Islands on August 21, 1949 (Coffman and Hake, 1973). The Vancouver Island event had a magnitude of 7.3 and a maximum intensity of VIII. Although the magnitude 8.1 Queen Charlotte Islands earthquake was felt over an area of more than 5,180,000 km^2, damage was minor because of the sparse population in the epicentral area.

Table 35. Ground-water depths in various parts of the Seattle metropolitan region.

[All values in feet, as originally measured or estimated from borings in study database. Values in parentheses are metric equivalents]

Area	Average depth	Maximum depth	Minimum depth	Standard deviation
Duwamish River valley (includes filled tideflats).	6.5 (2.0)	21.5 (6.6)	0.0 (0.0)	4.4 (1.3)
Alki Beach	10.5 (3.2)	25.0 (7.6)	6.0 (1.8)	3.7 (1.1)
Rainier Valley	8.7 (2.7)	26.0 (7.9)	0.0 (0.0)	8.3 (2.5)
Interbay (includes Lake Washington Ship Canal, unit Qys[1]).	6.4 (2.0)	13.0 (4.0)	0.0 (0.0)	4.3 (1.3)
West Point	15.0 (4.6)	30.0 (9.1)	9.0 (2.7)	6.9 (2.1)
Union Bay	4.0 (1.2)	6.5 (2.0)	2.0 (0.6)	1.3 (0.4)
Shilshole Bay	1.7 (0.5)	4.0 (1.2)	0.0 (0.0)	1.7 (0.5)

[1]Glacial recessional outwash deposit; upper part of the Vashon Drift. See plate 9 for description.

Table 36. Historical earthquakes in the Puget Sound region that exhibited a Modified Mercalli intensity (MMI) of VI or greater and occurred within 60 km of Seattle.

[Leaders (--), not measured. PST, Pacific Standard Time; M_s, surface-wave magnitude; m_b, body-wave magnitude]

Source[1]	Year	Date (mo/day)	Time, PST (hr:min)	Lat[2] N. (°)	Long[2] W. (°)	Magnitude	Maximum MMI	Depth (km)	Epicentral distance (km) and direction from Seattle
A,C	1880	08/22	13:25	48	122	--	VI	--	51 NNE.
A,C	1880	12/12	20:40	47.5	122.5	--	VI	--	16 SW.
A	1928	02/02	04:52	47.8	121.7	--	VI	--	53 NE.
A	1931	12/31	07:25	47.5	123.0	--	VI	--	51 WSW.
A	1932	08/06	14:16	47.7	122.3	--	VI	--	11 N.
A	1939	11/12	23:46	47.4	122.6	[3]5.75	VII	--	31 SW.
B	1945	04/29	12:16	47.4	121.7	--	VII	--	53 ESE.
A	1946	02/14	19:18	47.3	122.9	[3]5.75	VII	--	55 SW.
B,C,E	1949	04/13	11:56	47.1	122.7	7.1 (M_s)	VIII	71	63 SSW.
A	1950	04/14	03:04	48.0	122.5	--	VI	--	47 NNW.
A	1954	05/15	05:02	47.4	122.3	--	VI	--	23 S.
B	1955	03/25	22:56	48.05	122.03	--	VI	--	55 NNE.
B	1960	04/10	22:48	47.57	122.25	--	VI	--	8 SE.
A	1963	01/24	13:43	47.4	122.1	--	VI	--	27 SE.
B,E	1965	04/29	07:29	47.4	122.3	6.5 (m_b)	VII-VIII	60	23 S.
B,C	1965	10/23	08:28	47.5	122.4	[3]4.8	VI	--	13 SSW.
B	1975	04/22	15:04	47.08	122.65	4.0 (m_b)	VI	47	64 SSW.
B	1976	09/08	00:21	47.38	123.08	4.6 (m_b)	VI	48	61 WSW.

[1]The following sources were used in compiling the earthquake data:
A. Coffman and von Hake (1973).
B. U.S. Coast and Geodetic Survey (1928–1968).
C. U.S. Geological Survey (1975).
D. Stover and others (1978).
E. Weaver and Baker (1988).

[2]The range of uncertainty for epicentral locations may be taken as ±0.5° for earthquakes prior to 1960 and ±0.2° for those after 1960.

[3]Type of magnitude was not provided in the references prior to 1975.

EARTHQUAKE SOURCE MECHANISMS

Earthquake source mechanisms, which have been correlated with the observed historical seismicity, include shallow crustal events and deep subcrustal events. Maximum magnitudes of about 6.0 and 7.5 have been postulated for these two source zones, respectively (Rasmussen and others, 1974; U.S. Geological Survey, 1975). The deeper events are believed to be associated with faulting or release of extensional stresses in the subducted slab of the Pacific plate beneath the Puget lowland area (Taber and Smith, 1985; Weaver and Baker, 1988). The two major earthquakes in the region, the 1949 and 1965 events, both had focal depths in excess of 40 km, which is consistent with the deep-source-mechanism hypothesis. The majority of historical events, however, occurred at relatively shallow depths of about 24 km or less, which is consistent with the shallow-earthquake-mechanism hypothesis.

A third source mechanism, which is currently being debated within the scientific community, is the possible occurrence of a major earthquake on the Cascadia subduction zone off the coast of the Pacific Northwest (Heaton and Kanamori, 1984). Presently, the Cascadia subduction zone is quiet, with only scattered and diffuse seismicity, and no large subduction-zone earthquakes have occurred during historical times. However, Atwater (1987) has introduced geologic information that would suggest the possible occurrence of several subduction-zone events during the past 2,000 years.

POSTULATED GROUND MOTIONS

Estimates of seismic peak ground acceleration for the Seattle area have been postulated from regional studies conducted by the USGS and from local microzonational studies conducted by other researchers. Information on the ground acceleration of the area is an essential parameter in conducting a liquefaction-hazard evaluation.

The USGS has performed several regional studies on seismic hazards in the Pacific Northwest (Algermissen and others, 1982; Algermissen, 1988a, b). Figure 218 presents a regional, probabilistic evaluation of peak ground accelerations that could occur on rock within the Pacific Northwest. The accelerations shown in this figure have a 10 percent probability of being exceeded in a 50-year period, which corresponds to a 475-year seismic return period. Figure 219 compares the seismic exposure of Seattle to other areas of the United States. This figure presents ground accelerations on rock that have a 10 percent chance of being exceeded during the indicated time intervals. Both figures indicate that Seattle may be subjected to a ground acceleration of 0.30*g* an average of every 475 years.

Whereas the ground-motion estimates presented in figures 218 and 219 are based upon conventional earthquake source mechanisms (shallow and deep), recent work by Algermissen (1988a) suggests that ground accelerations in Seattle from a large subduction-zone earthquake occurring off the coast of Washington would not vary appreciably from the 475-year accelerations estimated from the conventional earthquake sources. However, the duration of ground shaking for a subduction-zone earthquake may be several times greater than that associated with more conventional earthquake source mechanisms. Increased duration of ground shaking would tend to increase the areal extent of liquefaction.

On a site-specific basis, Langston and Lee (1983) and Ihnen and Hadley (1987) performed ray-tracing studies to investigate the local variations in ground response in the Puget Sound region. Whereas Langston and Lee (1983) specifically evaluated amplification of ground motion in the Duwamish River valley, Ihnen and Hadley (1987) developed a seismic hazard map for the entire Puget Sound region that included considerations for ground-motion amplification due to soil type and wave-focusing effects. Results from both of these studies indicated that ground motions along the Duwamish River could be 50–100 percent greater than adjacent elevated areas. Both studies, however, indicated that the computed values of ground motion were highly dependent upon the focal mechanism and location of the generating earthquake. Because of the speculative nature and high degree of sensitivity associated with the results of the local microzonational studies, the results from these local studies have not been widely accepted or used for seismic design within the local engineering community.

STUDY METHODOLOGY

TECHNIQUE

Methods for evaluating liquefaction potential on a regional basis range from empirical techniques relating general liquefaction susceptibility to underlying geologic

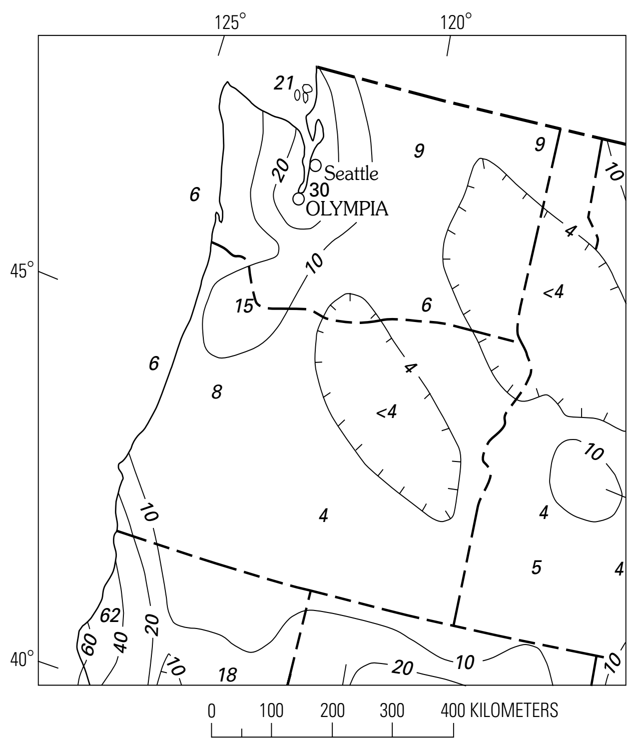


Figure 218. Earthquake peak ground accelerations for the Pacific Northwest. Numbers are peak accelerations in percent of *g* on rock with a 10 percent chance of exceedance within 50 years (475-year return interval). Contours hachured to indicate closed low. From Algermissen (1988a).

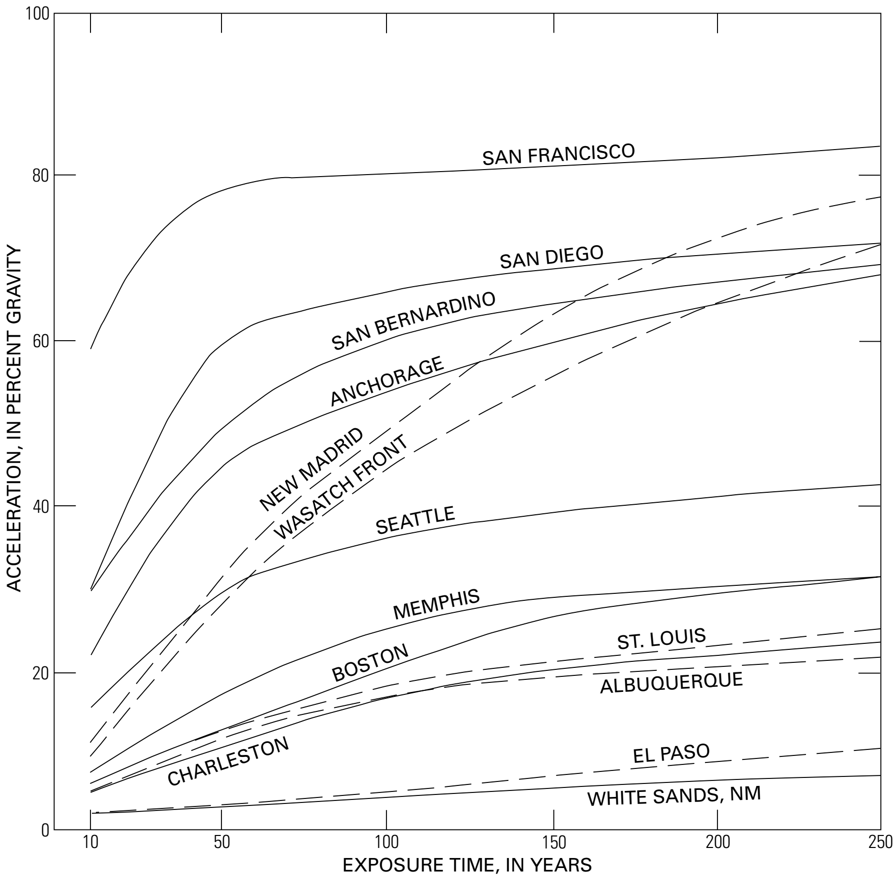


Figure 219. Seismic exposure map indicating peak accelerations on rock in various locations in the United States and corresponding to a 10 percent probability of occurrence for the indicated exposure times. From Algermissen (1988b).

conditions (Youd and Perkins, 1978), to more elaborate probabilistic, analytical evaluations (Power and others, 1986). These techniques have been applied to sites in southern California (Lee, 1977; Youd and others, 1979; Power and others, 1982; Tinsley and others, 1985; and Power and others, 1986), northern California (Youd and others, 1975; Blair and Spangle, 1979; Davis and others, 1982; Youd, 1982; Kavazanjian and others, 1985; Youd and Perkins, 1987; and Power and others, 1988), and other locations in the Western United States (Anderson and Keaton, 1982, 1986; Moriwaki and Idriss, 1987) and Eastern United States (Budhu and others, 1987; Hadj-hamou and Elton, 1989; Elton and Hadj-hamou, 1990).

Our liquefaction study of Seattle used empirical relations developed by Seed and Idriss (1971), Seed and others (1983), and Seed and others (1984) to establish the liquefaction potential of the various geologic units in the area. The procedures were used because of their acceptance and wide use in engineering practice. Furthermore, the use of these procedures permits a better conceptual understanding of the liquefaction phenomenon and the interrelation of the various parameters, such as subsurface geology and SPT N-values, that affect the occurrence of liquefaction.

The first step required the development of a database containing ground-water levels and SPT N-values for the various geologic units within the study area. This information was obtained from more than 350 borings in Seattle. The SPT N-values of the soils within the various geologic units were then compared with the threshold SPT N-values needed to resist liquefaction. The relative liquefaction hazard of the particular geologic unit was then assessed on the basis of the percentage of SPT values falling below the threshold SPT N-values. Additionally, the liquefaction hazard was assessed on the basis of the computed cumulative thickness of potentially liquefiable soil within the borings.

DATABASE

Because liquefaction susceptibility is affected by the geologic origin, depth, relative density, and gradation of the soil and the depth of the water table, a computerized database was developed to facilitate the storage and retrieval of subsurface data for subsequent use in the liquefaction evaluation (Grant, 1990). The database, which includes the logs of more than 350 borings, allows sorting of the data corresponding to various parameters including geographic location, drilling method, geology, and individual SPT N-value. Data recorded for each boring include UTM (Universal Transverse Mercator) coordinates, location description, date drilled, drilling method, surface elevation of the boring, static ground-water depth, and SPT N-value as a function of depth. Each SPT sample in a boring was assigned a code corresponding to the geologic unit of the material as well as a separate code describing the composition of the materials within the sample. The data corresponding to a particular geologic unit or material were subsequently retrieved to determine liquefaction susceptibility. By including individual SPT data from each boring, we were able to statistically account for variability of the SPT values within individual borings or within an entire geologic unit. This assessment is discussed subsequently in the evaluation-criteria section.

PEAK GROUND ACCELERATION

A key parameter in the liquefaction evaluation is the selection of a peak ground acceleration value for use in the numerical computations of the liquefaction potential. The following factors were considered in selecting the peak ground acceleration for the liquefaction study:

- Scenario earthquake or probabilistic assessment
- Criteria for probabilistic determination
- Uniform risk or site-specific studies

The first factor considered was whether to base the evaluation upon a scenario earthquake, such as a repeat of the 1949 or 1965 Puget Sound earthquakes, or to conduct the evaluation based upon a probabilistic risk assessment of the study area. One advantage of selecting a scenario earthquake is that other studies (U.S. Geological Survey, 1975; Langston and Lee, 1983; Ihnen and Hadley, 1987) have been conducted using such scenario events. Additionally, the results from a scenario-earthquake evaluation may be compared with historical earthquake damage in the area. The disadvantage to a scenario-earthquake study is that the earthquake sources in the area are not constrained to well-defined, known faults with surface rupture. Hence, it is quite probable that future earthquakes could occur at any location within the Puget Sound region and not at the epicenters of past events. Accordingly, it was decided to conduct the liquefaction evaluation based upon a probabilistic assessment of the earthquake hazard in the study area.

In selecting a probabilistic approach, it is necessary to establish the criteria for defining the design earthquake. In this regard, the design-earthquake ground acceleration was selected to correspond with motions having a 10-percent probability of being exceeded within 50 years. This approximately corresponds to a 475-year return interval. The criterion was selected to be consistent with local building practice in Seattle, which is based upon the Uniform Building Code (International Congress of Building Officials, 1991). Thus, the 475-year return interval provides consistency between the liquefaction-hazard map and nationally recognized standards for earthquake design of buildings.

The third factor considered in the liquefaction evaluation was whether to assume that the seismic risk or ground-shaking potential was uniform throughout the entire study area or whether the level of peak ground acceleration should be varied throughout the study area, considering amplification from topographic effects or subsurface soil conditions. Clearly, one would expect variations in ground accelerations throughout the study area for any given earthquake. These variations could be attributed to differences in subsurface geology or geometric attenuation of energy from the earthquake source. In fact, studies have been conducted to evaluate the local influence of such effects (Langston and Lee, 1983; Ihnen and Hadley, 1987). However, one limitation of microzonational studies of local ground motion is that the subsurface conditions throughout the study area are not perfectly known. Furthermore, the results of local studies of ground-motion effects in the Seattle area (Langston and Lee, 1983; Ihnen and Hadley, 1987) have shown that the calculated results were highly dependent upon the focal mechanism and location of the generating earthquake. Thus, it would appear that whereas techniques are available for computing ground motions on a microzonational level, these computed ground motions may be highly speculative and their application may be limited, considering the unconstrained location of future earthquakes in the Puget Sound region.

To avoid introducing additional uncertainties that are associated with the calculation of site-specific earthquake ground motions, it was decided to base the liquefaction evaluation upon a single level of ground acceleration. This would imply a uniform seismic risk throughout the entire study area. Although in reality ground motions may vary throughout the study area, there are several reasons that support selection of a single value of ground-surface acceleration. First, the fact that earthquakes in the Puget Sound region are not constrained to well-known structural features indicates that future earthquakes will likely occur at random in the region. This factor is consistent with the assumption of a uniform seismic risk. A second factor supporting the selection of a single ground-acceleration value is that the study area is predominantly underlain by similar soil conditions. Specifically, about 80 percent of the study area is underlain by glacially consolidated sedimentary deposits that would be categorized as “stiff soils,” or “S_2” soils using the Uniform Building Code (International Conference of Building Officials, 1991) soil classification scheme. The remaining 20 percent of the study area is underlain by alluvial soils that may have a somewhat greater potential for ground-motion amplification. These alluvial soils, however, generally do not include the thick sequences of clay that have characteristically resulted in large ground-motion amplifications in other areas, such as the San Francisco Bay region, during prior earthquakes. Thus, based upon the random location of future earthquakes in the Puget Sound region and the predominance of a single soil type underlying the study area, it was concluded that it is reasonable to use a single ground-acceleration value to represent the seismic risk in the liquefaction evaluation.

Based upon a 10-percent probability of exceedance during a 50-year interval, it was decided to use a peak ground acceleration of 0.30*g* for the liquefaction-hazard evaluation. This acceleration corresponds to the bedrock acceleration that is indicated in figures 218 and 219. Additionally, it is consistent with the seismic-hazard map recently developed by the USGS (Building Seismic Safety Council, 1991) for sites in the United States that are underlain by "stiff soils," or "S_2" soils as defined in the Uniform Building Code (International Conference of Building Officials, 1991). Thus, this acceleration would likely apply to at least 80 percent of the study area. Furthermore, it is assumed in the liquefaction analysis that this acceleration would correspond to an earthquake having a magnitude of about $7^1/_2$. This level of acceleration was used in the liquefaction studies of both Grant (1990) and Perkins (1991). In addition, Perkins (1991) used a peak ground acceleration of 0.15*g* to evaluate the effects of liquefaction from a smaller earthquake that may have a higher probability of occurrence.

EVALUATION CRITERIA

The final and, perhaps, most important factor in the liquefaction study was the selection of criteria for assigning the relative hazard ranking to the various geologic units in the study area. Selection of an appropriate hazard ranking scheme is complicated by the fact that no one criterion has been consistently used in prior liquefaction studies. Consequently, any liquefaction evaluation criteria used in a mapping study may appear arbitrary and require adjustments to reconcile the predicted performance with past observations of liquefaction. For example, the liquefaction study of San Mateo County, Calif. (Youd and Perkins, 1987), includes an adjustment factor of 10 to reconcile the study results with damage resulting from the 1906 San Francisco earthquake. Consequently, rating criteria developed for other geographic locations may not necessarily be applicable to the Pacific Northwest.

Two criteria were selected to assess the relative hazard rankings of the local geologic units: threshold and thickness. Threshold is based upon the relative percentage of SPT N-values in a geologic unit that would signify liquefaction during the 0.30*g* earthquake. Thickness differentiates the liquefaction hazard on the basis of the computed thickness of a geologic unit that may liquefy during a 0.15*g* and a 0.30*g* earthquake. Both the threshold and thickness criteria were selected to provide a reasonable segregation of the liquefaction hazard of the different geologic units in the area.

THRESHOLD CRITERION

The threshold liquefaction criterion (Grant, 1990) is based on evaluating the liquefaction resistance of a geologic unit, defined by the SPT N-values for the unit, as compared with a minimum SPT N-value needed to resist liquefaction for a 0.30*g* peak ground acceleration. Minimum SPT N-values needed to resist liquefaction, with appropriate adjustments for fines content, were determined from the following equation based on empirical correlations by Seed and others (1984):

$$N_{uncorr} = \frac{(N_1)_{60}}{C_N} = \frac{0.65(A_{max})\sigma r_d}{g\sigma' r_m C_N} \tag{1}$$

where

- N_{uncorr} is the uncorrected SPT value,
- $(N_1)_{60}$ are the corrected SPT values adjusted for fines content (Seed and others, 1984),
- C_N is the correction factor for overburden pressure (Seed and others, 1984),
- A_{max} is the peak ground acceleration (0.30*g*),
- σ is the total overburden pressure,
- σ' is the effective overburden pressure,
- r_d is the reduction factor for depth (Seed and others, 1984),
- r_m is the factor for earthquake magnitude (Seed and others, 1984), and
- g is the gravitational acceleration

The liquefaction evaluations primarily concentrated on the materials within 13 m of the ground surface because historical accounts of substantial damage from liquefaction have been concentrated within this depth range. The uncorrected SPT N-values characterizing a particular geologic unit were compared with the minimum SPT N-values to resist liquefaction for each 1.5-m depth interval of that unit. This incremental evaluation would account for potential variability of the N-values with depth within the geologic unit.

The following rating scheme was used to differentiate the hazard potential of the soils in the study area:

Percent of N-values below the 0.30*g* threshold criteria	Hazard rating
>50	High
25–50	Moderate
10–25	Low
<10	Very low

The percentage cutoff levels in the above tabulation were selected in an attempt to provide reasonable segregation of the data. Whether other cutoff values may be used, too stringent criteria could result in all of the soils falling in the high-hazard rating, and too lax criteria could result in all soils having a very low liquefaction potential. Thus, it is more important to develop rating criteria that segregate the data than it is to use criteria from other locations that may not adequately describe the relative local hazard.

THICKNESS CRITERION

The liquefaction potential of the various geologic units in the area was also evaluated using the thickness criterion (Perkins, 1991), which is based on not only a threshold acceleration but also a minimum thickness of liquefiable material. The total amount (cumulative thickness) of potentially liquefiable soil in each boring was computed using equation 1 and the peak ground accelerations of 0.15*g* and 0.30*g*. The calculations were completed for borings that were typically less than 16 m deep. Liquefaction was defined to be significant at locations where a minimum of 3 m of soil (cumulative thickness) would liquefy in the 0.30*g* earthquake and a minimum of 0.3 m soil would liquefy in the 0.15*g* earthquake. Although these thickness values are somewhat arbitrary, when combined with the 0.30*g* and 0.15*g* acceleration levels this criterion provides a basis for segregating the performance of the underlying geologic units under conditions of a large earthquake and a more common, but smaller event.

The following classification scheme was selected to differentiate the hazard potential of the soils in the study area using the thickness criterion:

Percent of borings with computed liquefaction[1]	Hazard rating
>50	High
25–50	Moderate
<25	Low

[1]3 meters liquefaction—0.30*g*; 0.3 meters liquefaction—0.15*g*.

SPT BIAS

One potential concern in the liquefaction evaluation was that the drilling method may have a significant effect on the SPT N-values obtained in the borings. Whereas rotary techniques have been recommended as a standard procedure in liquefaction evaluations (Seed and others, 1984), the vast majority of borings drilled in the Puget Sound region were advanced using hollow-stem auger drill rigs.

To evaluate the potential effect of drilling procedures upon the resulting SPT N-values, a comparative study was made of N-values at sites at the mouth of the Duwamish River, where there is a high concentration of both hollow-stem auger and rotary borings in a relatively confined area. The results from this study, which are presented in figure 220, indicate that the N-values obtained in the hollow-stem auger borings are about 6–7 blows per foot less than the N-values from the rotary borings. Additionally, the data presented in figure 220 indicate that the mean N-values from the hollow-stem auger borings reasonably approximate the lower quartile N-values from the rotary borings.

On the basis of these results, it is concluded that whenever feasible, the rotary-boring data set should be used in the liquefaction evaluations. Additionally, it was assumed that the mean N-values from the hollow-stem auger data would reasonably approximate the lower quartile N-values if all data were obtained using rotary techniques. This assumption is an integral part of our evaluation because of the lack of coverage of rotary borings within some of the geologic units.

STUDY RESULTS

As previously indicated, two separate but parallel studies (Grant, 1990; Perkins, 1991) were conducted to delineate the liquefaction hazard of the soils in Seattle. Although different criteria were used in these studies, the results of both research efforts were quite similar. Because of this similarity, a single liquefaction-hazard map (pl. 9) has been developed representing both research efforts and using the previously described methods and database. Both background studies focused upon ranking the relative liquefaction hazard of the major geologic units in the study area because it was assumed that units having the same general depositional characteristics should also have the same liquefaction resistance, provided all other factors are equal, such as the ground-water depth and assumed level of earthquake ground shaking. Three geologic groupings were evaluated for liquefaction resistance: fills, Holocene deposits, and Pleistocene deposits. The three groups were primarily differentiated by age because it was assumed that the youngest deposits would likely have the highest liquefaction potential and the oldest deposits would have the least potential. The areal extent of these geologic units and the assigned hazard rankings are indicated on plate 9.

FILLS

DUWAMISH TIDEFLATS

The liquefaction resistance of the fill and underlying alluvial soils in the Duwamish River tideflats was evaluated because this area represents the largest uncontrolled fill in Seattle (fig. 216). The area is bounded on the north by Elliott Bay, on the east by Beacon Hill, on the west by West Seattle, and on the south by Orcas Street. The ground surface is at about 3 m elevation (city of Seattle datum), and the ground-water table is typically present at depths ranging between 0.6 and 4 m below the ground surface. The subsurface geology typically consists of 3–5 m of fill materials, chiefly sands, underlain by alluvial deposits that are also predominantly sand. The fill material within the tideflat area has largely been deposited using hydraulic techniques. It is estimated that the fill consists of about 70 percent clean sand, 10 percent silty sand, and the remainder

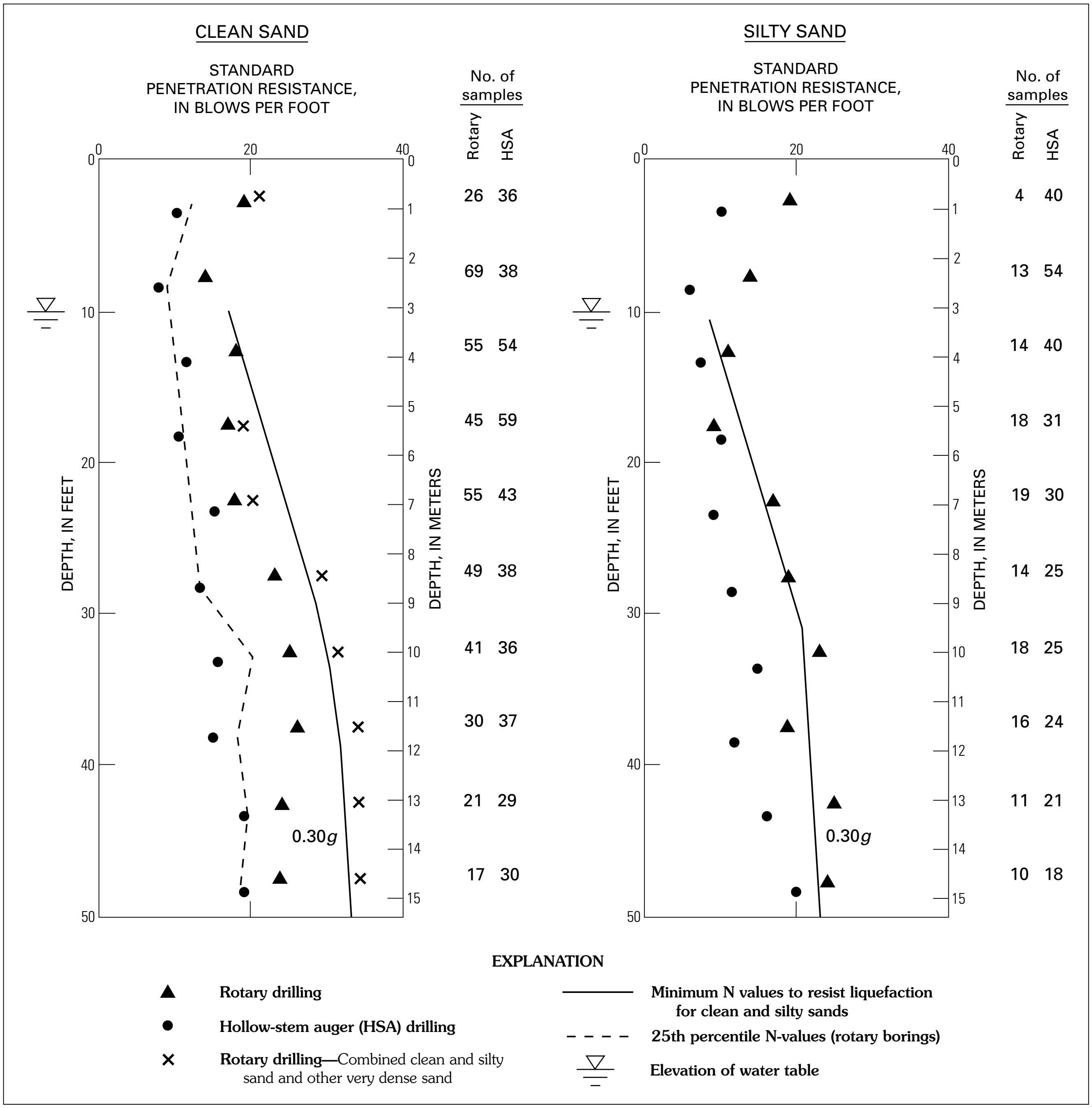


Figure 220. Liquefaction evaluation of the Duwamish River tideflats fill using the threshold criterion. The drilling data represent mean SPT values.

sandy silt and clayey silt. Based on the logs in the study area, the underlying alluvial materials are composed of about 50 percent clean sand and 20 percent silty sand. The remaining materials range from sandy silt to clayey silt.

The threshold criterion was applied to the fills and alluvial soils in the tideflats to evaluate their liquefaction susceptibility. The minimum SPT N-values needed to resist liquefaction from the 0.30*g* threshold earthquake are indicated, together with the SPT values for the underlying soils, in figure 220. Although the data in figure 220 have been segregated into both clean sand and silty sand units, the most significant characterization of the data is the composite plot of rotary boring data that includes not only clean and silty sands but also SPT N-values that were excluded from the other plots because the SPT N-values exceeded 40 blows/foot. These high SPT N-values were initially excluded from the data set because of a belief that any N-value of 40 blows/foot or greater may be the result of driving the sampler on a rock. However, a more detailed review of the logs indicated that very few rocks are present in the underlying soils in the tideflats area and that excluding N-values above 40 blows/foot would bias the data set. Thus, the composite data set represents the most accurate data set for evaluating the liquefaction resistance of the underlying soils.

Using the threshold criterion and the composite data, figure 220 indicates that the mean (50 percentile) SPT N-values fall below the threshold level in the zone within 10 m of the ground surface. This condition corresponds to a high hazard rating. Because 25–50 percent of the composite SPT N-values of soils below a depth of 10 m fall below the threshold level, it is concluded that the underlying soils would have a moderate liquefaction rating. The high liquefaction-potential rating given to the topmost 10 m of soil in the tideflats is consistent with the site-specific studies for the West Seattle Freeway Bridge replacement (Shannon & Wilson, 1980), which similarly showed depths of liquefaction in this area to be on the order of 6–9 m for an earthquake with a ground acceleration of about 0.30*g*.

Data supporting the thickness criterion evaluation of the liquefaction susceptibility of the tideflats fill are presented in figure 221*A*. The curves in the figure represent the percentage of borings in the Duwamish tideflats data set that would experience liquefaction over an interval ranging from 0 to 8 m as a result of earthquake ground shaking with peak accelerations of 0.15*g* and 0.30*g*. The cumulative thickness of liquefaction computed for each boring does not necessarily represent a continuous zone of liquefaction. The intent of these evaluations is to further quantify the liquefaction potential and qualitatively indicate the areal extent where liquefaction may occur to a significant degree.

On the basis of the data presented in figure 221*A* and the thickness criterion previously discussed (Perkins, 1991), we conclude that the fill soils along the Duwamish River tideflats have a high liquefaction potential. This conclusion is based on the observation that a cumulative thickness of 3 m of liquefaction would occur in about 65 percent of the borings for a 0.30*g* earthquake. Similarly, it is observed that a cumulative thickness of 0.3 m of liquefaction would occur in 68 percent of the borings for a 0.15*g* earthquake. A high liquefaction-hazard rating would apply to the tideflats fill soils because the computed cumulative thickness of potentially liquefiable soils would exceed the minimum thickness criterion in over 50 percent of the borings.

We conclude that the liquefaction potential of the soils in the filled Duwamish River tideflats is high on the basis of the criteria used in both methods of evaluation. This conclusion is in reasonable agreement with the historical record (fig. 216), which indicates that instances of reported liquefaction primarily occurred in the tideflats area. Furthermore, the high hazard rating of this area is consistent with the findings of the site-specific liquefaction study for the West Seattle Freeway Bridge replacement (Shannon & Wilson, 1980). Whereas the fill in the tideflats has been assigned a high liquefaction-hazard rating (pl. 9), areas on the tideflats within about 60 m of open bodies of water would have an even higher liquefaction potential and the potential for lateral spreading, based on the historical performance of the area.

INTERBAY

A liquefaction evaluation was performed for the fill soils found in the Interbay area, which is bounded by Salmon Bay on the north, Elliott Bay on the south, Queen Anne Hill on the east, and Magnolia on the west. This location was also identified for special study because it contains a significant amount of uncontrolled fill that was deposited during the early 1900's. Ground-surface elevations in this area typically range between 3 and 6 m (city of Seattle datum), and groundwater levels commonly are about 3 m below the ground surface. Soils in the Interbay area can include as much as 6–9 m of fill soils overlying alluvial deposits. The fill soils may have a variable composition including clean sand, silty sand, garbage, and construction debris or rubble. The underlying native soils range from clean sand to clayey silt.

Data relevant to the threshold evaluation of the liquefaction hazard of the Interbay fill are presented in figure 222. Conclusions drawn from the figure may be compromised somewhat because the data set is relatively small and consists exclusively of hollow-stem auger borings. Nevertheless, because the mean (50 percentile) SPT N-values for the Interbay fill soils fall below the threshold criterion for liquefaction corresponding to a 0.30*g* earthquake, it is concluded that the Interbay fills have a high liquefaction-hazard rating. Because the mean SPT N-values from the hollow-stem auger data set are typically 10–15 blows per foot below the threshold criterion, the high hazard ranking would not be changed if the hollow-stem auger data were increased by 6–7 blows per foot to provide equivalency with rotary borings (see fig. 220).

Data supporting the thickness evaluation of the liquefaction susceptibility of the Interbay fills are presented in figure 221*B*. About 65 percent of the borings were calculated to have 3 m and 68 percent to have 0.3 m of sediment that may liquefy during 0.30*g* and 0.15*g* events, respectively. Using the thickness criterion previously discussed, the soils in the Interbay area have high liquefaction potential.

Based on the application of both criteria, the Interbay area is judged to have a high liquefaction potential. This liquefaction rating, however, may be somewhat conservative when compared with the high hazard rating also given to the Duwamish River tideflats fill because historical liquefaction has not been reported at Interbay whereas numerous locations of liquefaction have been reported along the tideflats. Although this would not preclude liquefaction in the Interbay area, it does demonstrate a higher hazard potential for the Duwamish River tideflats. Nevertheless, considering the potential variability of soil conditions in the Interbay area, the Interbay fills were assigned a high liquefaction-hazard rating (see pl. 9).

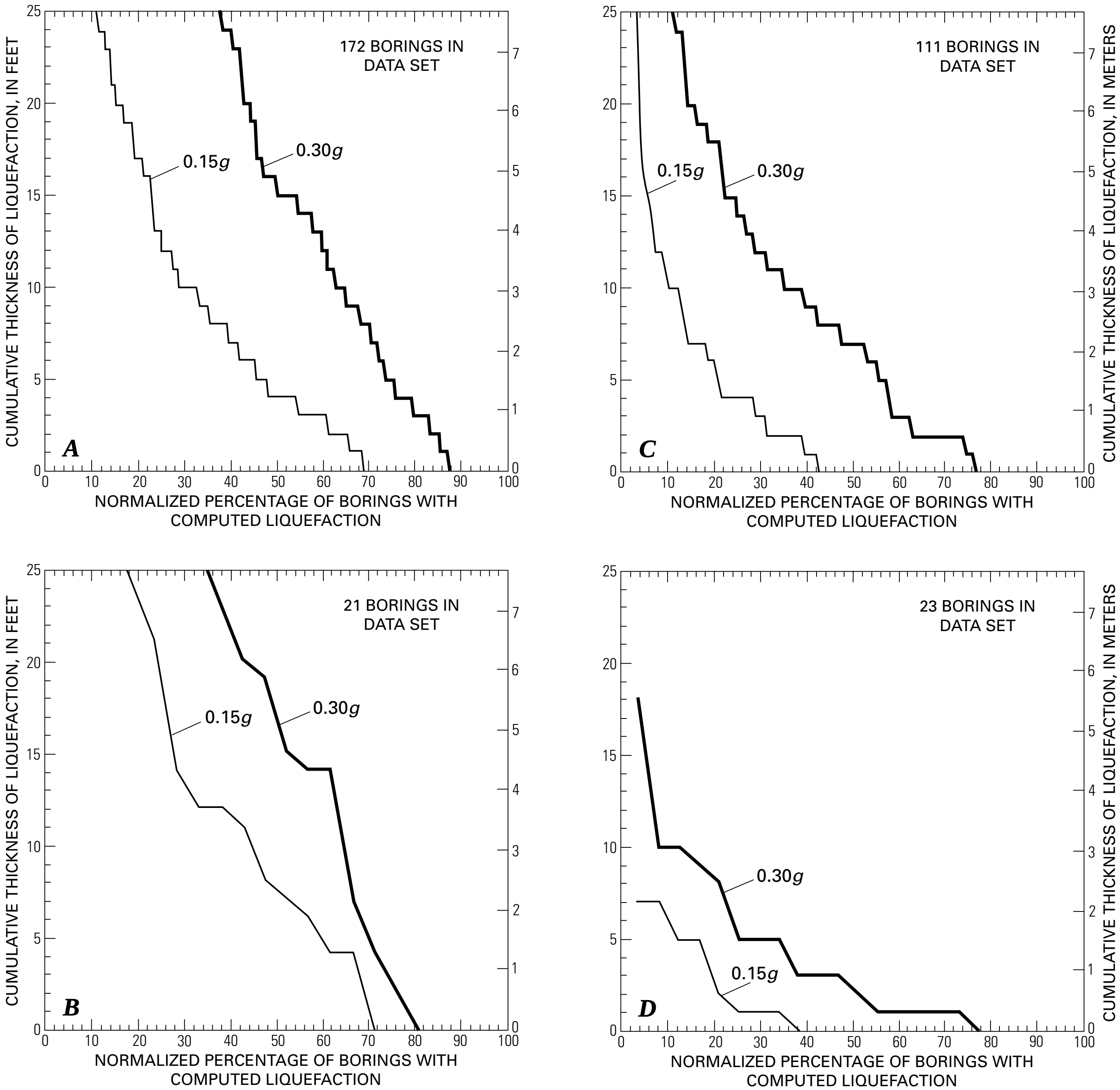


Figure 221. Liquefaction evaluation of soils in the Seattle area using the thickness criterion. Each curve represents the cumulative thickness of liquefaction for the indicated seismic ground acceleration. *A*, Duwamish River tideflats fill; *B*, Interbay fill; *C*, Duwamish River valley Holocene alluvium; *D*, Alki Point Holocene beach deposits.

OTHER FILLS

Other fills have been mapped by Waldron and others (1962) throughout the Seattle area. Although boring information was sparse or not available for these fills, it was judged prudent to conservatively represent these materials as having a high potential for liquefaction, considering their variable composition and density. This high hazard rating is partly substantiated by the performance of fills at the University of Washington athletic fields and at the south end of Green Lake (fig. 216), which experienced liquefaction during the 1965 Puget Sound earthquake. Therefore, all significant fills mapped by Waldron and others (1962) have been designated as having a high liquefaction-hazard rating (see pl. 9).

HOLOCENE DEPOSITS

ALLUVIUM

The most significant deposit of Holocene alluvium within Seattle consists of flood-plain material (hereafter

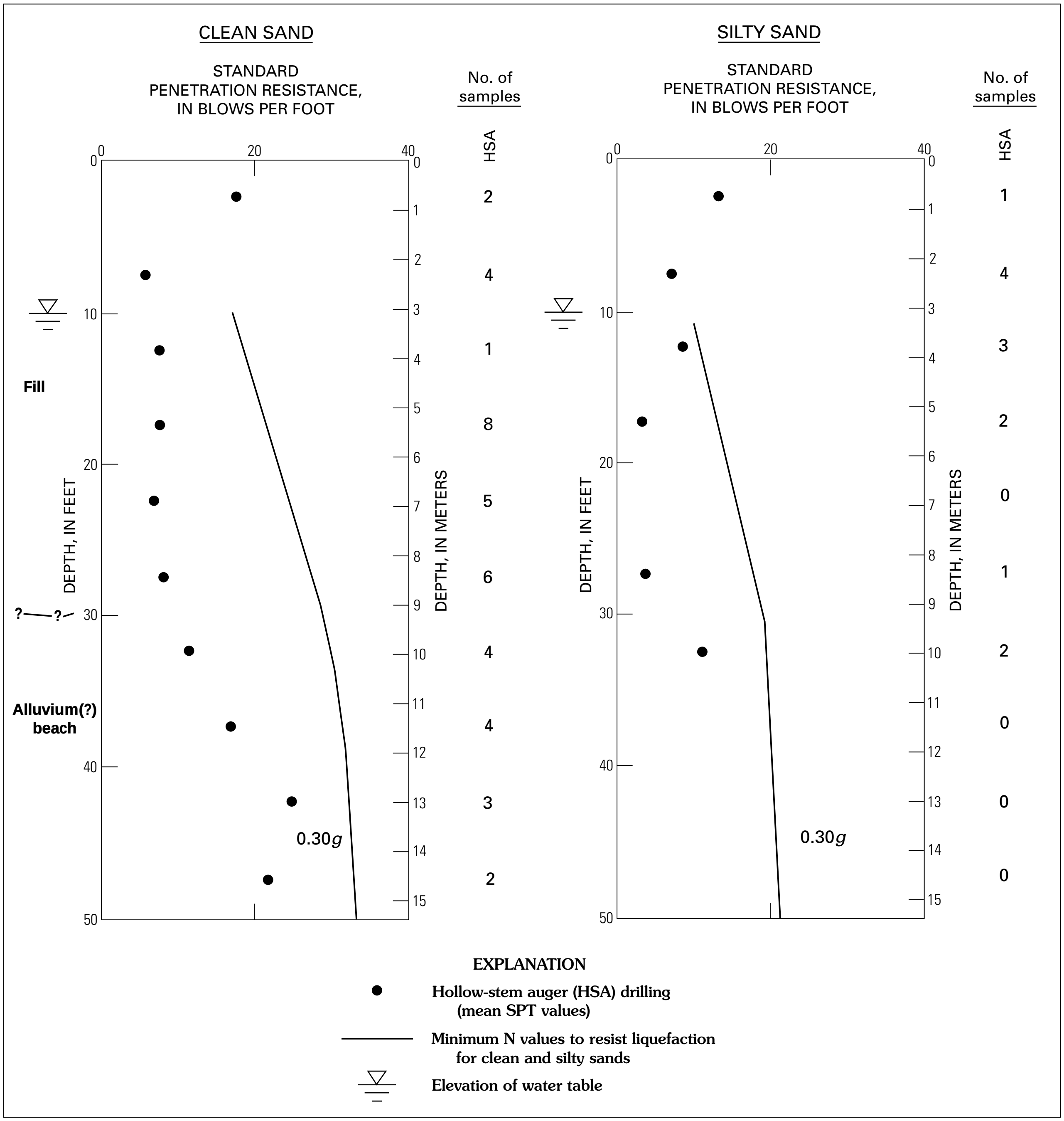


Figure 222. Liquefaction evaluation of the low-lying Interbay area fills using the threshold criterion.

informally referred to as the Duwamish alluvium for simplicity) in the Duwamish River valley. The valley typically extends several hundred to several thousand meters on either side of the Duwamish River. This zone is characterized by a relatively flat lying area with ground surface elevations ranging between 3 and 6 m (city of Seattle datum) and ground-water levels 0.6–3 m below the ground surface. Typically, soils within the area consist of shallow fill overlying alluvial deposits that may contain about 60 percent clean to silty sand and about 40 percent sandy to clayey silts. The alluvial material in the upper parts of the Duwamish alluvium contains a somewhat larger percentage of silt compared with the alluvial materials underlying the Duwamish tideflats.

Data relevant to the threshold evaluation of the liquefaction hazard of the Duwamish alluvium are presented in figure 223. The N-values in this plot have been segregated based upon drilling technique as well as the material encountered within the sampling depth. As indicated in the figure, there is a relatively small percentage of rotary borings

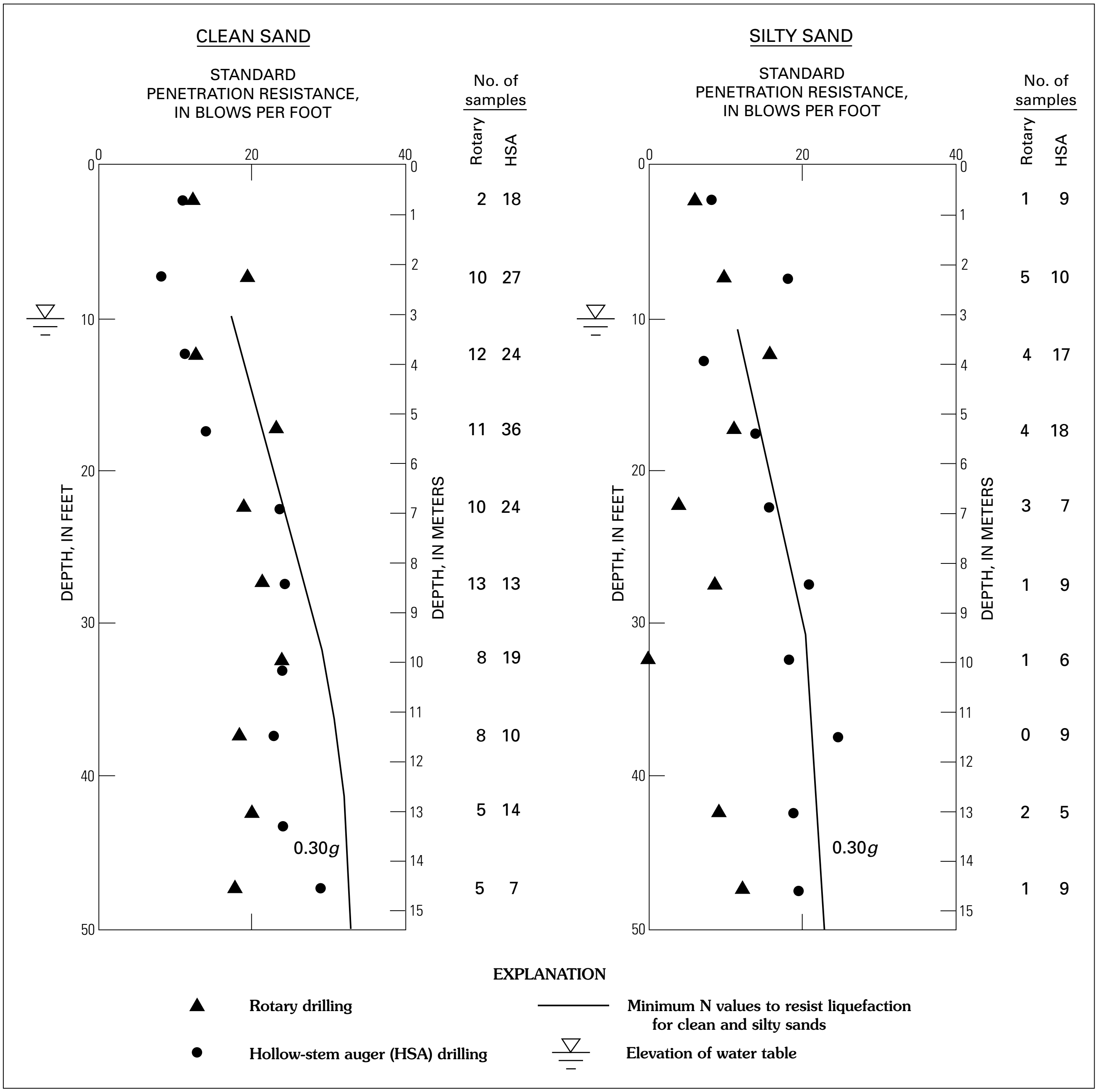


Figure 223. Liquefaction evaluation of Holocene alluvium in the Duwamish River valley using the threshold criterion. The drilling data represent mean SPT values.

in the data set, with most of the information obtained from hollow-stem auger drilling borings. Additionally, the smaller set of rotary-boring SPT data is somewhat suspect because the consistency that existed between the larger data set of rotary and hollow-stem auger borings in the Duwamish River tideflats (fig. 220) is absent in the data from the Duwamish alluvium. Furthermore, figure 223 shows the mean SPT data from the rotary borings to be erratic whereas the mean SPT data from the hollow-stem auger borings are less variable and similar to the data shown for the tideflats fill (fig. 220).

Due to these inconsistencies, it was decided to evaluate the liquefaction potential of the Duwamish alluvium based upon the hollow-stem auger data set. Because the SPT N-values shown in figure 223 suggest that between 25 and 50 percent of the data would fall below the 0.30*g* threshold criterion, it was concluded that the Duwamish alluvium has a moderate liquefaction potential. This conclusion is based on the assumption that the mean SPT N-values from the hollow-stem auger borings correspond to the 25-percentile values of the equivalent rotary data and that there would be a differential of about 6 blows/foot between the 25- and 50-percentile values (see fig. 220).

Data supporting the thickness criterion evaluation of the liquefaction susceptibility of the Duwamish alluvium are presented in figure 221*C*. As shown in this figure, about 40 percent of the borings in the area were calculated as having at least 3 m of sediment that may liquefy during a 0.30*g* earthquake. Also, about 38 percent of the borings were calculated as having at least 0.3 m of sediment that may liquefy during a 0.15*g* event. Thus, we conclude from the thickness criterion evaluation that the soils in the upper part of the Duwamish alluvium have a moderate liquefaction rating.

The moderate liquefaction rating of the Duwamish alluvium appears to be reasonably consistent with the rating given to the materials within the Duwamish tideflats area because the materials in the upper parts of the Duwamish alluvium appear to have higher SPT values, on the average, compared with the materials in the tideflats area. This conclusion is based on reviewing the SPT N-values from hollow-stem auger borings advanced in both areas where the SPT N-values in the upper part of the Duwamish alluvium are about 7 or 8 blows/foot higher than the values obtained at the mouth of the Duwamish River. Similarly, this liquefaction rating appears to be consistent with the historical performance of the area during the 1949 and 1965 earthquakes, which indicated relatively few instances of liquefaction in the upper Duwamish portion of the study area.

Whereas alluvial materials are present in areas other than along the Duwamish River, the boring coverage that exists in these areas is too sparse to support a significant evaluation of liquefaction resistance. Therefore, based on the Duwamish River valley data, all Holocene alluvial deposits in the study area were classified as having a moderate liquefaction-potential rating (see pl. 9).

BEACH DEPOSITS

Beach deposits within the Seattle area are primarily found along Puget Sound at West Point, west of Magnolia, and by Alki Point in West Seattle. These deposits form relatively local zones where there may be either residential development or municipal treatment plant facilities such as at West Point. These zones typically have ground-surface elevations ranging between 3 and 9 m (city of Seattle datum) and ground-water levels typically on the order of 3 m or more beneath the ground surface. The beach deposits are predominantly clean, fine sands.

Data relevant to the threshold evaluation of the liquefaction hazard of these Holocene beach deposits are presented in figure 224. Whereas there are relatively few borings in the data set, the data show that the mean SPT N-values from the rotary borings are consistently higher than the hollow-stem auger data, similar to the trend observed in the larger data set of the Duwamish tideflats area (fig. 220). Furthermore, the mean SPT N-values from both the hollow-stem auger and rotary data show consistency (absence of erratic N-values) at various depths below the ground surface. Thus, it was concluded that the rotary boring data presented in figure 224 are applicable for the liquefaction evaluation. Because the SPT N-values of the rotary borings in the figure indicate that between 25 and 50 percent of the data fall below the 0.30*g* threshold criterion (mean SPT N-values are above the threshold), it was concluded that the Holocene beach deposits have a moderate liquefaction potential.

A similar conclusion was derived using the thickness criterion and the data presented in figure 221*D* for the Alki Point area. As shown in this figure, about 35 percent of borings were found to have at least 0.3 m of sedimentary materials that may liquefy during a 0.15*g* event. This percentage corresponds to a moderate liquefaction rating. However, only 13 percent of borings were calculated to have at least 3 m of potentially liquefiable soil during a 0.30*g* earthquake, which would correspond to a low rating. In light of this variance, a moderate liquefaction-hazard rating was conservatively assigned to the Holocene beach deposits.

The moderate liquefaction-susceptibility rating of the beach deposits is reasonable when considering that only two instances of liquefaction of beach deposits were reported during the 1949 and 1965 Puget Sound earthquakes. Both observations occurred at the same residence in the Alki Point area. Liquefaction was not reported at West Point following either event. However, excavations conducted for the West Point treatment plant have encountered materials that would suggest ancient liquefaction (paleoliquefaction). Thus, on the basis of these limited and scattered observations, we conclude that the moderate liquefaction-hazard rating conservatively but accurately represents the relative hazard of the beach deposits. This rating is consistent when compared with the high hazard rating given to the Duwamish tideflats, where numerous instances of liquefaction occurred during prior historical earthquakes.

OTHER SEDIMENTARY DEPOSITS

Other Holocene sedimentary deposits mapped by Waldron and others (1962), such as their lacustrine sediments (Qsc) and peat (Qp) units, underlie small, isolated parts of the study area. Unfortunately, there is relatively little information in the database to characterize the liquefaction susceptibility of these units. Considering that these units may be largely composed of cohesive sediments, it is believed the liquefaction potential for these soils is relatively low. However, because the composition of these units is largely unsubstantiated by the information contained in the database, these materials were conservatively assigned a moderate liquefaction-potential rating, as shown on plate 9.

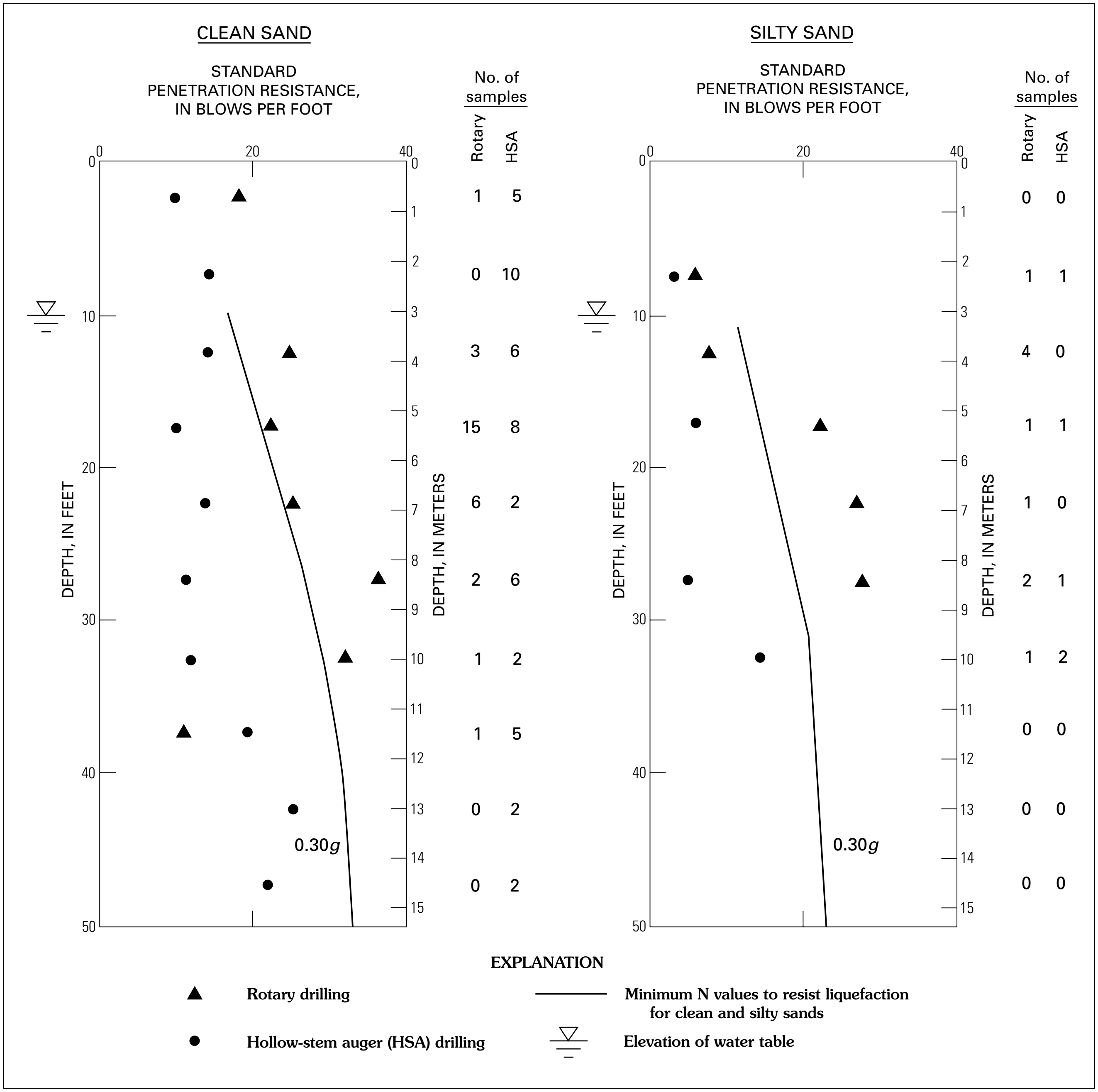


Figure 224. Liquefaction evaluation of Holocene beach deposits found in all borings in the database using the threshold criterion. The drilling data represent mean SPT values.

PLEISTOCENE DEPOSITS

NORMALLY CONSOLIDATED ALLUVIUM

Normally consolidated Pleistocene alluvial deposits typically are found at higher elevations (above 6 m) in scattered locations throughout the study area. Significant deposits of Pleistocene alluvium exist in West Seattle and have been described by Waldron and others (1962) as deposits of sand or gravel. These materials may typically include up to about 70 percent of clean to silty sand, with the remaining materials consisting of silt or gravel. Because these materials are recessional outwash deposits, they have not been glacially consolidated. Ground-water levels within these deposits may be quite variable, considering that perched water tables exist at higher elevations in the Seattle area. Shallow ground-water conditions would be anticipated within these deposits in areas adjacent to creeks or lakes.

Data relevant to the threshold evaluation of the liquefaction hazard of the Pleistocene alluvial deposits are

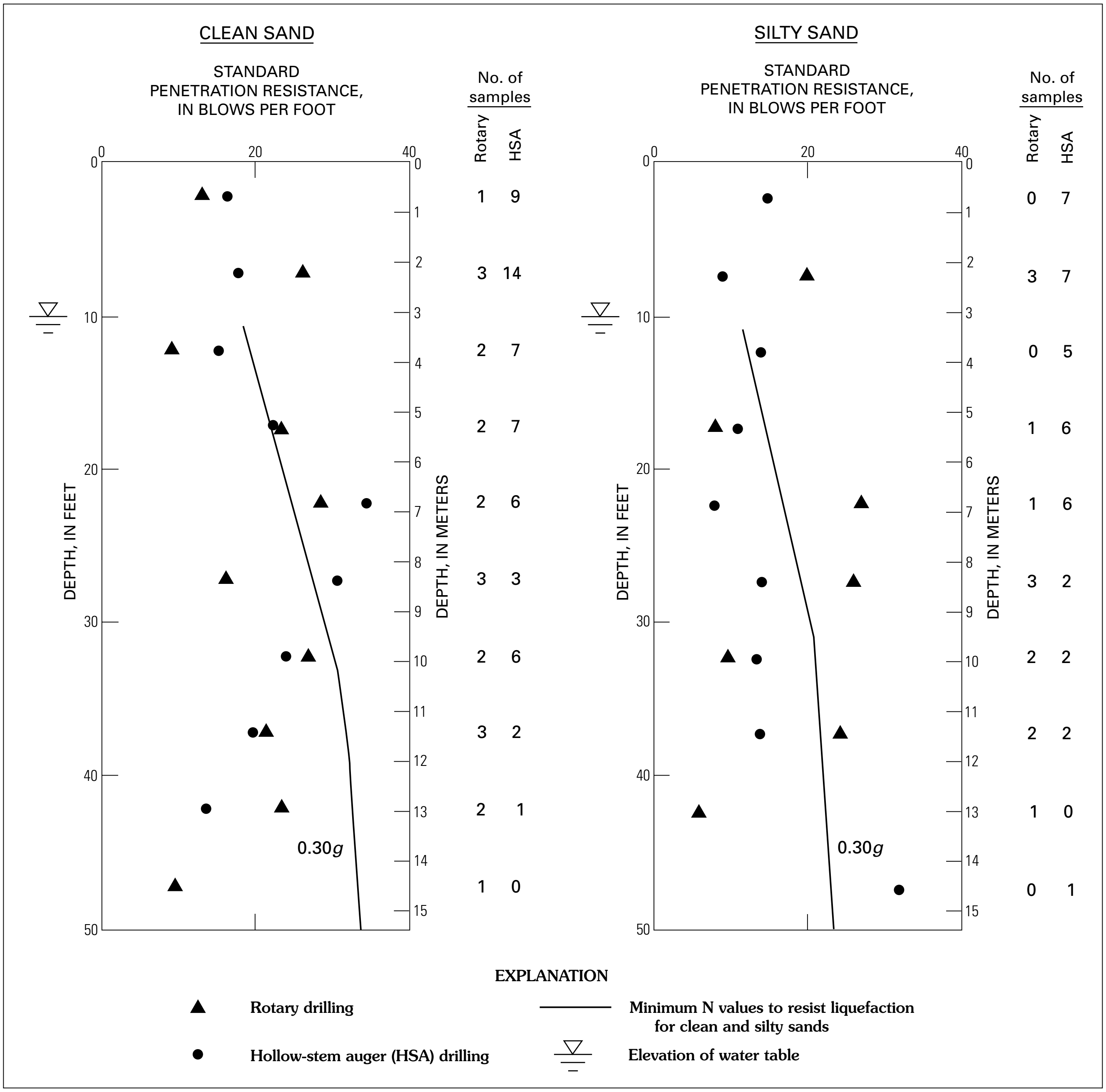


Figure 225. Liquefaction evaluation using the threshold criterion for Pleistocene alluvium found in borings where ground surface elevations exceed 6 m in the Seattle area. The drilling data represent mean SPT values.

presented in figure 225. Because of the size of the data set and some of the inconsistencies noted in the rotary boring data (such as erratic N-values and SPT resistance values lower than the hollow-stem auger data), it was decided to base the liquefaction evaluation on the hollow-stem auger data. The data in figure 225 generally show that the mean SPT values from the hollow-stem auger installations, which are assumed to be equivalent to the lower quartile values from rotary borings, are typically near the minimum SPT required to resist liquefaction during a 0.30*g* earthquake. Thus, these high SPT values, combined with the anticipated relatively low ground-water levels, lead to the conclusion that the deposits will be best categorized as having a low liquefaction-potential rating. This rating also is consistent with the observed historical performance of these materials during the 1949 and 1965 earthquakes, as no instances of liquefaction were reported within Pleistocene alluvial deposits.

GLACIALLY CONSOLIDATED SEDIMENTARY DEPOSITS

The majority of the soils within the study area are composed of glacially consolidated sedimentary materials ranging from till to sand and gravel. These materials are found throughout the city, typically at higher elevations, with variable perched ground-water tables.

SPT data obtained from these glacially consolidated sedimentary deposits are summarized in table 37. All the SPT data were obtained using hollow-stem auger drilling techniques. The data in the table have been differentiated on the basis of undetermined-origin material, till, and glaciolacustrine deposits. High blow counts were obtained in practically all cases, and the 10-percentile values are greater than the minimum SPT values required to resist liquefaction during a 0.30*g* earthquake. As such, we conclude that these materials would have a very low liquefaction-potential rating and that the cohesive soils within this grouping, such as glacial till, are not susceptible to liquefaction.

DISCUSSION

The liquefaction-hazard ratings that were developed for each of the generalized geologic units in the study area were based upon the data presented in figures 220–225 as applied to the threshold and thickness ranking schemes. To provide a means of evaluating the internal and external consistency of the results of the liquefaction study, the rankings of each of the individual geologic units have been summarized in table 38 along with information on their liquefaction performance and the relative liquefaction ranking that would be assigned to the deposits using the liquefaction classification system of Youd and Perkins (1978). Agreement between these rating schemes increases the confidence of the findings of the Seattle liquefaction study.

Several trends are apparent in the liquefaction hazard rankings shown in table 38. First, although the threshold and thickness criteria are not necessarily mutually inclusive, the hazard rankings developed from both criteria are identical except for the low rating for the Holocene beach deposits corresponding to a 0.30*g* earthquake. Additionally, the assigned relative hazard rankings are in agreement with the liquefaction performance of the soils. Specifically, (1) areas assigned a high hazard rating frequently had numerous instances of reported liquefaction, (2) areas assigned a moderate rating had minor, scattered occurrences of liquefaction, and (3) areas assigned a low hazard rating had no reported liquefaction. The final external consistency check is the comparison of the assigned hazard ratings and those that would have been assigned using the ranking scheme of Youd and Perkins (1978). As shown in the table, the assigned liquefaction rankings are identical to those that would be determined from the Youd and Perkins (1978) classificational scheme with the exception of fill soils that Youd and Perkins (1978) have ranked as having a very high hazard. On the basis of these favorable internal and external comparisons, we conclude that the liquefaction potential map presented in plate 9 provides reasonable and realistic seismic hazard rankings.

SUMMARY AND CONCLUSIONS

Seattle is located in a tectonic and geologic environment that is conducive to the development of liquefaction during

Table 37. Summary of Standard Penetration Test (SPT) data for glacially consolidated sedimentary deposits in the Seattle area.

[(--), no data available. n, number of samples; N, average standard penetration resistance (blows/foot); 10, 10th percentile of SPT N-values]

Depth range in feet (meters)	Soil source								
	Undetermined origin			Till			Lacustrine		
	n	N	10	n	N	10	n	N	10
0–5 (0–1.5)	1	40	--	--	--	--	--	--	--
5–10 (1.5–3.0)	2	100	--	3	103	--	--	--	--
10–15 (3.0–4.6)	8	100	34	5	120	82	1	68	--
15–20 (4.6–6.1)	15	91	50	6	170	150	2	104	--
20–25 (6.1–7.6)	20	71	32	6	115	33	5	109	38
25–30 (7.6–9.1)	16	101	38	13	118	50	13	113	36
30–35 (9.1–10.7)	27	92	28	7	98	42	7	91	34
35–40 (10.7–12.2)	26	107	39	8	133	100	5	57	31
40–45 (12.2–13.7)	31	135	46	3	120	39	6	102	31
45–50 (13.7–15.2)	32	124	39	2	125	--	4	60	32

Table 38. Comparison of the liquefaction ratings of geologic deposits in the Seattle area.

[(--), not available. *g*, acceleration due to gravity (approximately 9.8 m/sec)]

Deposit	Liquefaction potential					
	Threshold criterion	Thickness criterion		Assigned rating	Historical liquefaction	Relative ranking[1]
	(0.30*g*)	(0.15*g*)	(0.30*g*)			
FILLS						
Duwamish River	High	High	High	High	Numerous	Very high
Interbay	High	High	High	High	None	--
Other	--	--	--	High	Occasional	--
HOLOCENE ALLUVIUM						
Mouth of Duwamish River	High	High	High	High	Numerous	High
Flood plain	Moderate	Moderate	Moderate	Moderate	Occasonal	Moderate
HOLOCENE BEACH DEPOSITS	Moderate	Moderate	Low	Moderate	Occasional	Moderate
PLEISTOCENE ALLUVIUM	Low	--	--	Low	None	Low
PLEISTOCENE GLACIAL DEPOSITS	Very low	--	--	Very low	None	Very low

[1]Based on the classification system of Youd and Perkins (1978).

relatively strong earthquakes. Instances of liquefaction have been reported during the two largest historical earthquakes in the region, the April 13, 1949, magnitude 7.1 Olympia earthquake and the April 29, 1965, magnitude 6.5 Seattle-Tacoma earthquake. Although only moderate damage occurred in Seattle as a result of these earthquakes, the damage level is consistent with the low level of acceleration recorded locally (approximately 0.10*g*) during both these events. This historical damage, however, may not accurately represent the potential hazard in Seattle because the area may likely experience an earthquake with a ground acceleration of 0.30*g* (Algermissen, 1988b; International Conference of Building Officials, 1991). The liquefaction-hazard potential of the area may be even greater during a subduction-zone earthquake because the duration of such an earthquake may be several times greater than any historical event experienced in the Puget Sound region.

The methodology used for evaluating and mapping the local liquefaction hazard assumed that the entire study area would be subjected to a uniform peak ground acceleration of either 0.15*g* or 0.30*g*. The 0.30*g* level of acceleration has a 10-percent chance of being exceeded in 50 years (475-year return period), and this acceleration is consistent with either bedrock (Algermissen, 1988b) or stiff soil deposits (Building Seismic Safety Council, 1991). The 0.30*g* acceleration is also consistent with local practice for the seismic design of buildings (International Conference of Building Officials, 1991). This level of acceleration was coupled with the empirical liquefaction procedures of Seed and Idriss (1971), Seed and others (1983), and Seed and others (1984) to determine the liquefaction resistance of the various geologic units in the area. A generalized liquefaction-hazard rating for each geologic unit was evaluated using threshold performance and thickness criteria. The threshold criterion ranked the relative liquefaction potential on the basis of the percentage of SPT N-values falling below the minimum N-value required to resist liquefaction during the 0.30*g* event. A high liquefaction potential was assigned to units with a mean (50 percentile) SPT N-value below the threshold value. A low liquefaction-potential rating was given to materials with lower quartile N-values than the 0.30*g* threshold level. Intermediate values were ranked as having a moderate liquefaction potential.

The second evaluation method was based on the thickness, or vertical extent, of soils that would potentially liquefy in 0.15*g* and 0.30*g* earthquakes. A high hazard rating was given to geologic units in which the thickness of the liquefied layer was predicted to exceed 3 m during a 0.30*g* earthquake and 0.3 m during a 0.15*g* earthquake in at least 50 percent of the borings. A low rating was assigned to units in which these thicknesses would develop in less than 25 percent of the borings. Intermediate values were ranked as having a moderate liquefaction potential.

On the basis of the methodologies and criteria described, a liquefaction-hazard map was developed for the Seattle area (pl. 9). We conclude that fill soils and underlying alluvial deposits, particularly in the Duwamish River tideflats and the Interbay area, have a high potential for liquefaction during a 0.30*g* earthquake. Deposits having a moderate liquefaction potential at this seismic level include Holocene alluvium, beach deposits, and other sedimentary materials. The most significant Holocene alluvial deposits occur along the Duwamish River valley. Pleistocene alluvial deposits, which have not been glacially consolidated, were given a low liquefaction-potential rating. Pleistocene glacially consolidated sedimentary deposits received a very low liquefaction-potential rating.

The results from these studies are intended to provide a regional assessment of liquefaction potential and should not be considered as a substitute for site-specific studies for individual buildings or other structures. Because conditions vary locally, site-specific geotechnical investigations are required to accurately assess liquefaction potential at any given location.

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IMPLEMENTATION

Preceding page. *Insert,* masonry damage caused by the April 29, 1965, Seattle, Wash., earthquake. Photograph courtesy of NOAA/EDIS. *Background,* damage to unreinforced masonry wall and parapet in downtown Klamath Falls, Oreg., during the Sept. 20, 1993, *M* 5.9 and *M* 6.0 earthquakes (from Dewey, J.W., 1993, Damages from the 20 September earthquakes near Klamath Falls, Oregon: Earthquakes & Volcanoes, v. 24, no. 3, p. 121–128).

REDUCING EARTHQUAKE HAZARDS—AN INTRODUCTION

By William J. Kockelman[1]

Any effective program having earthquake-hazard reduction as a goal requires (1) scientific and engineering studies identifying and assessing the hazards; (2) translation of such studies for nontechnical users; (3) transfer of this translated information to those who will or should use it; (4) use of appropriate hazard-reduction techniques; and (5) review and revision of such techniques to ensure their effectiveness. Each is a prerequisite for its successor.

The preceding articles under the headings "Tectonic Setting" (volume 1 of this report) and "Earthquake Hazards" (this volume) are a major contribution to scientific and engineering studies and their translation. The publication and widespread distribution of this professional paper will contribute substantially to the transfer of this information. The following articles are a part of this transfer component, namely, an introduction to and discussion of hazard-reduction strategies and techniques. These reports are addressed to the potential users listed in table 9 of the Introduction to the report (Rogers and others, volume 1, p. 40).

May (this volume) addresses the prospects and strategies for reducing earthquake hazards. The article is based upon interviews with State and local officials in the Puget Sound and Portland areas and on analysis of current hazard-reduction policies and techniques. The author, a political scientist, observed that officials are generally aware of earthquake risk but that their concern is limited because of more pressing problems. He takes a closer look at the local political and economic factors that relate to reduction of earthquake hazards in the future. The relatively vulnerable cities are divided into "pacesetter," "resourceful," and "restrained" groups and the less vulnerable cities into "new sophisticate," "measured," and "non-player" groups. Counties are divided into "leader," "transitional," and "rural" groups. The understanding of these diverse groups provides a basis for considering the following four strategies whose strengths and limitations are discussed:

- Disseminating translated scientific information.
- Seeking improvements in State-level building codes or land-use mandates.
- Improving the practices of local building and planning departments.
- Improving the practices of the private engineering and design communities.

Preuss and Hebenstreit (this volume) develop a method for assessing multiple hazards created by tsunamis and apply that method to estimating impacts on coastal communities. The method includes (1) identifying the tsunami hazard using numerical simulation of wave direction and height; (2) analyzing the vulnerabilities of populations and land uses; (3) identifying secondary hazards—subsidence, battering, fire, and air contamination; and (4) delineating the hazard zones of tsunami impact, flooding, and subsidence, including the coastal highway system. Identifying the hazards and delineating the zones is difficult and requires specialized technical treatment. The authors, a planning consultant and an oceanographer, then relate these hazard zones to various impacts—casualties, damage, and socioeconomic disruption—and possible mitigation, response, and recovery techniques. Their work uses Grays Harbor, Washington, as a case study and is applicable to other areas and hazards.

Booth and Bethel (this volume) discuss four regulatory techniques for reducing earthquake hazards on undeveloped land: comprehensive land-use and development plans and policies, functional land-use plans, building codes, and zoning overlays. The authors, King County, Washington, geologists, identify and discuss five elements needed for any regulation to reduce earthquake hazards:

- Defining the hazard.
- Evaluating specific hazardous site conditions.
- Mapping of the hazard zones.
- Screening of development proposals.
- Adding appropriate conditions to the basic ordinance requirements.

King County used all four reduction techniques, and the authors were able to evaluate the effectiveness of these five elements. They conclude that the mapping and site-specific evaluations are particularly weak and are likely to

[1]Deceased.

be so in other jurisdictions. They then make pertinent recommendations to improve each of the above elements.

Perkins and Moy (this volume) examine the potential liability of local governments in Washington for losses in an earthquake. The Washington Tort Claims Act is analyzed, as well as legal concepts such as "act of God," negligence, discretionary immunity, and the public-duty doctrine. Pertinent case law is cited. The authors, a regional planner and an attorney, observe that the most likely source of liability for a local government is losses caused by the dangerous condition of its own property—hospitals, city hall, jails, and other public works. They make the following recommendations to local governments:

- Comply with all State and Federal regulations.
- Inspect, repair, and maintain public buildings and facilities.
- Use local government risk managers as allies in promoting safety.
- Do not assume that public liability exists for programs affecting private property.
- Act reasonably to promote public safety and welfare.

Kockelman (this volume) introduces 36 types of earthquake-hazard-reduction techniques and describes the following six, citing examples: preparing redevelopment plans, creating regulatory zones, securing nonstructural building components, informing the public, strengthening unreinforced masonry buildings, and making loss estimates. The specific objectives of these techniques are to create an awareness of, avoidance of, resistance to, response to, or recovery from the effects of an earthquake on people and their land uses, structures, and socioeconomic activities. The author, a planner, emphasizes that scientific and engineering studies are a prerequisite to the use of these reduction techniques. Thus, it is not prudent for urban planners to develop land-use regulations for civil engineers when designing structures and for lenders and public-works directors when adopting policies reducing earthquake hazards without scientific and engineering studies that assess the hazards.

TECHNIQUES FOR REDUCING EARTHQUAKE HAZARDS

By William J. Kockelman[1]

ABSTRACT

Six earthquake-hazard-reduction techniques are discussed: preparing redevelopment plans, creating regulatory zones, securing nonstructural building components, informing the public, strengthening unreinforced-masonry buildings, and making loss estimates. An overview of these techniques is useful to planners who prepare hazard-reduction programs, engineers who serve as advisors to local or State governments, and decisionmakers who select the most appropriate technique for a given situation.

INTRODUCTION

Many techniques for reducing earthquake hazards are available to planners, engineers, and decisionmakers. This report identifies 36 techniques and describes 6 in detail using examples. Some of these techniques, such as public acquisition of hazardous areas, are well known to the planning profession. Others, such as design of resistant structures, are commonly used by engineers. Still others, such as installation of warning systems and emergency preparedness, are obvious and practical but require maintenance and persistence in their implementation.

As an overview, the various techniques are listed in table 39. They are divided into six groups related to specific objectives; however, they can also be grouped in other ways, such as the following chronological order:

- Pre-earthquake mitigation techniques, which may take 1–20 years;
- Preparedness measures, which may take 1–20 weeks;
- Response during and immediately after an earthquake;
- Recovery operations after an earthquake, which may take 1–20 weeks; and
- Postearthquake reconstruction activities, which may take 1–20 years

These estimated time periods would vary depending upon the postulated or actual size of the earthquake, the damage it causes, and the resources available to a State, its communities, its corporations, and its citizens.

The specific objectives of the techniques listed in table 39 are to create an awareness of, avoidance of, resistance to, response to, or recovery from the effects of earthquake phenomena on people and their land uses, structures, and activities. The general goal of these objectives is to reduce human casualties, property damage, and socioeconomic interruptions. Many of the reduction techniques are complex, interconnected, and require special skills—legal, financial, legislative, design, economic, communications, educational, political, and engineering.

Many of the hazard-reduction techniques have been discussed and illustrated by Blair and Spangle (1979), Kockelman and Brabb (1979), Brown and Kockelman (1983), Kockelman (1985, 1986), Jochim and others (1988), Mader and Blair-Tyler (1988), Blair-Tyler and Gregory (1988), and the United Nations Office of the Disaster Relief Coordinator (Lohman and others, 1988).

Prerequisite to the use of these reduction techniques are scientific and engineering studies. Such studies are vital because, in the words of former U.S. Geological Survey director Walter C. Mendenhall, "There can be no applied science unless there is science to apply." Experience has shown that it is not prudent for urban planners to develop land-use regulations, civil engineers to design structures, and lenders and public-works directors to adopt policies reducing earthquake hazards without reliable scientific and engineering assessments.

The following six earthquake-hazard-reduction techniques and examples of how they are applied are detailed in this report:

1. Preparing redevelopment plans
2. Creating regulatory zones
3. Securing nonstructural building components
4. Informing the public
5. Strengthening unreinforced-masonry buildings
6. Estimating casualties, damage, and interruptions

[1]Deceased.

Table 39. Examples of various techniques for reducing earthquake hazards.

[(*), technique described in this report]

Incorporating hazard information into studies and plans:	Discouraging new development in hazardous areas:
Community-facilities inventories and plans	Adopting utility and public-safety service-area policies
Economic-development analyses and plans	Clarifying the liability of developers and government officials
Emergency and public-safety plans	Creating financial incentives and disincentives
Land-use and transportation inventories and plans	*Informing and educating the public
*Redevelopment plans (pre-earthquake and postearthquake)	Posting public signs that warn of potential hazards
Utility inventories and plans	Requiring nonsubsidized insurance related to the level of hazard
Regulating development:	**Strengthening, converting, or removing unsafe structures:**
*Creating special hazard-reduction zones and regulations	Condemning and demolishing unsafe structures
Enacting building and grading ordinances	Reducing land-use intensity or building occupancy
Enacting subdivision ordinances	Relocating community facilities and utilities
Requiring engineering, geologic, and seismologic reports	Repairing unsafe dams or lowering their impoundments
Requiring investigations in hazardous areas	Retrofitting bridges and overpasses
Reviewing annexation, project, and rezoning applications	*Strengthening unreinforced-masonry buildings
Siting, designing, and building safe structures:	**Preparing for and responding to emergencies and disasters:**
Evaluating specific sites for hazards	Conducting emergency or disaster training exercises
Reconstructing after a disaster	*Estimating casualties, damage, and socioeconomic interruptions
*Securing nonstructural building components and contents	Initiating community and corporate education programs
Selecting the most resistant building system and configuration	Operating monitoring, warning, and evacuation systems
Siting and designing critical facilities	Preparing emergency response and recovery plans
Training building designers and inspectors	Providing for damage inspection, repair, and recovery

These techniques are discussed and illustrated for nontechnical readers. The references cited for each technique will provide both scholars and practitioners with more details and examples.

ACKNOWLEDGMENTS

Earl Brabb and Albert Rogers of the U.S. Geological Survey and Jeanne Perkins of the Association of Bay Area Governments provided many valuable suggestions and critical comments that have improved this chapter. Special thanks are extended to Alice Olsen for word processing of the manuscript and to Barbara Hillier for editing.

PREPARING REDEVELOPMENT PLANS

Incorporating earthquake-hazard information into designs for the development or redevelopment of a community's land use, housing, transportation, and other public facilities is a common natural-hazard-reduction technique. One of the designs is the redevelopment plan. Most States authorize the creation of public redevelopment agencies that provide for the preparation and adoption of redevelopment plans; the acquisition, clearance, disposal, reconstruction, and rehabilitation of blighted (including damaged) areas; and the relocation of persons. These redevelopment agencies usually are empowered to issue bonds, receive part of the taxes levied on property included in the project, and use grants or loans available under various State and Federal programs. Redevelopment plans may be divided into three categories:

1. Those that incorporate damaged areas into redevelopment plans that had been created prior to damaging earthquakes
2. Those that include vulnerable structures (identified prior to an earthquake) in the redevelopment plans
3. Those that include damaged areas in redevelopment plans that are created after an earthquake

Santa Rosa, Calif., a city of about 50,000 people, has a redevelopment plan that illustrates the first category. Two earthquakes struck within 2 hours in 1969, and many old unreinforced-masonry buildings were damaged. Mader and others (1980, p. C1–C15) reported the following:

> In 1961, Santa Rosa embarked on a redevelopment project covering part of the downtown area. Just prior to the earthquakes, the city had adopted a central business district plan which covered an area adjacent to the redevelopment area. After the earthquakes, this area, with a high percentage of damaged buildings, was added to the original redevelopment area.

Figure 226. Part of the Santa Rosa, Calif., urban-renewal project area. Light shade, Phase I—the original project area; medium shade, Phase II—the area added following two 1969 earthquakes; black, Phase III—the area surveyed for additional land required for a regional shopping center. Modified from Mader and others (1980, p. C–8, fig. 7).

The time and effort required to get the revised redevelopment project funded and underway after the earthquakes was significantly shortened because of the existence of an up-to-date plan (fig. 226) adopted prior to the earthquakes.

Spangle and others (1987, app. A) described the second category—incorporating vulnerable structures identified prior to an earthquake into the redevelopment plan. It is a new technique called pre-earthquake planning for postearthquake rebuilding (PEPPER). It includes four pre-earthquake activities: evaluation of vulnerability to damage; organization for preparedness and response; mitigation of hazards; and planning for postearthquake response. Spangle and others (1987) believed it possible to develop damage estimates sufficiently accurate for pre-earthquake programming of postearthquake recovery activities and to define the nature of the postearthquake recovery organization needed.

The Whittier City Redevelopment Agency (1987) adopted a plan for Whittier, Calif., that represents the third category—redevelopment plans created after an earthquake. The plan provides for redevelopment powers to be used for projects to maintain, repair, restore, demolish, or replace property or facilities damaged or destroyed as a result of an earthquake in 1987. The earthquake damage in Whittier exceeded $70 million in 1987 dollars.

Preparing and implementing redevelopment plans that recognize and reduce earthquake hazards is very important because postearthquake reconstruction commonly takes place in the same hazardous areas. Youd and others (1978, p. 1111), for example, observed that after the 1971 San Fernando earthquake, "***buildings had been repaired, new buildings have been built, and a freeway interchange has been constructed across the trace of the 1971 fault rupture."

CREATING REGULATORY ZONES

Various types of land-use and land-development regulations meant to reduce earthquake hazards are available to State and local governments. Controlling use and development with regulatory zones can be one of the most economical and effective means available to government agencies. The regulations can be used to reduce damage from earthquake hazards such as a surface-fault rupture, ground shaking, liquefaction, landslides, and tsunamis. They may be divided into four categories:

1. Regulations requiring site investigations and building setbacks
2. Regulations reducing the density of development or the number of occupants
3. Regulations permitting only less vulnerable land uses and land development
4. Regulations requiring special seismic-design and construction standards

The first category can be illustrated by the Alquist-Priolo Special Studies Zone Act enacted by the California

Legislature (1972). The act provides for public safety by restricting development near or over the surface traces of active faults (fig. 227). In addition, the act requires or provides for geologic reports, approval of projects by cities and counties, and the charging of reasonable fees for administrative costs. The California State Geologist delineates appropriately wide zones that include "all potentially and recently active traces" of faults that "he deems sufficiently active and well defined to constitute a potential hazard to structures from surface faulting or fault creep" (Hart, 1988, app. A).

Before approval of any project in these zones, cities and counties must require "a geologic report defining and delineating any hazard of surface fault rupture." The legislature defines a project as including structures for human occupancy and subdivisions that contemplate the eventual construction of structures for human occupancy. The legislature exempts single-family wood-frame buildings (including mobile homes) not exceeding two stories when not part of a development of four or more dwellings. The approval of a project must be in accord with the policies and criteria established by the California Mining and Geology Board. The board prohibits a project from crossing the trace of an active fault (Hart, 1988, app. B), requires a geologic report if a project lies within 15 m of an active fault trace, and requires a registered geologist retained by the city or county to evaluate such reports. The act also allows cities and counties to establish more restrictive policies and criteria. Some local jurisdictions, such as the Portola Valley Town Council (1973), require multifamily buildings to be set back 40 m or more from fault traces.

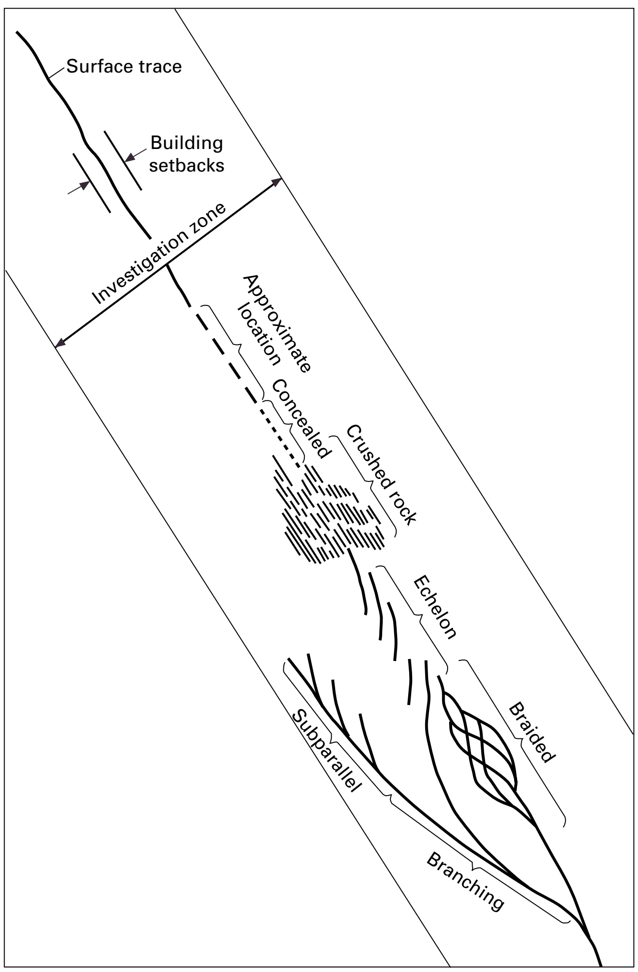


Figure 227. Hypothetical surface-fault-rupture regulatory zone in California showing different ways that the ground may break. The figure shows the complex faulting (solid, dashed, and dotted lines), the minimum 300-m-wide investigation zone required by the Alquist-Priolo Special Studies Zones Act, and the 15-m building setbacks required by the California Mining and Geology Board. From Brown and Kockelman (1983, p. 8, fig. 30).

The San Mateo County Board of Supervisors (1973) is using the second category—reducing the density of development. San Mateo County, Calif., has a resource-management zoning district that also carries out the objectives and policies of the county's open-space and resource-conservation plans. The district regulations limit the number of dwellings in zones with a surface-fault-rupture hazard, flood hazard, or unstable slopes to one unit per 16 hectares (40 acres) and require geologic site investigations to ensure that the reduced development is in nonhazardous areas (fig. 228). The lower net number of dwellings permitted may then be clustered at a higher density in the nonhazardous areas.

An example of the third category—permitting only less vulnerable land uses—can be seen in Colorado, where geologic hazards have been declared by the State legislature to be matters of State interest. To assist communities in designing land-use regulations, the Colorado Geological Survey prepared model geologic-hazard-area control regulations for adoption by local governments. The regulations permit only the following uses in areas designated geologically hazardous: (1) agricultural uses such as general farming, grazing, truck farming, forestry, sod farming, and wild-crop harvesting; (2) industrial/commercial uses such as loading areas, parking areas not requiring extensive grading or impervious paving, and storage yards for equipment or machinery easily moved or not subject to geologic-hazard damage; and (3) public and private recreational uses not requiring permanent structures designed for human habitation such as parks, natural swimming areas, golf courses, driving ranges, picnic grounds, wildlife and nature preserves, game farms, shooting preserves, target ranges, trap and skeet ranges, and hunting, fishing, skiing, and hiking areas, if such uses do not cause concentrations of people.

The fourth category is illustrated by a Redwood City Council (1974, 1977) ordinance in California that requires special seismic design and construction standards. These standards supplement those recommended by the International Conference of Building Officials (1991) for structures in seismic zone 4 under the Uniform Building Code—the code adopted by Redwood City as its own building code.

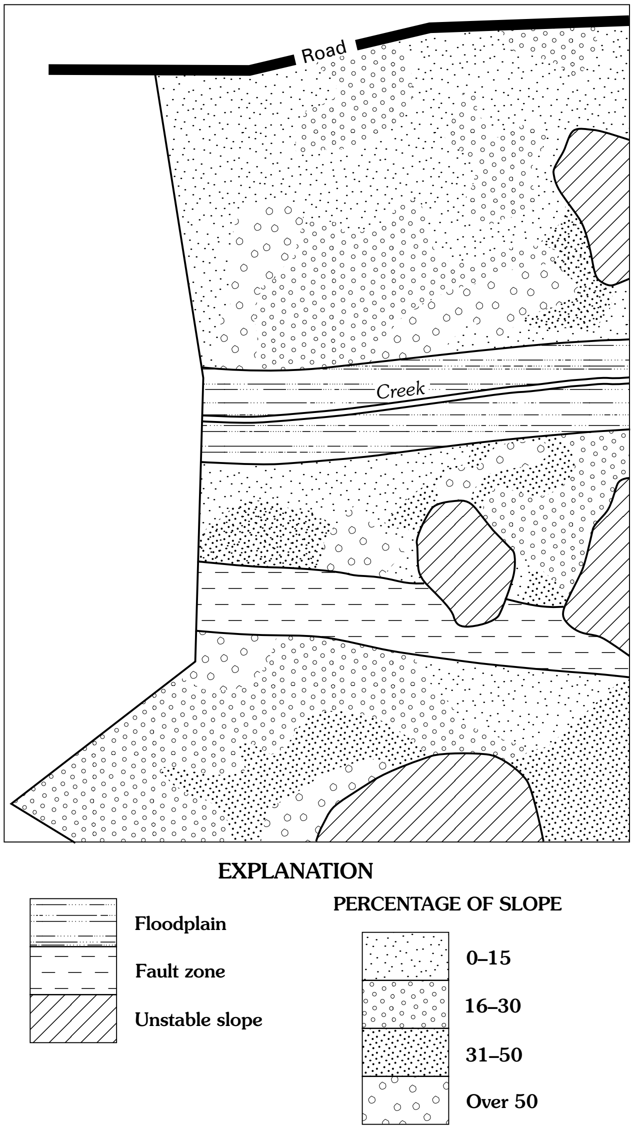


Figure 228. Regulatory zones in a hypothetical area of seismic and other geologic constraints. In San Mateo County, Calif., dwellings in floodplain, fault, and unstable slope zones are limited to one per 16 hectares (40 acres) by the San Mateo County Board of Supervisors (1973). Modified from Kockelman and Brabb (1979, p. 82, fig. 6).

The ordinance is consistent with the city's initial Seismic Safety Element (Redwood City Planning Department, 1974), which had placed the mud around the margins of San Francisco Bay in a moderately high-seismic-risk zone and recommended that the Uniform Building Code be reviewed and amended as "frequently as may be prudent." The supplemental standards called for in the city's ordinance relate to special foundation-design criteria, design provisions for greater lateral force, foundation systems to resist settlement, wood-frame sheathing, moment-resisting frames, response spectrum, reinforced-masonry construction, elements of structural redundancy, and reinforcement of structural members. These standards apply only to those lands within the city that are underlain by bay mud, as shown on a map adopted for the ordinance (fig. 229).

SECURING NONSTRUCTURAL BUILDING COMPONENTS

Proper siting, design, and construction of structures are well-known techniques for reducing earthquake casualties and damage, but often the contents and other nonstructural components of buildings are overlooked. People have been injured by falling light fixtures, flying glass, overturned shelves, and spilled chemicals. The Federal Emergency Management Agency (1981, table 2) (FEMA) estimates that one-third of the property lost in future earthquakes will be building contents. Such contents are only one part of the nonstructural components of buildings.

Nonstructural damage is caused by object inertia or distortion of the structure. For example, if an office computer is shaken, only friction will restrain it from sliding toward its user. As a structure bends or distorts, its windows, partitions, and other items are stressed, causing them to shatter, crack, or spring out of place. There are measures that can be taken to protect nonstructural components, among which are the following:

- Attaching sharp or heavy office equipment and fixtures to the floor or walls
- Attaching artwork securely to walls
- Connecting filing cabinets at their tops and to a wall
- Arranging free-standing, movable partitions in a zigzag pattern
- Installing locks on cupboards
- Boxing large containers that contain hazardous chemicals
- Strapping hot-water heaters to wall studs

An excellent guidebook on reducing the risk of nonstructural earthquake damage was prepared by Reitherman (1983). He described typical conditions found in office, retail, and government buildings. Measures are suggested for restraining more than 20 nonstructural building components such as office machines, electrical equipment, file cabinets, partitions, suspended ceilings, exterior ornamentation, elevators, piping, stairways, and parapets. Each component is rated for existing and upgraded vulnerability to life-safety hazards, percent of replacement-value damaged, and postearthquake outages for three levels of shaking intensity (fig. 230).

A second guidebook (Washington State Superintendent of Public Instruction, 1989) focuses on procedures for reducing nonstructural hazards in schools. This guidebook, issued by the Washington State Superintendent of Public Instruction, contains drawings of methods for securing hazardous objects commonly found in schools. The objects include ceiling panels, chemicals, doors, exterior chimneys, exterior

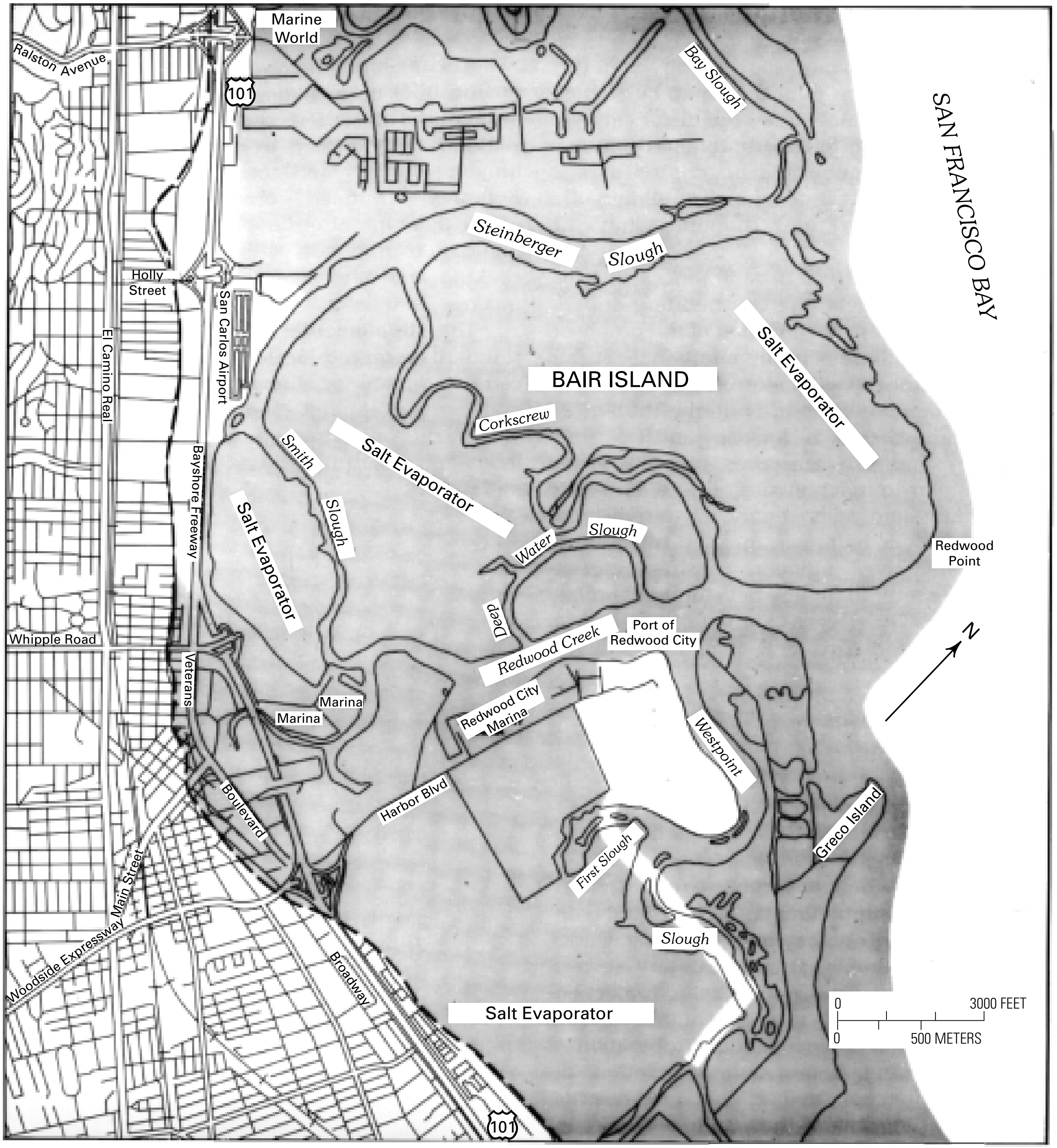
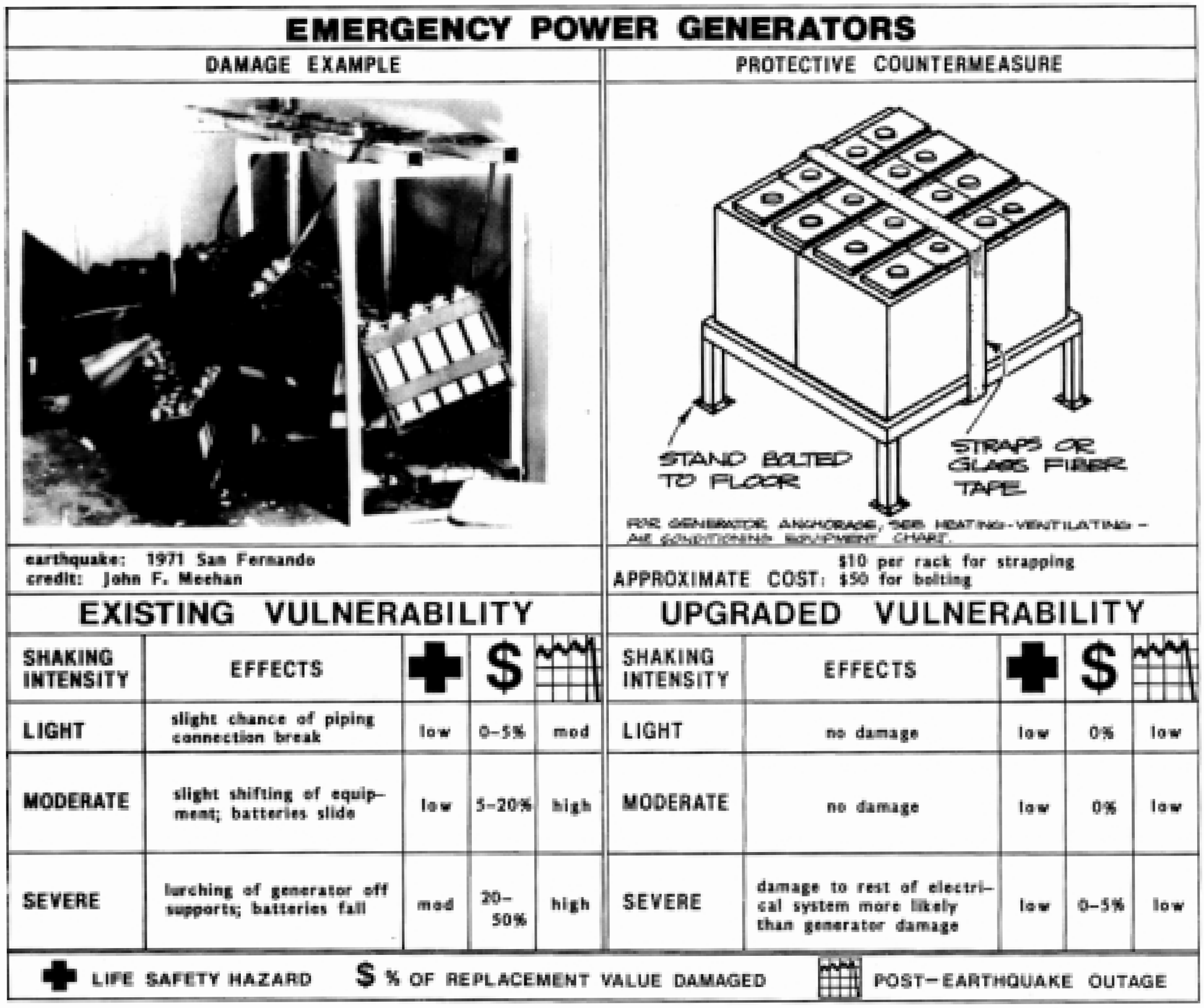


Figure 229. Map included with the Redwood City, Calif., ordinance that requires special seismic-design and construction standards for all new development on San Francisco Bay mud deposits. Bay mud is indicated by shading; its southwestern boundary is the dashed line. The unshaded areas lie outside the city's jurisdiction. From Redwood City Council (1977).

masonry, parapets, furniture, file cabinets, windows, mirrors, skylights, heaters, light fixtures, partitions, and water heaters. A general estimate of the earthquake risk for each object and the cost to secure each are provided. In addition, checklists for school administrators and custodians are included for both interior hazards, such as ceilings, floors, walls, boiler rooms, cafeterias, halls, stairways, and laboratories, and exterior hazards such as chimneys, ornaments, and parapets.

The application of such techniques to another type of public building was made by the city of Mountain View, Calif. Blair-Tyler and Gregory (1988, p. 19) observed that



EMERGENCY POWER GENERATORS

DAMAGE EXAMPLE	PROTECTIVE COUNTERMEASURE
earthquake: 1971 San Fernando credit: John F. Meehan	APPROXIMATE COST: $10 per rack for strapping $50 for bolting

EXISTING VULNERABILITY

SHAKING INTENSITY	EFFECTS	Life safety hazard	% of replacement value damaged	Post-earthquake outage
LIGHT	slight chance of piping connection break	low	0–5%	mod
MODERATE	slight shifting of equipment; batteries slide	low	5–20%	high
SEVERE	lurching of generator off supports; batteries fall	mod	20–50%	high

UPGRADED VULNERABILITY

SHAKING INTENSITY	EFFECTS	Life safety hazard	% of replacement value damaged	Post-earthquake outage
LIGHT	no damage	low	0%	low
MODERATE	no damage	low	0%	low
SEVERE	damage to rest of electrical system more likely than generator damage	low	0–5%	low

✚ LIFE SAFETY HAZARD $ % OF REPLACEMENT VALUE DAMAGED POST–EARTHQUAKE OUTAGE

Figure 230. An example of how to reduce the risk of earthquake damage to one type of nonstructural building component. From Reitherman (1983, p. 39).

the city had consultants prepare a room-by-room inventory of nonstructural hazards in the Emergency Operations Center—an alternate City Hall that would be used in the aftermath of an earthquake. Blair-Tyler and Gregory (1988) reported the following:

> Communications equipment was braced and interior glass is being replaced with safety glass or covered with a safety film. The City's maintenance staff is providing the estimated 320 man-hours to complete the nonstructural work during the next year. Any structural strengthening will be done by an outside contractor. Information gained from this experience will be used to reduce nonstructural hazards in the design of Mountain View's new Library and City Hall.

INFORMING THE PUBLIC

A fourth earthquake-hazard-reduction technique involves bringing earthquake-hazard information to the attention of the public. Both pre-earthquake and postearthquake hazard-reduction programs depend on the understanding and support of an informed public. Responsible developers and prudent citizens, when told of possible earthquake hazards, would not wish to risk property losses or expose their clients or families to danger and trauma. Preparing, announcing, and disseminating information on possible earthquake damage, risk, and hazard-reduction techniques can be accomplished in many ways (see examples in tables 40 and 41).

STRENGTHENING UNREINFORCED-MASONRY BUILDINGS

Many techniques for strengthening, converting, or removing unsafe structures are available to State and local governments. One practice, strengthening unreinforced-masonry buildings, has been used by several communities. California has begun the first phase of this process, the identification of unsafe buildings by cities and counties.

These structures include unreinforced-masonry bearing-wall buildings and steel- and concrete-frame buildings with infill walls of unreinforced masonry. According to the California Seismic Safety Commission (1987, p. 2), these structures typically have four weaknesses:

1. Masonry walls, lacking reinforcement, cannot resist earthquake shaking without degrading, which sometimes leads to collapse.
2. The practice of not structurally tying the walls to the roof and floor can allow excessive movements in the walls, which may lead to collapse.
3. Ground floors with open fronts and little crosswise bracing may allow excessive movement and twisting motions, damaging the building.
4. Unbraced parapets may fall into the street.

An ordinance adopted by the Los Angeles City Council (1981) outlines procedures and standards for identifying and classifying buildings having unreinforced-masonry bearing walls; these procedures and standards are based on a building's present use and occupancy (fig. 231). Priorities, deadlines, and standards are also established under which buildings are required to be structurally analyzed and anchored. Whenever analysis determines deficiencies, the ordinance requires that the building be strengthened or removed. The ordinance applies to all buildings having bearing walls of unreinforced masonry that were constructed before 1933 or those structures for which a building permit was issued prior to 1933, the effective date of the city's first seismic building code. The ordinance does not apply to detached one- or two-story single-family dwellings and detached apartment houses containing less than five dwelling units and used solely for residential purposes.

Affected buildings are classified according to type of function and occupancy as essential, high risk, medium risk, and low risk (see SEC. 91.6803 in fig. 231). The strengthening standards and time schedules for notification and compliance vary with the risk category. A structural analysis of each building is also required in order to determine the remedial measures necessary to meet the appropriate standards. The city provides a specific time schedule.

An alternative compliance schedule, intended to lessen the financial and social impacts of the ordinance, gives a building owner the option of performing part of the remedial work within 1 year of notification in exchange for a longer time in which to reach full compliance. The work to be performed within that year involves the anchoring of all unreinforced-masonry walls to roof and floor with bolts and washers. According to the Los Angeles City Planning Department (1979, p. 5), this procedure yields an immediate and substantial improvement in safety for perhaps one-fifth the cost of full compliance.

Using the knowledge and experience gained from the procedures used in Los Angeles, the California Legislature (1986) requires all cities and counties in seismic zone 4 to identify hazardous unreinforced-masonry buildings, notify the building owners, and establish a mitigation program. Local building departments are authorized to establish fees to recover the costs of identification. The California Legislature (1986) specifies that the mitigation program may include the following:

> The adoption by ordinance of a hazardous buildings program, measures to strengthen buildings, measures to change the use to acceptable occupancy levels or to demolish the building, tax incentives available for seismic rehabilitation, low-cost seismic rehabilitation loans, * * * application of structural standards necessary to provide for life safety above current code requirements, and other incentives to repair the buildings which are available from federal, state, and local programs.

Compliance with a hazardous-buildings ordinance or mitigation program is the responsibility of building owners. Nothing in the law makes any local government responsible for paying the cost of strengthening a privately owned structure, reducing the occupancy, demolishing a structure, preparing engineering or architectural analyses, conducting investigations, or other costs associated with compliance of locally adopted mitigation programs.

A guidebook addressing the hazards of unreinforced-masonry buildings has been developed by the California Seismic Safety Commission (1987). The guidebook contains a series of steps for both identifying potentially hazardous buildings and developing and implementing a hazard-mitigation program, including a model ordinance that provides for strengthening or removal of unsafe buildings. Other discussions include costs to local government, costs to building owners, incentives, and sources of information.

Some of the advantages of such ordinances are that deaths and injuries will be substantially reduced, economically obsolete buildings may eventually be removed, land will be reused more efficiently, and repair or demolition will provide work for the construction industry. Some of the disadvantages of such ordinances are that some low-income housing may be lost, tenants probably will have to be relocated, and businesses could be interrupted.

ESTIMATING CASUALTIES, DAMAGE, AND INTERRUPTIONS

Several techniques to assist State and local governments in preparing for, responding to, and recovering from earthquake emergencies and disasters are available. One of the techniques is commonly called a loss estimate. A National Research Council (1989) panel defines an earthquake loss estimate as "a forecast of the effects of a hypothetical earthquake. Depending on its purpose, a loss study may include estimates of deaths and injuries; property losses; loss of function in industries, lifelines, and emergency facilities; homelessness; and economic impacts." These estimates are effective techniques in creating public awareness of hazards and support for preparedness measures and response and recovery operations. Three examples of loss estimates follow.

Table 40. Examples of information and dissemination techniques for informing the public about earthquake hazards.

General, introductory, and index materials

"Washington State Earthquake Hazards" (Noson and others, 1988)
"Facing Geologic and Hydrologic Hazards—Earth-Science Considerations" (Hays, 1981)
A newspaper home-guide section on how a house withstands an earthquake, by Kerch (1988)
"Getting Ready for a Big Quake" (Sunset Magazine, 1982)
"Seismic Hazards of Western Washington and Selected Adjacent Areas—Bibliography and Index" (Manson, 1988)
"Policy Recommendations" (Washington State Seismic Safety Council, 1986)

Serial publications

Oregon Geology (published bimonthly by the Oregon State Department of Geology and Mineral Industries)
Earthquake hazard-reduction booklets published by the Federal Emergency Management Agency (see table _3_)
Earthquakes and Volcanoes (formerly the Earthquake Information Bulletin, published by the U.S. Geological Survey beginning 1971)
Washington Geologic Newsletter (published quarterly by the Washington State Division of Geology and Earth Resources)
Wasatch Front Forum (published quarterly by the Utah Geological and Mineral Survey beginning 1984)

Guidebooks and guidelines

"The Next Big Earthquake in the Bay Area May Come Sooner Than You Think" (U.S. Geological Survey, 1991)
"Geologic Principles for Prudent Land Use—A Decisionmaker's Guide for the San Francisco Bay Region" (Brown and Kockelman, 1983)
"An Earthquake Advisor's Handbook for Wood-Frame Houses" (University of California Center for Planning and Development Research, 1982)
"Reducing Earthquake Risks—A Planner's Guide" (Jaffe and others, 1981)
"Preparing a Safety Element of the City and County General Plan" (Mintier, 1987, p. 146–153)
"California at Risk—Steps to Earthquake Safety for Local Government" (Mader and Blair-Tyler, 1988)
"Landslide Loss Reduction—A Guide for State and Local Government Planning" (Wold and Jochim, 1989)

Conferences and workshops

"Governor's Conference on Geologic Hazards" (Utah Geological and Mineral Survey, 1983)
"Proceedings of Conference XLVIII—3d Annual Workshop on Earthquake Hazards in the Puget Sound, Portland, Area" (Hays, 1989)
"Proceedings of Conference XLIIV—A Workshop on Evaluation of Earthquake Hazards and Risk in the Puget Sound and Portland Areas" (Hays, 1988)
"Workshop on Future Directions in Evaluating Earthquake Hazards of Southern California, Proceedings of Conference XXXII, Nov. 12–13, 1985, Los Angeles, Calif." (Brown and others, 1986)
"Third International Earthquake Microzonation Conference, Proceedings, June 28-July 1, 1982, Seattle, USA" (Sherif, 1982 [particularly sessions 3, 6, and 10])

Outreach programs

"The Circuit-Rider Geologist in the State of Washington" (Thorsen, 1981)
"Engineering Geology at the Local Government Level—Planning, Reviewing, and Enforcement" (McCalpin, 1985)
"Advisory Services [of the California Division of Mines and Geology]" (Amimoto, 1980)
Educational, advisory and review services provided by the Southeastern Wisconsin Regional Planning Commission
Emergency Management Institute's mitigation and natural hazards curriculum (Federal Emergency Management Agency, 1991, p. 37–43)
"Perspectives on Public Information and Awareness Programs in the Puget Sound, Washington, Area" (Martens, 1988)
"Final Technical Report—Wasatch Front County Hazards Geologist Program" (Christenson, 1988)

Discussions of adopted reduction techniques

"Anticipating Earthquakes—Risk Reduction Policies and Practices in the Puget Sound and Portland Areas" (May, 1989)
"Washington State School Earthquake Emergency Planning" (Noson and Martens, 1987)
"Hazardous Buildings—Case Studies" (Bay Area Regional Earthquake Preparedness Project, 1988)
"Using Earth-Science Information for Earthquake-Hazard Reduction" (Kockelman, 1985)
"Putting Seismic Safety Policies to Work" (Blair-Tyler and Gregory, 1988)
"Examples of Seismic Zonation in the San Francisco Bay Region" (Kockelman and Brabb, 1979)

Table 41. Federal Emergency Management Agency (FEMA) earthquake-hazards-reduction reports available to the public.

[Modified from an Earthquake-Hazards-Reduction Series (EHRS) list prepared by the Federal Emergency Management Agency (1989). Publications are free of charge; copies may be obtained by writing to Federal Emergency Management Agency, P.O. Box 70274, Washington, D.C. 20024]

EHRS number	Title	FEMA number
1	Reducing the risks of nonstructural earthquake damage: A Practical guide (June 1985, 87 p.)	74
2	Comprehensive earthquake preparedness planning guidelines: City (May 1985, 94 p.)	73
3	Comprehensive earthquake preparedness planning guidelines: County (May 1985, 107 p.)	72
4	Comprehensive earthquake preparedness planning guidelines: Corporate (May 1985, 57 p.)	71
5	Earthquake preparedness information for people with disabilities (May 1985, 16 p.)	70
6	Pilot project for earthquake hazard assessment (May 1985, 108 p.)	69
7	Earthquake insurance: A public policy dilemma (May 1985, 67 p.)	68
8	Earthquake public information materials: An annotated bibliography (September 1986, 92 p.)	67
12	Guidelines for local small businesses in meeting the earthquake threat (September 1985, 16 p.)	87
13	Societal implications: A community handbook (June 1985, 54 p.)	83
14	Societal implications: Selected readings (June 1985, 148 p.)	84
15	Proceedings: Workshop on reducing seismic hazards of existing buildings (December 1985, 214 p.)	91
16	An action plan for reducing earthquake hazards of existing buildings (December 1985, 75 p.)	90
17	NEHRP (National Earthquake Hazard Reduction Program) recommended provisions for the development of seismic regulations for new buildings, part 1: Provisions (January 1992, 199 p.)	222
18	NEHRP recommended provisions for the development of seismic regulations for new buildings, part 2: Commentary (February 1986, 200 p.)	96
19	NEHRP recommended provisions for the development of seismic regulations for new buildings, part 3: Appendix (February 1966, 142 p.)	97
20	Improving seismic safety of new buildings: A nontechnical explanation of NEHRP provisions (March 1986, 64 p.)	99
21	Guidelines for preparing code changes based on the NEHRP recommended provisions (March 1986, 120 p.)	98
22	Preparedness in apartments and mobile homes (September 1986, 15 p.)	L–143
23	A guide to marketing earthquake preparedness: Community campaigns that get results (September 1986, 39 p.)	111
24	Marketing earthquake preparedness: Community campaigns that get results (September 1986, 39 p.)	112
25	Guide to application of the NEHRP recommended provisions in earthquake-resistant building design (July 1987, 360 p.)	140
26	Abatement of seismic hazards to lifelines, Volume I: Water and sewer (July 1987, 185 p.)	135
27	Abatement of seismic hazards to lifelines, Volume II: Transportation (July 1987, 163 p.)	136
28	Abatement of seismic hazards to lifelines, Volume III: Communications (July 1987, 103 p.)	137
29	Abatement of seismic hazards to lifelines, Volume IV: Power (July 1987, 79 p.)	138
30	Abatement of seismic hazards to lifelines, Volume V: Gas and liquid fuels (July 1987, 135 p.)	139
31	Abatement of seismic hazards to lifelines, Volume VI: Papers on political, economic, social, legal, and regulatory issues (August 1987, 237 p.)	143
32	Abatement of seismic hazards to lifelines: An action plan (August 1987, 241 p.)	142
33	Comprehensive earthquake preparedness planning guidelines: Large city (September 1987, 61 p.)	146
34	Seismic considerations: Elementary and secondary schools (April 1988, 105 p.)	149
35	Seismic considerations: Health-care facilities (May 1990, 102 p.)	150
36	Seismic considerations: Hotels and motels (May 1990, 106 p.)	151
37	Seismic considerations: Apartment buildings (November 1988, 120 p.)	152
38	Seismic considerations: Office buildings (November 1988, 110 p.)	153
39	Typical costs for seismic rehabilitation of existing buildings, Volume I: Summary (July 1988, 65 p.)	156
40	Typical costs for seismic rehabilitation of existing buildings, Volume II: Supporting documentation (September 1988, 150 p.)	157
41	Rapid visual screening of buildings for potential seismic hazards: A handbook (July 1988, 185 p.)	154
42	Rapid visual screening of buildings for potential seismic hazards: Supporting documentation (September 1988, 137 p.)	155
43	Earthquake damaged buildings: An overview of heavy debris and victim extrication (September 1988, 95 p.)	158
44	Differences between the 1985 and 1988 editions of the NEHRP recommended provisions for the development of seismic regulations for new buildings (October 1988, 46 p.)	162
45	Establishing programs and priorities for the seismic rehabilitation of buildings: A handbook (May 1989, 122 p.)	174

Table 41. Federal Emergency Management Agency (FEMA) earthquake-hazards-reduction reports available to the public—Continued.

EHRS number	Title	FEMA number
46	Establishing programs and priorities for the seismic rehabilitation of buildings: Supporting report (May 1989, 190 p.)	173
47	A handbook for seismic evaluation of existing buildings [preliminary] (June 1989, 169 p.)	178
48	Seismic evaluation of existing buildings: Supporting documentation (May 1989, 160 p.)	175
49	Techniques for seismically rehabilitating existing buildings [preliminary] (May 1989, 172 p.)	172
50	Estimating losses from future earthquakes: Panel report [a nontechnical summary] (June 1989, 82 p.)	176
51	Estimating losses from future earthquakes [panel report and technical background] (June 1989, 231 p.)	177
52	Landslide loss reduction: A guide for state and local government planning (August 1989, 50 p.)	182
53	Estimated future earthquake losses for St. Louis city and county, Missouri (June 1990, 204 p.)	192
53A	Estimated future earthquake losses for St. Louis city and county, Missouri: Executive summary (June 1990, 10 p.)	192A
54	Financial incentives for seismic rehabilitation of hazardous buildings, An agenda for action, Volume I: Findings, conclusions, and recommendations (September 1990, 102 p.)	198
55	Financial incentives for seismic rehabilitation of hazardous buildings, An agenda for action, Volume II: State and local case studies and recommendations (September 1990, 128 p.)	199
56	Earthquake resistant construction of electric transmission and telecommunication facilities serving the Federal government: Report (September 1990, 41 p.)	202
57	Financial incentives for seismic rehabilitation of hazardous buildings, An agenda for action, Volume III: Applications workshops report (July 1991, 187 p.)	216
58	Seismic vulnerability and impact of disruption of lifelines in the conterminous United States (September 1991, 439 p.)	224
59	Colocation impacts on the vulnerability of lifelines during earthquakes with applications to Cajon Pass, California: Study overview (October 1991, 20 p.)	221
60	Inventory of lifelines in the Cajon Pass, California (February 1992, 92 p.)	225
61	Colocation impacts on the vulnerability of lifelines during earthquakes with applications to the Cajon Pass, California (February 1992, 103 p.)	226
62	A benefit-cost model for the seismic rehabilitation of buildings, Volume I: A user's manual (April 1992, 115 p.)	227
63	A benefit-cost model for the seismic rehabilitation of buildings, Volume II: Supporting documentation (April 1992)	228
64	NEHRP recommended provisions for the development of seismic regulations for new buildings and NEHRP map, part 1 (January 1992, 199 p.)	222
65	NEHRP recommended provisions for the development of seismic regulations for new buildings, part 2: Commentary (January 1992, 237 p.)	223

The Federal Emergency Management Agency (1981) estimated the number of dead and hospitalized, the number of injured but not hospitalized, and losses to buildings and their contents resulting from postulated earthquakes in four California locations (table 42). In addition, damage to or impact on selected facilities was discussed as were post-seismic needs; these included temporary housing, key communication facilities, military command circuits, all transportation modes, businesses, and industries. FEMA and the California Office of Emergency Services then conducted an analysis of readiness for each of these categories and discussed Federal, State, and local responses and response planning.

The second example of a loss estimate was prepared by Davis and others (1982). They created a planning scenario for a postulated earthquake in the Los Angeles region that can be used to gauge the severe impact on this urban area by assessing the effects on principal lifelines for emergency planning purposes. An analysis of readiness can then be used to provide planning insights, recommend further work, and serve as a basis for making or improving emergency preparedness, response, recovery, and reconstruction plans.

Davis and others (1982) included individual scenarios that show damage to lifelines such as highways, airports, railroads, marine facilities, communication lines, water-supply and waste-disposal facilities, and electrical power, natural gas, and petroleum lines. The scenarios are based on evaluation of earthquake-engineering literature, comments

Figure 231 (overleaf). Part of the Los Angeles, Calif., earthquake-hazard-reduction ordinance requiring owners of buildings having unreinforced-masonry bearing walls constructed before 1933 to obtain a structural analysis. If the building does not meet the minimum standards, the owner is required to strengthen or remove it according to a specific time schedule. From Los Angeles City Council (1981).

Ordinance No. 154,807

An ordinance adding Division 68 of Article 1 of Chapter IX of the Los Angeles Municipal Code relative to earthquake hazard reduction in existing buildings.

Section 1. Article 1 of Chapter IX of the Los Angeles Municipal Code is hereby amended to add a Division 68 to read:

DIVISION 68 — EARTHQUAKE HAZARD REDUCTION IN EXISTING BUILDINGS

SEC. 91.6801. PURPOSE:

The purpose of this Division is to promote public safety and welfare by reducing the risk of death or injury that may result from the effects of earthquakes on unreinforced masonry bearing wall buildings constructed before 1934. Such buildings have been widely recognized for their sustaining of life hazardous damage as a result of partial or complete collapse during past moderate to strong earthquakes.

The provisions of this Division are minimum standards for structural seismic resistance established primarily to reduce the risk of life loss or injury and will not necessarily prevent loss of life or injury or prevent earthquake damage to an existing building which complies with these standards. This Division shall not require existing electrical, plumbing, mechanical or fire safety systems to be altered unless they constitute a hazard to life or property.

This Division provides systematic procedures and standards for identification and classification of unreinforced masonry bearing wall buildings based on their present use. Priorities, time periods and standards are also established under which these buildings are required to be structurally analyzed and anchored. Where the analysis determines deficiencies, this Division requires the building to be strengthened or demolished.

Portions of the State Historical Building Code (SHBC) established under Part 8, Title 24 of the California Administrative Code are included in this Division.

SEC. 91.6802. SCOPE:

The provisions of this Division shall apply to all builings constructed or under construction prior to October 6, 1933, or for which a building permit was issued prior to October 6, 1933, which on the effective date of this ordinance have unreinforced masonry bearing walls as defined herein.

EXCEPTION: This Division shall not apply to detached one or two story-family dwellings and detached apartment houses containing less than five dwelling units and used solely for residential purposes.

SEC. 91.6803. DEFINITIONS:

For purposes of this Division, the applicable definitions in Sections 91.2301 and 91.2305 of this Code and the following shall apply:

Essential Building: Any building housing a hospital or other medical facility having surgery or emergency treatment areas; fire or police stations; municipal government disaster operation and communication centers.

High Risk Building: Any building, not classified an essential building, having an occupant load as determined by Section 91.3301(d) of this Code of 100 occupants or more.

EXCEPTION: A high risk building shall not include the following:

1 Any building having exterior walls braced with masonry crosswalls or wood frame crosswalls spaced less than 40 feet apart in each story.

2. Any building used for its intended purpose, as determined by the Department, for less than 20 hours per week.

Historical Building: Any building designated as an historical building by an appropriate Federal, State or City jurisdiction.

Low Risk Building: Any building, not classified an essential building, having an occupant load as determined by Section 91.3301(d) of less than 20 occupants.

Medium Risk Building: Any building, not classified as a high risk building or an essential building, having an occupant load as determined by Section 91.3301(d) of 20 occupants or more.

Unreinforced Masonry Bearing Wall: A masonry wall having all of the following characteristics:

1. Provides the vertical support for a floor or roof.
2. The total superimposed load is over 100 pounds per linear foot.
3. The area of reinforcing steel is less than 50 percent of that required by Section 91.2418(e) of this Code.

SEC. 91.6804. RATING CLASSIFICATIONS:

The rating classifications as exhibited in Table No. 68-A are hereby established and each building within the scope of this Division shall be placed in one such rating classification by the Department. The total occupant load of the entire building as determined by Section 91.3301(d) shall be used to determine the rating classification.

EXCEPTION: For the purpose of this Division, portions of buildings constructed to act independently when resisting seismic forces may be placed in separate rating classifications.

TABLE NO. 68-A
RATING CLASSIFICATIONS

Type of Building	Classification
Essential Building	I
High Risk Building	II
Medium Risk Building	III
Low Risk Building	IV

SEC. 91.6805. GENERAL REQUIREMENTS:

The owner of each building within the scope of this Division shall cause a structural analysis to be made of the building by a civil or structural engineer or arthitect licensed by the State of California; and, if the building does not meet the minimum earthquake standards specified in this Division, the owner shall cause it to be structurally altered to conform to such standards; or cause the building to be demolished.

The owner of a building within the scope of this Division shall comply with the requirements set forth above by submitting to the Department for review within the stated time limits:

a. Within 270 days after the service of the order, a structural analysis. Such analysis which is subject to approval by the Department, shall demonstrate that the building meets the minimum requirements of this Division; or

b. Within 270 days after the service of the order, the structural analysis and plans for the proposed structural alterations of the building necessary to comply to the minimum requirements of this Division; or

c. Within 120 days after service of the order, plans for the installation of wall anchors in accordance with the requirements specified in Section 91.6808(c); or

d. Within 270 days after the service of the order, plans for the demolition of the building.

After plans are submitted and approved by the Department, the owner shall obtain a building permit, commence and complete the required construction or demolition within the time limits set forth in No. Table 68-B. These time limits shall begin to run from the date the order is served in accordance with Section 91.6806(a) and (b).

TABLE NO. 68-B
TIME LIMITS FOR COMPLIANCE

Required Action By Owner	Obtain Building Permit Within	Commence Construction Within	Complete Construction Within
Complete Structural Alterations or Building Demolition	1 year	180 days*	3 years
Wall Anchor Installation	180 days	270 days	1 year

*Measured from date of building permit issuance.

Owners electing to comply with Item c of this Section are also required to comply with Items b or d of this Section provided, however, that the 270-day period provided for in such Items b and d and the time limits for obtaining a building permit, commencing construction and completing construction for complete structural alterations or building demolition set forth in Table No. 68-B shall be extended in accordance with Table No. 68-C. Each such extended time limit, except the time limit for commencing construction shall begin to run from the date the order is served in accordance with Section 91.6806 (b). The time limit for commencing construction shall commence to run from the date the building permit is issued.

TABLE NO. 68-C
EXTENSIONS OF TIME AND SERVICE PRIORITIES

Rating Classification	Occupant Load	Extension of Time if Wall Anchors are Installed	Minimum Time Periods for Service of Order
I (Highest Priority)	Any	1 year	0
II	100 or more	3 years	90 days
III	100 or more	5 years	1 year
	More than 50, but less than 100	6 years	2 years
	More than 19, but less than 51	6 years	3 years
IV (Lowest Priority)	Less than 20	7 years	4 years

SEC. 91.6806. ADMINISTRATION:

(a) Service of Order. The Department shall issue an order, as provided in Section 91.6806(b), to the owner of each building within the scope of this Division in accordance with the minimum time periods for service of such orders set forth in Table No. 68-C. The minimum time period for the service of such orders shall be measured from the effective date of this Division. The Department shall upon receipt of a written request from the owner, order a building to comply with this Division prior to the normal service date for such building set forth in this Section.

(b) Contents of Order. The order shall be written and shall be served either personally or by certified or registered mail upon the owner as shown on the last equalized assessment, and upon the person, if any, in apparent charge or control of the building. The order shall specify that the building has been determined by the Department to be within the scope of this Division and, therefore, is required to meet the minimum seismic standards of this Division. The order shall specify the rating classification of the building and shall be accompanied by a copy of Section 91.6805 which sets forth the owner's alternatives and time limits for compliance.

(c) Appeal From Order. The owner or person in charge or control of the building may appeal the Department's initial determination that the building is within the scope of this Division to the Board of Building and Safety Commissioners. Such appeal shall be filed with the Board within 60 days from the service date of the order described in Section 91.6806(b). Any such appeal shall be decided by the Board no later than 60 days after the date that the appeal is filed. Such appeal shall be made in writing upon appropriate forms provided therefor, by the Department and the grounds thereof shall be stated clearly and concisely. Each appeal shall be accompanied by a filing fee as set forth in Table 4-A of Section 98.0403 of the Los Angeles Municipal Code.

Appeals or requests for slight modifications from any other determinations, orders or actions by the Department pursuant to this Division, shall be made in accordance with the procedures established in Section 98.0403.

(d) Recordation. At the time that the Department serves the aforementioned order, the Superintendent of Building shall file with the Office of the County Recorder a certificate stating that the subject building is within the scope of Division 68 — Earthquake Hazard Reduction in Existing Buildings — of the Los Angeles Municipal Code. The certificate shall also state that the owner thereof has been ordered to structurally analyze the building and to structurally alter or demolish it where compliance with Division 68 is not exhibited.

If the building is either demolished, found not to be within the scope of this Division, or is structurally capable of resisting minimum seismic forces required by this Division as a result of structural alterations or an analysis, the Superintendent of Building shall file with the Office of the County Recorder a certificate terminating the status of the subject building as being classified within the scope of Division 68 — Earthquake Hazard Reduction in Existing Buildings — of the Los Angeles Municipal Code.

(e) Enforcement. If the owner or other person in charge or control of the subject building fails to comply with any order issued by the Department pursuant to this Division within any of the time limits set forth in Section 91.6805, the Superintendent of Building shall order that the entire building be vacated and that the building remain vacated until such order has been complied with. If compliance with such order has not been accomplished within 90 days after the date the building has been ordered vacated or such additional time as may have been granted by the Board and the Superintendent may order its demolition in accordance with the provisions of Section 91.0103(o) of this Code.

SEC. 91.6807. HISTORICAL BUILDINGS:

(a) General. The standards and procedures established by this Division shall apply in all respects to an historical building except that as a means to preserve original architectural elements and facilitate restoration, an historical building may, in addition, comply with the special provisions set forth in this Section.

(b) Unburned Clay Masonry or Abode. Existing or re-erected walls of abode construction shall conform to the following:

1. Unreinforced abode masonry wall shall not exceed a height or length to thickness ratio of 5, for exterior bearing walls and must be provided with a reinforced bond beam at the top, interconnecting all walls. Minimum beam depth shall be 6 inches and a minimum width

Table 42. Estimated consequences of postulated catastrophic earthquakes occurring on four California faults at different times of the day.

[All estimates have an uncertainty factor of 2 to 3. Injuries not requiring hospitalization are estimated to be 15–30 times greater than the number of fatalities. Modified from Federal Emergency Management Agency (1981, p. 23, table 3)]

Fault	Time	Fatalities	Hospitalized
Northern San Andreas (near San Francisco).	2:30 a.m.	3,000	12,000
	2:00 p.m.	10,000	37,000
	4:30 p.m.	11,000	44,000
Hayward (near Oakland).	2:30 a.m.	3,000	13,000
	2:00 p.m.	8,000	30,000
	4:30 p.m.	7,000	27,000
Southern San Andreas (near Los Angeles).	2:30 a.m.	3,000	12,000
	2:00 p.m.	12,000	50,000
	4:30 p.m.	14,000	55,000
Newport-Inglewood (in Los Angeles).	2:30 a.m.	4,000	18,000
	2:00 p.m.	21,000	83,000
	4:30 p.m.	23,000	91,000

by numerous engineers and officials of public agencies, and judgments by the authors. The assessment evaluated the postearthquake performance of lifeline segments throughout the region. Figure 232 shows the communications map, which assesses telephone-system performance following the postulated earthquake. Other maps (water-supply and waste-disposal facilities, for example) show the locations and estimates of damage to specific facilities. Most of these planning maps contain notations that are explained further in their text, such as "Water deliveries through the MWD Upper Feeder will be temporarily interrupted by pipe rupture where this major transmission line crosses the Santa Ana River." The scenarios indicate that most of the lifelines will sustain significant damage that could require a major emergency-response effort. Each scenario map is accompanied by a discussion of the general patterns of earthquake effects, as in the following:

> Interstate 5 from the San Joaquin Valley and Interstate 15 through Cajon Pass will be closed, leaving U.S. 101 along the coast as the only major viable route open from the north. Highway connections with San Diego will remain open.

And,

> Not all of the [telephone] systems in the greater Los Angeles region are set up to process emergency calls automatically on previously established priority bases. Thus overloading of equipment still in service could be very significant.

Similar scenarios have been prepared for other postulated earthquakes, such as on the Hayward fault in the San Francisco Bay region, by Steinbrugge and others (1987).

The third example of a loss estimate was one prepared by the U.S. Geological Survey (1975). It postulated earthquakes for two locations in the Puget Sound, Wash., region and concluded that under the worst circumstances, there could be as many as 2,200 dead, 8,700 injured, and 23,500 homeless. Anticipated damage patterns for five counties in the region were also estimated for both events. The degree of impairment was assigned to selected critical facilities, equipment, or supplies (fig. 233). Detailed assessments are included, as in the following:

- Damage to hospitals having capacities of 50 or more beds
- Physician and nurse fatalities at nonhospital locations
- Losses of stock at retail drugstores and pharmacies
- Damage to railroad bridges and tunnels
- Probability of fatalities based upon siting of schools in areas of high damage intensities

These loss estimates, damage scenarios, and degrees of impairment are intended for planning purposes only, and some may consider them overly pessimistic. However, in emergency planning, it is important to plan for the most severe levels of casualties and socioeconomic disruption in order to be better able to prepare, respond, and recover.

PREREQUISITES FOR EARTHQUAKE-HAZARD-REDUCTION TECHNIQUES

Prerequisites for the selection and implementation of an appropriate earthquake-hazard-reduction technique from table 39 are as follows:

- Conducting scientific and engineering studies of the physical processes of earthquake phenomena—source, location, size, likelihood of occurrence, triggering mechanism, path, ground response, structure response, and equipment response
- Translating the results of such studies into reports and onto maps at an appropriate scale so that the nature and extent of the hazards and their effects are understood by nontechnical users
- Transferring this information to those who will need to use it and then assisting and encouraging them in its use

SCIENTIFIC AND ENGINEERING STUDIES

It is not prudent for planners to develop land-use regulations, engineers to design structures, and lenders and public-works directors to adopt policies reducing earthquake hazards without adequate and reliable scientific and engineering assessments. As an overview of some of these assessments, the nontechnical reader is referred to Hays (1989, p. 193–194, list 1). Many studies were envisioned and are described in the "Regional Earthquake Hazards Assessments" draft work plan for the Pacific Northwest by Hays (1988, p. 12–33).

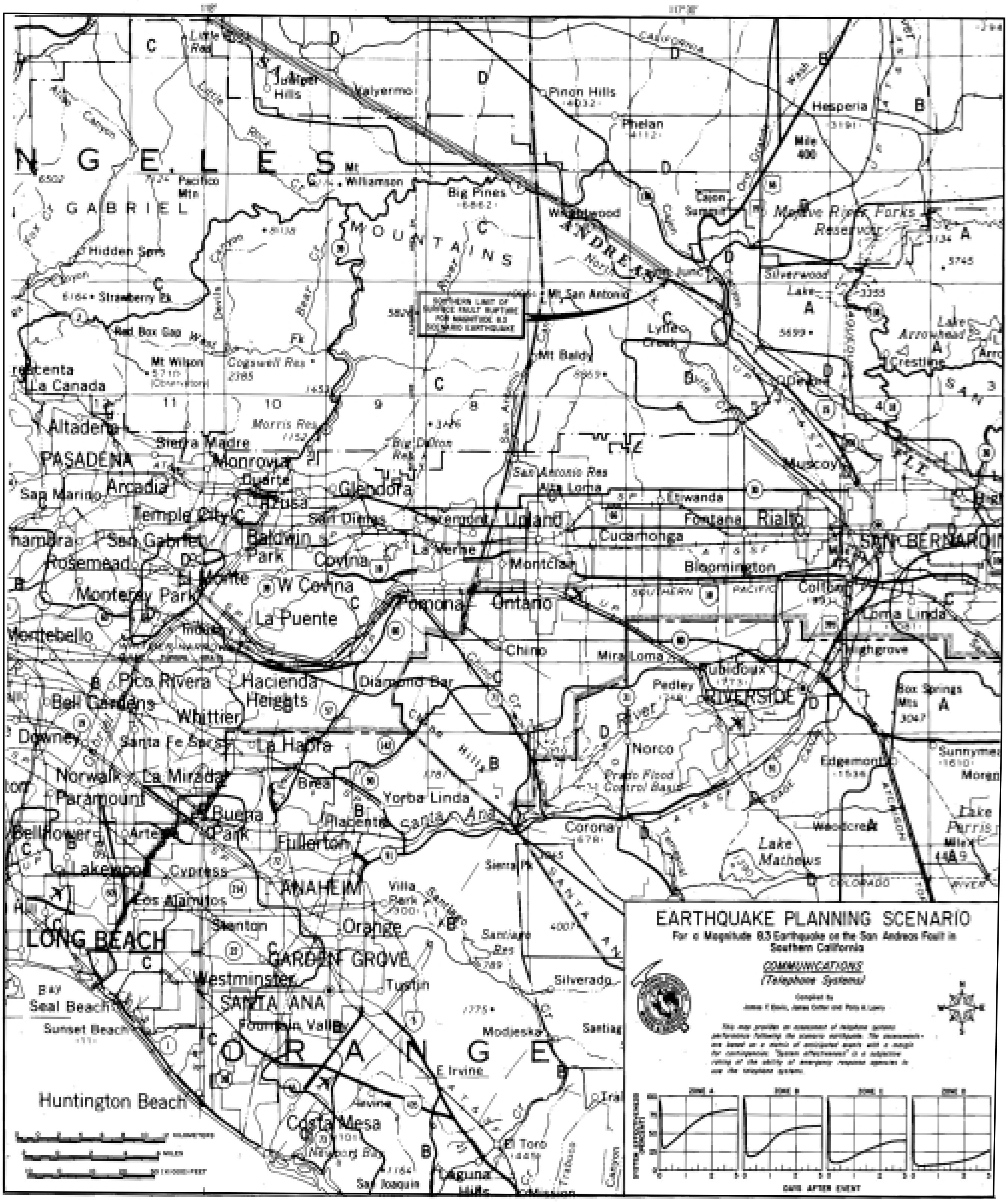
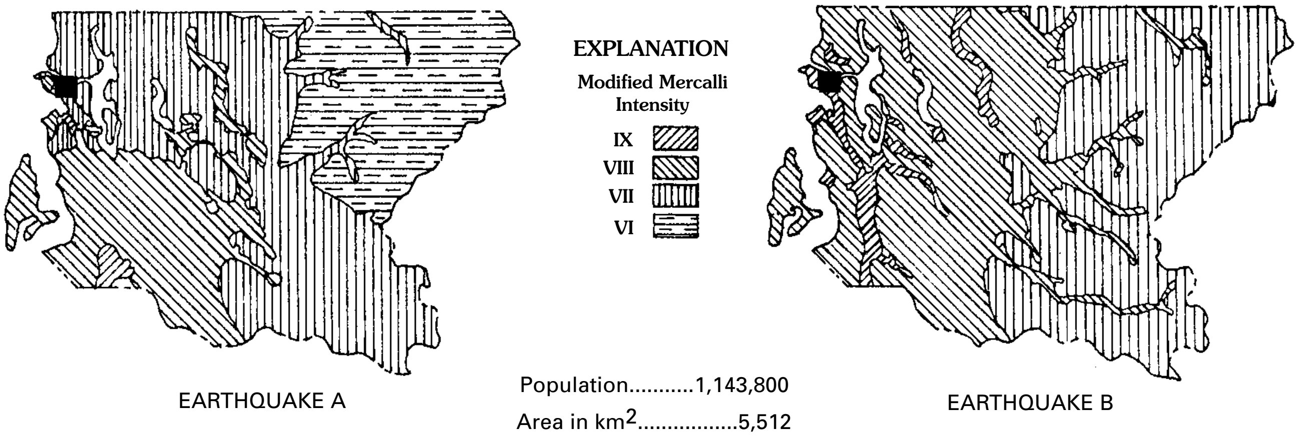


Figure 232. Planning-scenario map showing the impact of a postulated earthquake on the telephone system for part of the Los Angeles, Calif., metropolitan area. This compilation by Davis and others (1982) shows the percentage of telephone-system effectiveness in four zones (designated A, B, C, and D) as much as 3 days after the event. For example, in zone D near San Bernardino, only about 25 percent of the telephone system would be in operation 3 days after the earthquake.



	DEGREE OF IMPAIRMENT					
	EARTHQUAKE A			EARTHQUAKE B		
VITAL NEEDS	Minimal	Minor	Major	Minimal	Minor	Major
Communications		●				●
Fire		●				●
Police		●				●
Electric power			●			●
Water		●				●
Access roadways			●			●
Medical:						
Manpower			●			●
Hospitals			●			●
Ambulances		●				●
Blood bank		●				●
Supplies		●			●	
Food supplies	●				●	
Schools (as shelters)		●				●

	ESTIMATED LOSSES	
	EARTHQUAKE A	EARTHQUAKE B
Deaths	1,500	1,650
Serious injuries	6,000	6,600
Homeless	7,130	18,630

Figure 233. Anticipated damage and casualties from two postulated earthquakes in King County, Wash. The black square indicates the general location of Seattle. From U.S. Geological Survey (1975, p. 5, table 2).

TRANSLATION OF RESULTS FOR NONTECHNICAL USERS

Translating scientific and engineering data into formats that can be readily used by lay people provides those users with an awareness that a hazard exists that may affect them or their interests; gives them information that they can easily present to their superiors, clients, or constituents; and provides them with materials that can be directly used as hazard-reduction techniques. My experience with reducing potential natural hazards indicates that for the seismic-hazard information to be successfully used by nontechnical users, it must have the following three elements in one form or another:

1. The likelihood of occurrence of an earthquake that will cause casualties, damage, or disruption
2. The location and areal extent of ground effects by the earthquake

3. The estimated severity of the ground effects and effects on structures and equipment

These elements are needed because engineers, planners, and decisionmakers usually will not be concerned with a potential hazard if its likelihood is rare, its location is unknown, or its severity is slight, and neither will lenders, politicians, or citizens.

TRANSFER OF INFORMATION TO NONTECHNICAL USERS

The objective of transferring hazard information to nontechnical users is to assist in and encourage its use in order to reduce losses from future earthquakes. Translated hazard information is a prerequisite for transfer to nontechnical users. A comprehensive example of both the translation and transfer of geologic information for use by county planners and decisionmakers is provided by Brabb (1987).

Various terms are used to convey information transfer to users, including “dissemination,” “communication,” “circulation,” “promulgation,” and “distribution.” These terms are often interpreted conservatively, such as when merely issuing a press release on hazards or distributing research information to potential users. This level of activity usually fails to result in the formulation of effective hazard-reduction techniques and may even fail to make users aware of the hazard. Therefore, I suggest that we use the term “transfer” to mean the delivery of a translated product (report, map, video, or poster) in a usable format at a scale appropriate to its use by a specific person or group interested in or responsible for hazard reduction. In delivering such a product, assistance and encouragement in its use must also be provided.

EVALUATION AND REVISION OF TECHNIQUES

The effectiveness of each hazard-reduction technique varies with the time, place, and persons involved. Therefore, it is prudent to include a continuing systematic evaluation as part of any comprehensive earthquake-hazard-reduction program. An inventory of uses made of the information, reports of interviews with the users, and analysis of the results and responses will also result in identifying new users and innovative uses as well as any problems concerning the scientific and engineering studies themselves and their translation, transfer, and use. The evaluation will be helpful, even necessary, to those involved in producing, translating, transferring, and using the research information as well as to those funding and managing the program.

Performing the studies and then translating and transferring the research information is expensive and difficult because of the limited number of scientists and geotechnicians, particularly when considering the number of communities faced with possible seismic hazards throughout the United States. The adoption and enforcement of an appropriate hazard-reduction technique is time consuming and requires many skills—planning, engineering, legal, and political—as well as strong and consistent public support.

Scarce financial and staff resources must be committed, and persistent and difficult actions must be taken to enact laws, adopt policies, or administer hazard-reduction programs for long periods of time. To discover later that the specific hazard-reduction technique selected is ineffective or unenforceable or its cost is greatly disproportionate to its benefits not only is disheartening but also may subject the persons involved to the criticism and loss of financial support!

CONCLUSIONS

The earthquake-hazard-reduction techniques presented in this report include preparing redevelopment plans, creating regulatory zones, securing nonstructural building components, informing the public, strengthening unreinforced-masonry buildings, and estimating casualties, damage, and interruptions. These techniques are designed to provide greater public safety, health, and welfare for individuals and their communities. The decision to adopt a technique is influenced by many factors—the nature of the earthquake hazard, public concern, strong community interest, State-enabling legislation, the availability of scientific and engineering information, and the ability of geologists, engineers, planners, and lawyers to incorporate the information into an effective hazard-reduction technique.

Some of the geologic and seismologic information needed for land-use and general planning in the Pacific Northwest region is available but generally not at the level of detail and scale needed for engineering and decisionmaking. Even greater detail at larger map scales ranging from 1:1,200 to 1:12,000 is needed for development planning, site investigation, ordinance administration, project review, and permit issuance.

Earthquake-hazard research is continuing, the information base is growing, new methods for evaluating hazards are being developed, and hazard-reduction techniques may be tested. Planners, engineers, and decisionmakers (both public and private) need to recognize these facts and use the latest information, methods, and techniques. However, they cannot be expected to have the training or experience necessary to understand and use untranslated scientific and engineering information. Therefore, if nontechnical users are to benefit from this information, it must be translated and transferred to them before effective hazard-reduction techniques can be adopted.

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EARTHQUAKE RISK-REDUCTION PROSPECTS FOR THE PUGET SOUND AND PORTLAND, OREGON, AREAS

By Peter J. May[1]

ABSTRACT

This chapter addresses current efforts and future prospects for earthquake risk reduction among major cities and counties within the the Puget Sound and Portland, Oregon, areas. There is a clear distinction among leading and lagging jurisdictions within the region with respect to existing and future efforts for earthquake risk reduction. The differences result not only from different risk profiles, but also from differing political and economic circumstances. The understanding of differing situations leads to four State- or regional-level risk-reduction strategies that might be undertaken as new information about seismic risk is produced. These strategies range from relatively passive hazards-information dissemination to more active efforts to seek policy reforms or to influence design practices.

INTRODUCTION

One of the important lessons of the U.S. Geological Survey's hazard-assessment program in Utah and California is that simply providing technical information about earthquake risks will not stimulate changes in local practices or policies. The design of State- or regional-level risk-reduction strategies requires identification of key features of the political and economic environment that are likely to shape future opportunities for and obstacles to local risk reduction. This chapter develops such an understanding for major cities and counties in the Puget Sound and Portland, Oreg., areas. It is important to remember that the scientific study of seismic risk in the Puget Sound–Portland region is still underway. This chapter also suggests how risk-reduction efforts might be altered as more is learned about the extent of seismic hazards and the risks they pose.

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ACKNOWLEDGMENTS

The author thanks Patricia Bolton of Battelle Human Affairs Research Centers, Thomas Yellin of the U.S. Geological Survey, and William Kockelman of the U.S. Geological Survey for reviews of earlier drafts of this report, and is grateful for assistance provided by Edward Fox and Nancy Stark. Funding for the research and preparation of this report was provided by the U.S. Geological Survey under awards 14-08-001-G1535 and 14-08-0001-G1778.

JURISDICTIONS STUDIED

Thirteen counties within the Puget Sound area (Clark, Cowlitz, Grays Harbor, Island, King, Kitsap, Jefferson, Mason, Pierce, Skagit, Snohomish, Thurston, and Whatcom) and 6 counties within the Willamette Valley area (Clackamas, Marion, Multnomah, Polk, Washington, and Yamhill) were selected for this study. There are 43 cities of more than 10,000 population within these 19 counties (table 43), which are referred to as a single region in the following discussion.

Table 43. Oregon and Washington cities studied for this report.

Oregon	Washington	
Beaverton	Aberdeen	Mercer Island
Forest Grove	Anacortes	Mount Vernon
Gresham	Auburn	Mountlake Terrace
Hillsboro	Bellevue	Oak Harbor
Keizer	Bellingham	Olympia
Lake Oswego	Bothell	Puyallup
McMinnville	Bremerton	Redmond
Milwaukie	Des Moines	Renton
Newberg	Edmonds	Seattle
Oregon City	Everett	Tacoma
Portland	Kelso	Vancouver
Salem	Kent	
Tigard	Kirkland	
Tualatin	Lacey	
West Linn	Longview	
Woodburn	Lynnwood	

Within the 19-county region are 97 incorporated cities, more than 200 school districts, more than 200 special districts, and 22 port districts. The special districts consist of separately governed entities such as water and sewer districts, public utility districts, drainage districts, road districts, soil-conservation districts, and metropolitan councils of government. Within many of these cities and other local jurisdictions are multiple agencies with responsibility and overlapping authority for addressing public safety. Earthquake-risk-reduction efforts in this region include more than 500 jurisdictions and 4.7 million people as of 1987.

The potential vulnerability of this region to earthquake damage is indicated by statistics about the region. In 1988, the total value of all property in the region was estimated to be $180 billion. The value of new construction of apartment, office, commercial, and industrial buildings in 1987 was reported by the U.S. Census Bureau to be nearly $1.5 billion. This amount is an almost-50-percent increase since 1980. Because many newcomers, some who have left earthquake-prone areas of California, are moving to the region, the population and assessed property values will certainly grow over the coming decade.

The region's counties, utilities, port districts, and 43 largest cities were chosen for inclusion in the study because they have the greatest populations and property values. Within the 13 Washington counties studied are 27 cities of more than 10,000 population, including Bellingham, Bellevue, Everett, Olympia, Seattle, Tacoma, and Vancouver. Some 3.3 million people lived in these 13 counties as of 1987. Within the six Oregon counties studied are 16 major cities, including Beaverton, Gresham, Portland, and Salem, having a 1987 combined population of 1.4 million.

The study is based on interviews with 177 persons, conducted over a period of 6 months, beginning in September 1988. The following were interviewed:

- Those directly responsible for land-use and building regulation in the 43 cities and 19 counties
- Public-works or other utility personnel responsible for water and sewer functions for municipal systems in 41 of the cities
- Engineering directors of six of the larger port districts (Bellingham, Everett, Olympia, Portland, Salem, and Tacoma)

The interviews of personnel in cities and counties entailed talking with the planning director and the chief building official (or an individual they designated). The study's focus on risk reduction rather than response to seismic events led to the decision to exclude emergency-services personnel except in a few jurisdictions where such personnel had broader responsibilities. In many jurisdictions, personnel with public safety responsibilities in the office of the mayor, city manager, or county administrator were also interviewed. Additional interviews were conducted with State officials in State-level building-regulation and land-use agencies. In-person interviews lasting 30 minutes to 1 hour were conducted with officials at the State level and within the larger jurisdictions. The remaining interviews were by telephone.

The interviews were used to develop profiles of the earthquake-related policies and practices of the cities and counties and to develop the information that follows. Draft profiles were shared with key officials in each jurisdiction and were revised to correct factual errors.

DIFFERING RISK PERCEPTIONS

One aspect of the study characterized different risk perceptions within the jurisdictions. One set of questions addressed elected officials' perception of the likelihood of significant property damage, deaths, or injuries from an earthquake in the next 20–30 years.[2] Another set of questions was addressed to building officials and engineering directors to obtain their perceptions of the vulnerability to a major earthquake of the building stock or facilities within their jurisdictions.

RISK PERCEPTIONS OF ELECTED OFFICIALS

Information about risk perceptions of elected officials helps to depict the broad political context of earthquake risk reduction. The study results show a general awareness of seismic risks in the region, with a somewhat greater awareness by local officials in Washington. Some respondents reported reading in local newspapers about the U.S. Geological Survey research on seismic risk, commented about media reports of earthquake swarms, or recalled the 1965 or 1949 earthquakes. On the other hand, some respondents seemed to discount the risk. Whatever the risk perception, earthquake hazards appeared to be of relatively little concern to elected officials, because of other, more pressing concerns.

These results are consistent with similar investigations in other areas of moderate to high seismic risk, including California (for example, Berke and Wilhite, 1988; Drabek and others, 1983; Mushkatel and Nigg, 1987). Earthquake risk falls at the less dreaded and more accepted ends of the spectrum of attention to various risks by politicians and the general public.

The profile of responses by elected officials (fig. 234) suggests a general awareness of the potential for a moderate

[2] The responses for elected officials were based on asking an appropriate administrative-level employee in each jurisdiction: "On a scale of 0 to 100, how likely do you think most officials in this jurisdiction think the chances are in the next 20 to 30 years of significant property damage, injuries, or loss of life are from each of the following***"

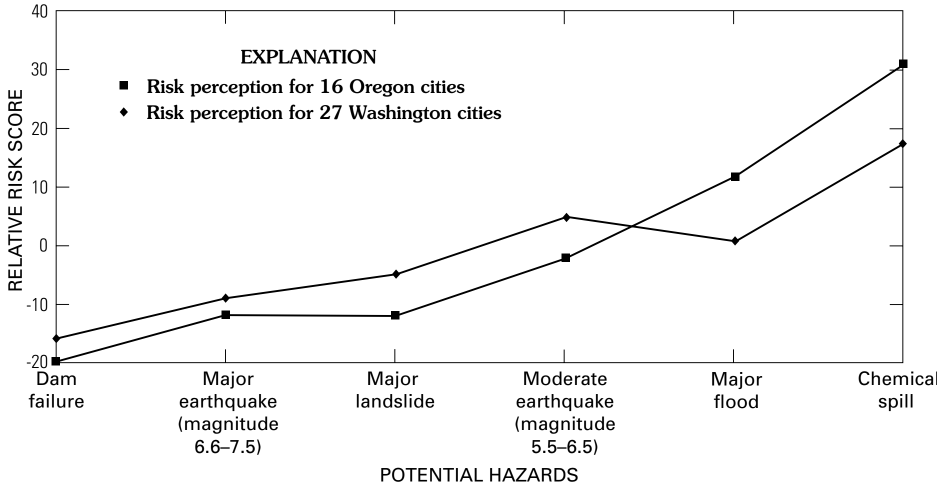

Figure 234. Hazard-risk perceptions of elected officials of Oregon and Washington cities in the study area. Relative risk scores are deviations from mean rating of risks posed by the combined hazards.

earthquake and a lesser sense of the potential for a major earthquake.[3] Because the absolute risks posed by these hazards are unknown, it is more appropriate to refer to relative comparisons of risks as represented by deviation scores.[4] In addition, the tendency for some respondents to rate all risks very highly and other respondents to rate all risks less high is accommodated by using relative scores.

Chemical spills are considered by elected officials to be the greatest risk (fig. 234). Moderate earthquakes were rated the second greatest risk by Washington city officials and the third greatest risk by Oregon city officials. Major earthquakes are considered less significant risks than major landslides but more significant than dam failures. Although major earthquakes are presumed to be more damaging than moderate earthquakes, elected officials appeared to discount the likelihood that major earthquakes will occur and thus rated them a lesser risk.

The results for county elected officials (not shown) are somewhat different than those for city officials. For both Oregon and Washington counties, flooding is considered to be the greatest risk, followed in decreasing order by chemical spills, landslides, moderate earthquakes, major earthquakes, and dam failures.

These results for elected officials suggest an awareness level that corresponds to some degree with the way in which seismic risks have been characterized in this region in the past. Earthquake risks are perceived to be lower in Oregon than in Washington. Yet, officials in both Oregon and Washington discount the potential for significant damage or loss of life, whereas earthquake engineers have said that even moderate events in this region can be very damaging.

In both States, moderate earthquakes were perceived to be more probable than major earthquakes. On the absolute rating scale (0 to 100), the mean rating by Oregon city officials for the likelihood of significant effects of a moderate earthquake is 28 and of a major earthquake is 18. The corresponding figures for Washington city officials are 48 and 34. Earthquake risks were generally perceived by county officials to be lower. On the same rating scale, the mean likelihood rating by Oregon county officials for significant effects of a moderate earthquake is 29 and of a major earthquake is 14. The corresponding figures for Washington county officials are 31 and 15.

DAMAGE PERCEPTIONS OF BUILDING OFFICIALS

Perhaps more important barometers for future risk-reduction efforts are the perceptions of building officials. This study attempted to learn these views in two ways. First, building officials were asked about potential earthquake-vulnerable classes of buildings in each jurisdiction. Because none of the jurisdictions maintain building inventories, the responses only reflect officials' impressions of vulnerability. Second, building officials and engineering directors were asked to assess the impacts of various earthquakes upon the building stock (or facilities) within their jurisdiction.

Three classes of buildings were considered to be potentially vulnerable: (1) unreinforced masonry buildings; (2)

[3]A "moderate" earthquake was defined as Richter magnitude 5.5–6.5 and a "major" earthquake as Richter magnitude 6.6–7.5. Duration, depth, and location were not specified. Most respondents seemed to understand the labels "moderate" and "major" better than information about potential magnitude of an event. "Great" earthquakes (greater than magnitude 7.5) were not addressed.

[4]Deviation scores were calculated for each respondent by subtracting the average rating of all hazards for that respondent from the respondent's ratings for each hazard.

tilt-up concrete buildings built before 1975, typically used as warehouses, as light-industrial facilities, or for other similar purposes; and (3) reinforced-concrete frame buildings built before the early 1960's, typically 3–10 stories, used as office buildings, schools, or apartments. Unreinforced masonry buildings (table 44) appear to pose the most widespread existing risk in the region's cities. Tilt-up concrete buildings built before the mid-1970's are about equally prevalent among cities in the two States. Reinforced-concrete frame buildings are more common in Washington cities than in Oregon cities. Unincorporated areas of counties are somewhat less at risk. Most unincorporated county areas are rural or suburban and have mainly single-family homes and newer commercial buildings. The most common hazardous-building type, reported to be "somewhat common" or "very common" in one-third of the counties, is tilt-up concrete buildings built before 1975.

To understand the risks that potentially hazardous buildings pose, building officials were asked to think about the damage that might follow from various earthquakes.[5] Because respondents were asked to assess damage as a result of a particular earthquake, their responses do not entail judgments about likelihood of an earthquake. Both lack of specific information about the location and duration of the seismic events and the difficulty that they had in envisioning the degree of damage that might follow constrained their responses.

City building officials perceived that the greatest potential for damage would be from major earthquakes, followed, in order, by moderate earthquakes, major flooding, and major landslides (fig. 235). On the absolute rating scale (0 to 100), the mean of responses by city building officials in Washington of the likelihood of significant damage from a major earthquake in the region was 46 (range from 10 to 90). The mean of responses for a moderate earthquake was 27 (range from 0 to 75). The corresponding mean for Oregon cities for a major earthquake was 44 (range from 15 to 85), and for a moderate earthquake event the mean was 21 (range from 5 to 60). County building officials in Washington and Oregon had similar damage perceptions.

The building officials' perception of prospective damage is consistent with their perception of the prevalence of the different types of hazardous buildings. For cities, the Pearson correlation (r) between prevalence of unreinforced masonry buildings and likelihood of significant damage from a major earthquake is a moderately strong +0.41. The corresponding Pearson correlations between the prevalence of tilt-up concrete buildings and prospective damage is +0.46 and between the prevalence of reinforced concrete frame buildings and prospective damage is +0.14.

[5]Specifically, they were asked: "Please think about what damage would follow if the following events actually occurred. On a scale of 0 to 100, how would you characterize the potential for damage to a significant number of structures from ***"

Table 44. Potentially hazardous buildings in Oregon and Washington cities studied for this report.

[Percentage of cities reporting that each building type is either somewhat or very common]

Building type	Oregon	Washington
Unreinforced masonry	31	52
Tilt-up concrete built before the mid-1970's.	25	22
Reinforced concrete frame built before the 1960's.	13	25

DAMAGE PERCEPTIONS OF UTILITIES AND PORT OFFICIALS

Utility and port officials viewed earthquake hazards as a potentially broader risk than flooding or landslides. Landslides are likely to affect only part of the utility system, whereas earthquake-related ground shaking would affect the whole system. As part of risk management, utilities and ports seek to protect the more valuable aspects of their facilities—reservoirs, storage facilities, and treatment plants for water or sewer utilities, and piers and cranes for ports. About one-third of the respondents from water utilities identified reservoirs as potentially vulnerable to a major earthquake. An equal number were concerned about disruption of major water-transmission lines within their system.

Utility personnel had perceptions of damage potential comparable to those of building officials. Both Oregon and Washington utility respondents rated major earthquakes as having the highest damage potential, followed, in order, by moderate earthquakes, major flooding, and major landslides. Oregon utility personnel as a group reported slightly higher likelihood of damage from moderate earthquakes (mean 22) and major earthquakes (mean 47) than the corresponding likelihood reported by Washington utility personnel. Washington respondents had much broader ranges of likelihood of damages.

Utility personnel reported considerably more experience with occasional flooding and landslide damage, such as transmission breaks in parts of their systems, broken connections to households, and so forth, than with earthquake damage. Only Seattle and Kent municipal water system officials reported more than minor damage from the 1965 earthquake. The response to flooding and landslides, particularly by the larger utilities, has been to build greater redundancy into their systems. Because of this redundancy and the localized nature of flood and landslide impacts, it is not surprising that personnel of larger utility systems tended to perceive less likelihood of significant damage from major flooding (Pearson r= –0.41) or from landslides

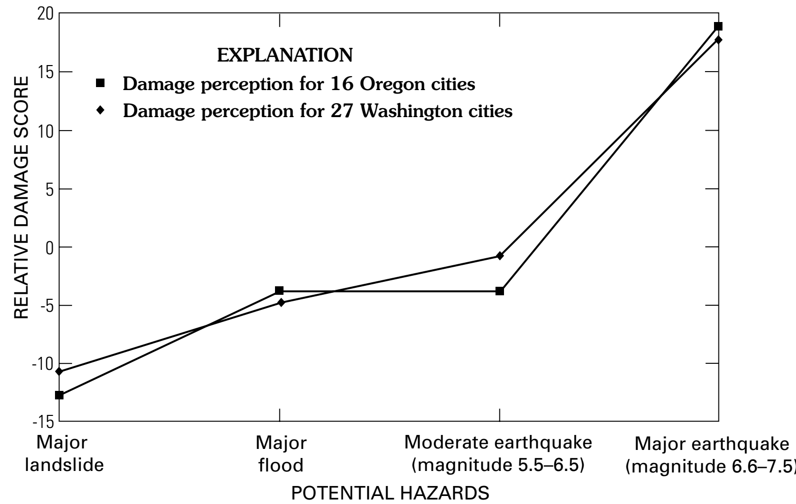

Figure 235. Expected-damage perceptions of building officials of Oregon and Washington cities in the study area. Relative damage scores are deviations from mean rating of expected damage from the combined hazards.

(Pearson *r*= –0.31) than officials of smaller utilities.[6] In contrast, the perceived likelihood of significant damage tended to increase with utility size for moderate earthquakes (Pearson *r*= +0.27) and for major earthquakes (Pearson *r*= +0.16).

Engineering personnel at the six major ports that were part of this study reported a likelihood of damage that generally corresponded to the perceptions of municipal utility and building personnel. However, the likelihood data and the qualitative responses to the interviews indicated a lower perception of the probability of prospective earthquake damage to port facilities. The likelihood of prospective damage from major earthquakes averaged 40 (on the 0 to 100 absolute scale) with a range of 20–50. Port personnel tended to be more confident than the utility officials that seismic forces had been adequately considered as part of facility design.

CURRENT RISK-REDUCTION POLICIES AND PRACTICES

Policies (as the term is used here) are officially adopted laws or regulations at the State level and local ordinances at the local level (May and Williams, 1986). Policies may be general in establishing broad goals, or they may be specific in specifying standards or in referencing other sources of standards as part of legislation. They may be strongly directive in mandating particular actions by other levels of government. Policies commonly have associated administrative regulations that provide specific guidelines about how to comply with the policies. At the State level, such regulations are part of administrative codes subject to State-level rule-making procedures.

An important category of policies considered here is State mandates that either require local governments to adopt policies consistent with certain State goals or require local governments to comply with State policies. The State mandate may allow discretion in the way local governments formulate policy, or the local policy may be highly prescribed. For example, Oregon's statewide land-use planning mandate requires local adoption of comprehensive plans consistent with 19 State planning goals. The State planning mandate establishes broad planning goals, and associated regulations specify the steps for local compliance with the mandate. The local comprehensive plans officially adopted by local governments establish local land-use policies.

Practices (as the term is used here) are the actions of local building officials, land-use administrators, and other government officials in carrying out their functions. Practices are governed by policies and their implementing regulations. The policy or associated regulations may be vague enough to allow discretion in carrying out the policy. As a result, there can be differences between written policies and actual practice. For some situations, no applicable policy may exist. Therefore, the realities of practice are often difficult to study.

BUILDING REGULATION

Building regulation is a shared governmental function for which Oregon and Washington specify State building

[6] The correlations reported in this paragraph were calculated by using deviation scores for risk perceptions and omitting relevant outliers. Previous flood experience and future damage potential were very weakly related (Pearsons *r*=+0.04) and previous landslide experience and future landslide damage potential were weakly related (Pearsons r=+0.28). Insufficient variation in earthquake-damage experience prevented analysis of the relationship between past earthquake experience and future damage perception.

codes, and local governments implement and enforce the codes through local ordinances and building regulatory practices. The State codes are based on the UBC (Uniform Building Code) (International Conference of Building Officials, 1988) as amended in each State. Discretion in building regulation comes both through local amendments to the State code (prohibited in Oregon) and through building officials' exercise of discretion as permitted by amended UBC provisions and relevant local ordinances.

Perhaps the greatest limit to the increase in earthquake-hazard risks in this region has been the adoption by Oregon in 1974 and by Washington in 1975 of State laws and associated administrative provisions establishing State building codes.[7] These may not seem like big steps forward, because some 80 percent of Washington cities and 60 percent of Oregon cities in this study had building codes with seismic provisions prior to these mandates, which were typically adopted in the 1950's or 1960's. Fewer counties had building codes prior to the State mandates. Yet, the establishment of State codes was important for jurisdictions where no building codes of any kind existed and for establishing a way to update the codes to reflect changes in UBC provisions. Neither State has enacted or even considered State policy mandates governing retrofit of existing hazardous buildings beyond the relevant UBC provisions concerning change in use or occupancy.

The two States' building-code mandates (table 45) are similar in approach but are different in some important specifics. Both mandates establish State building codes, require local compliance with those codes, and create means for updating the codes and monitoring local code compliance. The States adopt relevant structural code provisions by referencing and amending provisions of the Uniform Building Code.[8] As newer versions of the UBC have been produced, both States have adopted them with amendments. The 1988 edition has been recently adopted with amendments as the basis for each State's structural building code.

Because of differing seismic-zone delineations for Oregon (now designated zone "2B") and Washington (now designated zones "2B" and "3") and differing State-level amendments, there are important differences in seismic provisions between the two States. Oregon also has adopted the Council of American Building Officials One and Two Family Dwelling Code (Council of American Building Officials, 1986) as a basis for State code governing residential construction.

The main differences between the two mandates are in the degree of local discretion permitted in amending State provisions. Oregon does not permit any amendment by local jurisdictions. The Oregon code is a genuine State code for which the implementing responsibility is delegated by the State to local governments.[9] Washington permits amendments to the State building code as long as they do not weaken code provisions. Since 1986, State-level review and approval of amendments affecting one- to four-unit residential buildings has been required. The local discretion in amending the code combined with municipal building codes that existed prior to the State mandate has resulted in a greater variety of local codes in Washington than in Oregon.

Although local updating of ordinances to correspond with new versions of State building codes may lag, localities seem to have policies that comply with State mandates. The critical question about the effectiveness of the State building codes is the extent to which seismic provisions are enforced. Enforcement relates to the capabilities of the relevant local building departments (the quality of plans review and inspection) and the use of discretion by local building officials where permitted by the codes. Oregon has attempted to strengthen enforcement capabilities for all aspects of the code by requiring certification of building officials, plans examiners, and inspectors.

Data concerning local building regulation enforcement are very sketchy. A recently completed Washington study of code enforcement noted "a perception, and even public acknowledgment, that the level of building code enforcement varies throughout the state" (Washington State Building Code Council, 1989).[10] Some building officials who were interviewed as part of this study hinted at political pressures on them to be less stringent in interpreting codes. Others, including some building officials in relatively small jurisdictions, were very aggressive in code enforcement. The overall impression from the interviews was that current levels of enforcement for new commercial construction are high. Considerably more variation in code enforcement was suggested for code provisions regarding renovation of commercial structures. This variation reflects differences both in building officials' attitudes and in their use of discretion.

Data about building-department staffing provide a limited basis for assessing enforcement capabilities with respect to seismic-hazard provisions. Only 15 percent of the Washington cities and 20 percent of the Oregon cities in this study reported having structural engineers as part of the

[7]Each State has laws that specify seismic design for public facilities and "public places of assembly" dating from 1963 in Oregon (Oregon Revised Statutes 456.965 "Public Structures") and 1955 in Washington (Revised Code of Washington, Chapter 70.86, "Earthquake Resistant Standards"). Each of these laws has been superseded by State building-code provisions. The extent to which these provisions were enforced in the 1950's and 1960's is unknown but likely to have been limited because of the lack of State-level enforcement mechanisms at that time.

[8]Other codes govern electrical, mechanical, fire, and other aspects of construction.

[9]The delegation of responsibility for codes follows a hierarchy in Oregon (Oregon Building Codes Agency, 1988). If a municipality elects not to enforce the State code, the responsibility falls to the county. If the county elects not to enforce the State code, the responsibility falls to the State. Enforcement of the structural code has been delegated to the cities and counties in this study.

[10]The limited nature of the data is underscored by the fact that only 17 people gave public testimony at the five regional hearings held by the Washington State Building Code Council on this topic.

Table 45. State building-code mandates, Oregon and Washington.
[UBC, Uniform Building Code; CABO, Council of American Building Officials]

State mandate	Provisions	Local discretion
OREGON—1974 State Building Code (as amended).	Establishes State building code and agency with rule-making authority to update code provisions.	Unable to amend provisions to meet local conditions.
	1988 edition of UBC with amendments administratively adopted in 1989 (regularly updated since 1973 edition); CABO One- and Two-Family Dwelling Code also adopted.	Local enforcement with county and State backup (structural provisions almost always locally enforced).
	Mandates certification of building officials, plans examiners, and inspectors.	Discretion as provided within UBC as amended.
WASHINGTON—1975 State Building Code (as amended).	Establishes State Building Code Council with rule-making authority to update code provisions.	Able to amend provisions to meet local conditions, as long as minimum State standards are met.
	1988 edition of UBC administratively adopted in 1989 (regularly updated since 1976 edition with some technical modifications).	Solely local enforcement of building-code provisions.
	State Building Code Council authority to review local amendments for residential structures with 1–4 units (since 1986).	Discretion as provided within UBC provisions and in adding local amendments.

building-department staff. (The corresponding figures for the counties in this study are 12 percent in Washington and 33 percent in Oregon.) Seattle's building department has the greatest staff capability, consisting of a construction review staff of 19, of which 6 are licensed structural engineers, 4 have other engineering certification, and 9 have building-construction or architectural degrees. Some 60 percent of cities in the region reported sending complex drawings for plan review to the regional office of the International Conference of Building Officials or hiring consultants for the review. Not surprisingly, the smaller jurisdictions reported more limited ability to interpret seismic-hazard code provisions. This difficulty was summarized by one building official who stated, "I often have questions about what the seismic provisions are based on; it is hard for a non-engineer to tell."

The code-enforcement gaps in some of the smaller jurisdictions and more rural counties prior to the establishment of the State codes are illustrated by the following quotes from interviews with building officials:

- "We were derelict prior to 1975 or so in keeping up with UBC changes, but we are now tightly tied to State law."
- "There were blatant problems in the 1970's with bad engineering practice that we were unable to address."
- "Shifting the building function back and forth between the city and county made consistent code compliance difficult."

The existence of State building codes in Oregon and Washington may seem to make local building regulatory policies and practices less important aspects to consider for future earthquake-risk-reduction strategies in the region. For newly constructed, engineered buildings this is probably a reasonable conclusion. Given the apparent relatively good enforcement of seismic provisions as applied to such buildings, the degree of risk for engineered buildings built since the early 1970's (or even the early 1960's in larger cities) is essentially determined by UBC seismic provisions in place at the time the buildings were constructed. The judgment that seismic risk is low for these buildings presumes that good engineering practices were followed in building design and that the seismic zones were properly designated in the codes in place at the time of construction.[11]

Local policies and practices are especially important concerning (1) existing, potentially hazardous buildings, such as unreinforced masonry buildings (URM), tilt-up concrete buildings, and reinforced concrete frame buildings described earlier in this chapter; and (2) building and excavation provisions for steep slopes and unstable soils. The variation in local policies and practices concerning these hazards stems from multiple sources of code provisions and latitude within those codes.

[11] Oregon's zone classification has been changed somewhat, particularly in the 1988 edition of the UBC. This in itself provides a basis for wondering about risk posed even by the "newer" engineered buildings.

Two relevant UBC discretionary provisions define the trigger for applying seismic-code provisions to buildings undergoing renovation. Section 104 states that "additions, alterations, or repairs" may be made without requiring the existing building to comply with all of the code requirements. In addition, section 502 provides an exemption for proposed uses that are less hazardous than existing use for buildings undergoing a change in "character of occupancy or use." These provisions allow for interpretation for buildings that are remodeled in stages or for where the change of use can be debated. This is less of a problem for tilt-up concrete buildings, for which changes in use are less frequent than for other categories of potentially hazardous buildings.

The main UBC discretionary exemption that applies to older, potentially earthquake prone buildings consists of "historic building" provisions of the UBC Section 104(f). This section allows discretion in meeting current code requirements for buildings certified as having special architectural or historical significance. The key provision is that the restored building or structure be no more hazardous than the original.

Local ordinances referencing suggested model codes for other aspects of building regulation are an additional source of differing code-enforcement policies and practices in Washington and to a lesser extent in Oregon. Some jurisdictions incorporated provisions of the Uniform Code for Abatement of Dangerous Buildings in ordinances about dangerous buildings. That code allows building officials discretion concerning dangerous buildings. A few building officials reported using such ordinances to require demolition of earthquake-vulnerable buildings, but such actions were rare. In addition, the ordinances of some jurisdictions specifically refer to the Uniform Code for Building Conservation in establishing guidelines for renovation of buildings.

Another source of differences in local regulation of existing buildings is jurisdiction-specific building codes. Seattle has done the most in this regard (Perbix and Burke, 1989; Skolnik and Wood, 1975), beginning in 1973 with the enactment of amendments to the Seattle Building Code, which states:

> In cases where total compliance with all the requirements of this building code is physically impossible and/or impracticable, the applicant may arrange a pre-design conference with the design team and the building official to identify design solutions which will provide equivalent protection. The building official may waive specific requirements in this building code which he/she has determined to be impracticable. (Sec. 104 of the 1985 edition of the Seattle Building Code)

The only other examples of locally adopted seismic policies for existing buildings among the jurisdictions in this study were parapet provisions enacted in Tacoma and Seattle. (UBC seismic provisions concerning parapets and chimneys are in section 3704(c) of the 1988 edition.) Tacoma's ordinance was adopted after the 1965 earthquake (ordinance 17842, May 18, 1965). The ordinance made it possible to declare buildings with unanchored parapets dangerous and therefore a hazard requiring abatement. Seattle's provisions, in a section of the Seattle Building Code, are similar in making it possible to declare buildings with unanchored parapets unsafe. There have been various spurts of enforcement of these parapet provisions. Seattle, for example, reportedly looked actively for problem parapets in 1975 after a large chunk of a parapet fell from a now-demolished hotel. Some 200 building owners were cited for unsafe parapets at the time.

Important differences in practices concerning existing buildings involve negotiations for seismic-safety upgrading of buildings undergoing renovation. Seattle's building code appears to codify the existing practice in many jurisdictions. Seattle, Tacoma, and Portland appear to have done the most to establish administrative procedures for negotiating seismic-safety requirements in building renovation. Portland was particularly innovative in establishing a Structural Advisory Committee, composed of external structural engineers, for advising the city's building official about appropriate requirements for design changes as part of major renovations. The volume of renovations of unreinforced masonry buildings alone has been enough in these jurisdictions, about 20–30 per year in Seattle, 2 or 3 per year in Tacoma, and 20 per year in Portland, to justify having such procedures. Within jurisdictions having less experience with major renovations of potentially earthquake hazardous buildings, the practices are less formalized but are sometimes guided by the Uniform Code for Building Conservation.

LAND-USE AND SECONDARY HAZARDS

The contrast between State-level land-use planning mandates in Oregon and Washington is between a single, relatively strong Oregon land-use mandate and a set of relatively weak, more general environmental mandates in Washington. Despite differences in the written mandates, the differences in local practices between Oregon and Washington jurisdictions are not that great concerning seismic hazards other than landslides.

The primary State-level land-use planning mandate in Oregon relevant to earthquake hazards comes from provisions contained in legislation first enacted in 1973 as the Oregon Land Use Act. This legislation established 19 statewide planning goals and required local governments to develop comprehensive plans to be reviewed for consistency with the statewide planning goals (Oregon Land Conservation and Development Commission, 1986). Goal Seven is a statewide goal "to protect life and property from natural disasters and hazards." The guidelines for Goal Seven call for identification of areas subject to natural hazards and the development of "appropriate safeguards" as part of the planning process.

The Oregon mandate and associated administrative guidelines provide discretion in implementing Goal Seven. The Oregon jurisdictions in this study fully complied with the State mandate provisions requiring a State-approved local comprehensive plan. Goal Seven compliance appears to be very strong with respect to flood hazards (in complying with Federal Emergency Management Agency flood-insurance mandates), moderately strong for landslide hazards (in identifying areas of potential landslides and considering compatible land uses), and weak for other earthquake hazards. Planners cited lack of awareness of earthquake hazards and difficulties in identifying areas other than steep slopes as possibly subject to earthquake hazards as a primary limitation of their ability to apply land-use measures to earthquake risk reduction. State personnel who review local comprehensive land-use plans reported very few plans in which seismic hazards other than landslides were even mentioned.

The most relevant Washington State mandate for consideration of earthquake hazards is the State Environmental Policy Act of 1971 (SEPA).[12] This legislation and associated administrative regulations require cities and counties to adopt procedures for environmental review and designation of mitigating actions for certain categories of development (for example, planned developments, annexations, shoreline development) likely to have "significant" environmental impacts. Because many categories of development are exempted and the nature of mitigating actions is not specified, the SEPA process is not a very comprehensive approach for regulating development in areas subject to seismic hazards.

Administrative amendments, enacted in 1984, to the SEPA regulations allowed cities and counties to designate "environmentally sensitive areas," a procedure which would allow for review of land-use and development proposals that might normally be exempt from SEPA review. This more recent SEPA provision has been the basis for several of the "sensitive-areas ordinances" discussed in the following section.

The Federal flood-insurance program, authorized by Congress in 1968 and substantially strengthened in 1973 by providing penalties for communities failing to participate, provides a different set of mandates for local adoption of ordinances for management of land use and development within flood-prone areas. In this discussion, the flood-insurance provisions are relevant to localities potentially vulnerable to earthquake-induced water waves (tsunami). These provisions are potentially relevant to some coastal communities in Oregon and Washington, but relatively few of the relevant jurisdictions were included in this study (Urban Regional Research, 1988).

One of the central points in evaluating policies addressing secondary earthquake hazards is that, with relatively few exceptions, the relevant local ordinances do not prohibit development in potentially hazardous areas; they only control it to some degree. The typical approach is to require appropriate engineering in the form of special pilings or strengthened foundations for structures along steep slopes or in areas with expansive soils. This requirement is more or less routine as many building officials reported acting daily on geotechnical or soils reports they require under UBC provisions. More extensive approaches to mitigation of secondary hazards entail special review processes for development in areas with steep slopes or that are vulnerable to other seismic hazards.

The most specific local policies concern landslide hazards. Nearly 60 percent of the cities reported having some form of steep-slope or landslide-hazard ordinance. (All the Oregon counties and more than half the Washington counties reported having landslide regulations.) Those jurisdictions without specific steep-slope ordinances cited UBC provisions regarding excavation and foundations (UBC sections 2905 and 2910) as one basis for allowing building officials to request soils or geotechnical reports for proposed buildings. Excavation and grading ordinances based on appendix Chapter 70 of the UBC serve as the basis for some local ordinances requiring mitigating actions in areas subject to landslide hazards. Other jurisdictions have specific steep-slope ordinances that specify limits on construction and (or) requirements for geotechnical reports and mitigating actions. And yet other jurisdictions had more generic "sensitive-areas ordinances" that included special review and permit processes for development in designated areas subject to landslide hazards.

Liquefaction and subsidence hazards appear to be dealt with less directly. The UBC excavation and foundation provisions (section 2905) make general reference to "expansive soils," thereby providing building officials with a basis for requiring mitigating actions for areas subject to liquefaction and subsidence. However, building officials reported considerably more difficulty in deciding when to require the reports that trigger engineering solutions. Some officials appear to be very aggressive (for example, in requesting reports when in doubt), whereas others seem to be more restrained.

Sensitive-areas ordinances are more comprehensive approaches used by jurisdictions in establishing overlays on land-use maps that designate areas subject to such hazards as expansive soils, steep slopes, or subsidence. When development is proposed within the designated sensitive areas, special review processes that include consultant reports or

[12]Subsequent to completion of this study, Washington enacted in 1990 and further amended in 1991 the State Growth Management Act. This act requires every county and city in the State to designate critical areas within its planning jurisdiction, including areas with geologic hazards. Other provisions of the act require the faster growing counties, including those in this study, to protect the designated critical areas from incompatible land uses. In practice, the critical-areas provisions of the State Growth Management Act supersede the sensitive-areas provisions of the State Environmental Policy Act. The State Shoreline Management Act of 1971 is less directly relevant to earthquake-risk reduction. It establishes a cooperative program between the State and local governments under which specified local governments with coastal or riverine shorelines must establish plans for managing the shorelines.

other actions are required. The specific requirements for development in sensitive areas vary among the ordinances. Two different examples are the King County sensitive-areas ordinance and Bellevue's "natural determinants code." King County's ordinance requires geotechnical reports and negotiated mitigating actions. Bellevue's code is more prescriptive in specifying such things as the type of footings required for foundations of buildings in sensitive areas and in establishing a transfer of development credits to other sites for developers who agree to limit development in sensitive areas. Personnel involved with both programs report noteworthy success in modifying development in areas having steep slopes, moderate success in areas subject to subsidence, and limited attention to other seismic hazards.

Seismic hazards are only indirectly considered as part of longer range zoning or land-use decisions. Many Washington jurisdictions reported having comprehensive plans that generally refer to seismic hazards. Oregon jurisdictions are required by the State land-use planning mandate to evaluate natural hazards as part of their planning processes. In practice, most Oregon jurisdictions' land-use plans appear to be fairly general evaluations of earthquake potential.

The only way that jurisdictions in this study appeared to use land-use planning as a longer term response to seismic risks was public land acquisition so that the acquired property could remain as open space. For example, Bellingham planners cited their extensive open-space acquisition program as a long-term means for addressing seismic risks. In jurisdictions where such open-space acquisition was done, seismic concerns were a relatively minor impetus. These programs tend to be undertaken to protect wetlands, limit vulnerability to landslides, protect marine bluffs, or to reduce flood risk.

UTILITIES AND PORTS

The utilities and ports engineers who participated in this study reported considering seismic hazards as normal practice in constructing new facilities or upgrading existing ones. Good engineering practices were presumed to provide adequate seismic-risk resistance. Interviewees reported only rare instances when seismic-risk considerations entered into siting or land-use decisions. Only a few of the utilities included in this study have initiated formal reviews of the earthquake vulnerability of their systems.

The design of facilities for a water system or a port is obviously very different than the design of a major building. Utility personnel design a range of facilities including reservoirs, storage tanks, pumping stations, control centers, and transmission lines. Port personnel design piers, cranes, loading and storage facilities, drydocks, and other ship repair facilities. Because of the variety of facilities involved, ports and utilities depend greatly upon experienced and knowledgeable engineering consultants for all aspects of facility design. The larger ports and utilities have very sophisticated engineering units and spend large amounts (several reported hundreds of thousands to millions of dollars per year) on geotechnical and other engineering consultants for facility design.

Engineering practices relating to seismic-risk considerations for such facility design might be considered more an art than a science. Engineers who design such facilities do not have a single reference source like the UBC to guide sesismic-risk design. Instead, nearly a dozen professional associations provide guidance or standards concerning design elements for these facilities.[13] "Good" engineering results from knowing what guidelines might be helpful, what seismic forces to design for, and how to extrapolate from existing codes or standards to the particular design situation. Experience and professional knowledge are at the heart of this process.

This study provides little information about the adequacy of engineering practices for seismic safety in this region. Utility and port engineering personnel who were interviewed for this study reported confidence in the consultants they had worked with over the years. Earthquake hazards appeared to be only one of many engineering design concerns, of less concern than high winds to many of the respondents (particularly among ports). Although they acknowledged potential vulnerability of parts of water systems or port facilities to seismic hazards, most interviewees thought that seismic hazards were adequately addressed, particularly in newer facilities.

Only three utilities in this study, the Everett, Portland, and Seattle water departments, have initiated formal reviews of the seismic vulnerability of their systems. For two of these utilities, an engineering director who had previous experience with seismic design considerations in California provided an impetus for the review. Some of the other utilities had addressed seismic risk in isolated aspects of their systems, such as slope stability around some reservoirs, foundations in older pumping stations, and spillways for dams. These seismic-risk-reduction efforts typically emerged from facility reviews undertaken for other purposes.

Many water utilities reported ongoing renovation programs for their major pipelines and other water mains. In some jurisdictions, the water system contains major elements that are quite old. Tacoma has a water pipeline dating from 1915; Everett has one dating from 1929. Even newer pipelines constructed in the 1930's or 1940's were reported by utilities for which cast iron and brittle cement piping is common. Replacement of older pipes with ductile iron pipes

[13]For example, guidelines prepared by the Technical Council on Lifeline Engineering of the American Society of Civil Engineering address oil and gas piping systems, buried pipelines, and numerous other aspects of lifeline engineering. The American Water Works Association has created standards for welded-steel water-storage tanks. The American Concrete Association provides standards for concrete sanitary storage facilities used in treatment plants. Other compilations of existing practices have been published by the Structural Engineers Association of California and by the Building Seismic Safety Council.

and use of flexible piping for joints are common practices as part of renovations. Although such renovations are primarily to reduce future maintenance costs, they also increase seismic resistance.

Ports appear to be in a somewhat different situation regarding older structures. Modernizing facilities has been an important part of the business because of competitive pressures. All the ports in this study had substantially upgraded or replaced piers over the past few decades, except for one older wooden pier used by one of the ports. Most of the remaining older structures are warehouses that are planned to be replaced or whose use is limited to lower valued purposes.

Perhaps the greatest potential seismic vulnerability for ports is liquefaction. Port facilities in this region are mostly built on alluvial plains and extensive filled areas. The primary response to the liquefaction hazard has been incorporation of the potential in engineering designs. The liquefaction hazard was seldom cited by interviewees as an important land-use consideration. The examples respondents cited were of a proposed warehouse and other buildings for which more suitable sites were selected. The engineering directors commenting on these siting decisions were confident that engineering designs could have been developed to address the hazard, but it made more economic sense to put the buildings elsewhere. Such choices are more limited when it comes to the design of piers or other water-dependent elements of port operations.

THE POLITICAL AND ECONOMIC ENVIRONMENT FOR RISK REDUCTION

Risk reduction policies and practices are shaped by a host of local political and economic factors that are influenced by State and other mandates. Earthquake risks and the political-economic situation of the jurisdictions studied vary considerably. In the following discussion, cities and counties are categorized according to existing and potential risk-reduction efforts.

RELATIVELY VULNERABLE CITIES

Thirteen cities in the study can be classified as relatively vulnerable to earthquake hazards (table 46). The vulnerability of these cities is a function of the scale of existing development and of population size. Consideration of existing earthquake-risk-reduction practices and the political-economic environment for future risk-reduction efforts leads to further delineation of three categories of future risk-reduction prospects among the 13 more vulnerable cities (table 46).

The three largest cities in the region are in this grouping. The population of this group of cities has been fairly stable (median in 1987 of 44,000) with a median population growth from 1980 to 1987 of less than 2 percent. Valuable buildings are being constructed in these cities (median 1987 commercial building-permit values of about $20 million with a range of $1 million to $500 million). However, the value of new construction is a relatively small percentage of the total value of the building stock.

The extent of existing development and lack of substantial population growth of these cities have four main implications:

- Unreinforced masonry buildings, reinforced concrete frame buildings built before the 1960's, and concrete tilt-up buildings built before the mid-1970's constitute considerable potential risk
- The potential for property loss is substantial because of the amount of development in these cities

Table 46. Risk-reduction prospects for cities that are relatively vulnerable to seismic hazards, Oregon and Washington.

Category of cities	Cities	Risk-reduction prospects
"Pacesetter": Large cities with advanced building departments; weaker land use provisions.	Seattle and Tacoma, Wash.; Portland, Oreg.	Good: Potential for continued innovation for upgrades of existing buildings; retrofit provisions more difficult.
"Resourceful": Moderate-sized cities with risk-reduction initiatives spurred by individual efforts.	Aberdeen, Bremerton, Olympia, and Renton, Wash,; Salem, Oreg.	Mixed: Receptive to risk reduction, but limited resource base and political support; practices easier to influence than local policies.
"Restrained": Moderate to larger size cities constrained by economic conditions or lower risk perception.	Bellingham, Everett, Kelso, Longview, and Vancouver, Wash.	Constrained: Uphill effort to establish seismic-risk reduction because of economic and political factors.

- Land-use policies and practices with respect to seismic hazards are relatively weak at present and are likely to be relatively ineffective in the future. There is very little undeveloped land for which to apply traditional land-use risk-reduction measures
- The degree of earthquake-risk reduction in these areas is and will be largely determined by policies and practices concerning existing buildings and their renovation

PACESETTER CITIES

This category comprises the three largest cities in the region, Portland, Seattle, and Tacoma (average 1987 population of 360,000). These cities have the most knowledgeable building departments in the region and the most experience in negotiating renovation of existing potentially hazardous buildings. Seismic provisions in the building codes of these cities date to the late 1940's or early 1950's, although these early provisions were very minimal compared to today's standards. These cities are also leaders in developing advisory groups for negotiating the particulars of seismic-resistant building renovations, in establishing parapet ordinances, and in Tacoma, instituting a strong-motion instrument program for measuring earthquake forces in buildings.

The capabilities and experience of the building departments in these cities provide confidence that these cities are doing as good a job as any major city in the country in assuring adherence to current seismic standards for new construction.[14] Because these cities have their own building codes, local strengthening of code provisions is possible, except in Portland whose code is constrained by State law.

Modification of codes would not necessarily be done readily. One policy official, incorrectly referencing current practice, commented about the U.S. Geological Survey hazard assessment program:

> We've got conservative codes. They provide considerable protection. Right now, we're designing to what California has been designing for the past 20 years. But we're not going to start changing the codes just because of some new reports. There'd have to be considerable evidence before we make any changes. And if seismology has become an exact science, that's news to us.[15]

Building officials interviewed from these cities as a group gave the highest ratings for the likelihood of potential significant damage to buildings in their cities from moderate earthquakes (mean of 50 for the 0 to 100 scale used in the building officials' risk assessment) or major earthquakes (mean of 80 for the 0 to 100 scale). In contrast, elected officials from these cities appeared to have the same degree of concern (or indifference) to earthquake hazards as officials from other cities. The political-economic environment is such that building officials for these jurisdictions doubted that retrofit programs requiring seismic upgrading could be instituted. As one official stated: "We have kicked the idea [of a retrofit program] around at administrative levels, but it won't fly politically, and there are technical difficulties in establishing appropriate standards."

These cities tend to be much less innovative with traditional land-use practices such as the use of overlay zones to land-use plans, open-space zoning, or other measures to limit seismic risk. The comment of one planning director summarized the approach of this category of cities: "Besides landslide controls, we have done very little [in the way of land-use measures]. The building department is in the driver's seat since they handle geotechnical reviews and building regulation."

RESOURCEFUL CITIES

This category (table 46) comprises five cities of moderate population (average 1987 population 42,000) that are distinguished more by having initiated earthquake-risk-reduction practices than by having innovative seismic-hazard-reduction policies or sophisticated building departments. For example, Aberdeen personnel have participated in tsunami-warning studies, and at the time of our interviews were funding a study of risks posed by unreinforced masonry buildings. Bremerton officials have condemned potentially earthquake vulnerable buildings as unsafe and have upgraded school buildings for seismic safety (both undertakings were apparently controversial for the personnel involved). The building departments of Olympia, Renton, and Salem reportedly have been relatively aggressive in enforcing seismic-risk-abatement requirements, particularly regarding homes.

The label "resourceful" is applied to this category of cities because the impetus for risk reduction appears to have come through individual efforts to affect building practices rather than from external mandates or policy decisions. In most instances, a building official willing to endure criticism for being too stringent was a key factor in initiating risk-reduction efforts. For this category of cities, a strong base of support for pursuing risk reduction seems to exist in relevant administrative levels of government. However, the political climate, broadly defined in terms of elected officials and the building community, and the economic climate do not necessarily support further risk-reduction efforts. As one official said, "This jurisdiction struggled to institute its only retroactive ordinance—requiring smoke detectors in certain situations." Because of the tenuousness of these risk-reduction efforts, there is a potential that they could decline, moving these cities into the "restrained" category (see following) of

[14]The Building Seismic Safety Council trial-designs review of implications of designing different classes of new buildings according to the council's recommended provisions showed that following these new provisions in Seattle would result in lower construction costs than those incurred by following current Seattle building codes (Webber, 1985). Tacoma and Portland were not included in the trial-design program.

[15]Statement of the Director of Seattle's Department of Construction and Land Use, quoted from "Seattle Could Face 'Great' Quake But Building Officials Skeptical," Seattle Business Journal, September 10, 1984, p. 20.

relatively vulnerable cities. Practices change quickly as new directions are established by elected officials, as key employees leave, or as budgets are further constrained.

RESTRAINED CITIES

This category comprises five moderately populated (1987 average population 38,000), low-growth cities for which State-mandated actions appear to be well integrated with building regulatory and planning practices, but sustained earthquake-specific risk-reduction policies or practices have not been initiated. Yet, these communities have potentially noteworthy earthquake risk because of the nature of the building stock.

Many respondents from cities in this category indicated that earthquake-risk-reduction initiatives are constrained by political-economic circumstances that vary among jurisdictions, for example, resistant policy officials, unreinforced masonry buildings with concentrated ownership, vacant buildings that are not being renovated because of depressed economic conditions, and so forth. A component of the restrained response to seismic risk is the relatively depressed economies of these cities, as reflected by an average population growth from 1987 to 1988 of less than 1 percent and a 1987 median value of building permits issued for apartments, office buildings, and industrial buildings of only about $3 million.

The challenge for future risk-reduction efforts for this group of cities is building both a supportive political and economic climate and the capacity to undertake needed measures. As a group, elected officials of these five cities gave the lowest average ratings of the likelihood of significant deaths, injuries, or damage in the next 20–30 years from a moderate earthquake (average score 19) as well as the lowest average ratings of the likelihood of significant losses from a major earthquake (average score 13). These ratings are about one-half the corresponding averages reported in the other two categories of relatively vulnerable cities.

LESS VULNERABLE CITIES

The category of less vulnerable cities includes 30 cities for which earthquake risks are lower when compared with the more highly populated, more developed cities discussed previously. This lower risk is relative, as these cities still have considerable earthquake risks. As for the relatively vulnerable cities, this less vulnerable group can be further differentiated into three categories (table 47) in terms of existing risk-reduction practices and the general political and economic evironment.

The median population as of 1987 for these cities was 19,100. Newer development is indicated by the rapid growth rates of these cities, which had a median population growth rate of 13 percent and a median growth rate in commercial building permits of 19 percent from 1980 to 1987. The recent development of these cities and the lower population sizes have several implications in comparing these less vulnerable cities to the relatively vulnerable cities:

- Although there is an existing hazard posed by tilt-up concrete buildings and unreinforced masonry buildings in at least some of the cities, the rate of development forces attention to seismic considerations for new construction

Table 47. Risk-reduction prospects for cities that are less vulnerable to seismic hazards, Oregon and Washington.

Category of cities	Cities	Risk-reduction prospects
"New sophisticate": Rapidly growing cities for which building-code enforcement and planning efforts have been spurred by extensive commercial development.	Auburn, Bellevue, Kent, Kirkland, Mercer Island, and Redmond, Wash., Beaverton, Gresham, Lake Oswego, and Tigard, Oreg.	Good: Land-use considerations a key aspect of growth controls; capable and interested building departments.
"Measured": Smaller cities where varying hazards are addressed by existing building and land-use provisions.	Anacortes, Bothell, Edmonds, Lacy, Puyallup, and Mount Vernon, Wash.; Milwaukie and McMinnville, Oreg.	Mixed: Potential for hazard reduction limited by economic or other city-specific factors; local practices easier to influence than policies.
"Nonplayer": Smaller cities where earthquake hazards are not considered to pose much risk.	Des Moines, Lynnwood, Mountlake Terrace, and Oak Harbor, Wash.; Newberg, Forest Grove, Hillsboro, Keizer, Oregon City, Tualatin, West Linn, and Woodburn, Oreg.	Poor: Need to be convinced that there is noteworthy earthquake-hazard risk.

- Because most of these cities still have vacant land for further development, land-use measures can be used to reduce risk

As many of these cities cope with growth-control issues, land-use regulation is especially volatile. Thus both opportunities and problems exist: opportunities for linking earthquake risk reduction to growth controls and problems in adding risk-reduction measures to a highly charged political environment.

NEW-SOPHISTICATE CITIES

This category comprises 10 of the fastest growing moderate-sized cities in the region. The average 1987 population was 37,000, and the average population growth from 1980 to 1987 was 32 percent. The average growth in value of building permits issued for apartment, commercial, and industrial buildings during this period was 105 percent. The rapid growth, accompanied by development of commercial and manufacturing facilities in many of these cities, has stimulated an increase in the capacity of building and planning departments. Building and planning departments in these cities are relatively advanced compared to those of similar-sized cities of no or little growth.

Private engineering and design consultants have been important in increasing the sophistication of new construction within these cities. For example, Gresham city building department employees described how Japanese electronic firms and their California structural consultants brought them greater understanding of the need for seismic design. Auburn, Bellevue, Beaverton, Kent, Kirkland, Redmond, and Tigard have all had substantial growth in commercial development. Mercer Island and Lake Oswego are more residential in character and have lower growth rates. Their increased attention to seismic risk comes from a combination of building-department awareness and more custom designed homes than most communities have.

Because of the high growth rate of the cities in this category, land-use issues are more controversial for this category. All of the cities have some form of steep-slope regulation, typically involving some form of map-overlay zone designating areas where geotechnical reports are required prior to development. This category in general has the greatest potential for linking future land-use risk-reduction measures to growth controls.

MEASURED CITIES

This category (table 47) consists of eight smaller moderate-growth cities for which State-mandated earthquake-risk-reduction efforts appear to be integrated into normal practice. However, other risk-reduction policies or practices are limited. The primary reasons for designating these cities as less vulnerable are the smaller populations and lesser value of new commercial development. The average 1987 population for these eight cities was 16,500. Most of them have at least a few unreinforced masonry buildings in historic downtown areas. Building officials of cities in this category gave a somewhat higher average rating of the likelihood of significant damage from a major earthquake (57 on the 0 to 100 scale) than the corresponding rating of building officials in the new-sophisticate category (average rating of 39). The reported seismic-risk perception of elected officials was about the same for the two categories.

Cities in this category have potential for joining the new-sophisticate category, but that potential appears to be limited by economic circumstances. These cities do not have the new commercial development or redevelopment that the new-sophisticate category has. The median value of building permits issued in 1987 for apartment, commercial, and industrial buildings was $1.3 million, compared with a value for the “new sophisticates” of $17.3 million. These cities are not as sophisticated in their approach to land use and its relationship to risk reduction as are the “new sophisticates.” Because growth is not as great in cities of this category, there has been less pressure to develop land-use controls that concurrently reduce earthquake risk.

Relevant city personnel seem to have a reasonably strong recognition of earthquake risks. However, their ability to act is severely constrained by economic circumstances. A change in economic circumstances, which might move some of these cities into the “new sophisticates” category, is difficult to forecast.

NONPLAYER CITIES

This category (table 47) comprises somewhat smaller cities (average 1987 population 16,000) for which seismic hazards appear to be of lesser concern to both elected and building officials. The “nonplayer” name indicates the perception of officials in these cities that seismic risks are not particularly relevant to them. The label does not imply that these cities are not enforcing seismic components of building codes or following reasonable planning practices.

Building officials for nonplayer cities had the lowest average ratings for the likelihood of significant losses from a moderate earthquake (14 on the 0 to 100 scale) and from a major earthquake (average rating of 30): These ratings are about one-half the corresponding ratings of building officials in each of the other categories of cities. Whether relative indifference is justified is difficult to judge—thus the need and purpose of the overall U.S. Geological Survey hazard-assessment process. Building officials from these cities consider their areas at lower risk because they are primarily residential, comprise wood-frame buildings, and have only newer commercial development.

The challenge for future risk-reduction efforts for this category of cities is to document the extent of earthquake hazards and then, if the documented hazard is serious, to convince relevant personnel that the hazard should be addressed.

COUNTIES

Relevant county risk-reduction policies and practices apply, with a few minor exceptions, only to unincorporated areas within the counties. Compared to their municipal counterparts, the unincorporated areas have lower population, less developed building stocks, and much lower densities of both population and structures. Although these factors no doubt have produced a lower sense of earthquake vulnerability, the recurring flooding and landslides in unincorporated areas of many counties are reminders that these areas are not insulated from natural hazards.

The unincorporated areas of the counties in the study area are undergoing the most change. Unincorporated fringes of urban areas are rapidly becoming urbanized, and rural areas are rapidly becoming suburbanized. The extent of development of the counties and how they have responded to increased pressure for both building and land-use regulation define the three categories of risk-reduction prospects for counties discussed in this section (table 48).

LEADING COUNTIES

This category (table 48) comprises the three most populated counties that surround the largest urban areas in the region. Nearly 1 million people (1987 estimate) live in unincorporated areas of these counties. The growth in these unincorporated areas can be characterized as increased urbanization accompanied by development of commercial, professional, and light manufacturing facilities. The counties are called "leaders" because they have relatively older building codes (since the 1950's and into the 1960's), relatively larger building departments than other counties, and some land-use provisions concerning seismic hazards.[16]

Compared to the other two categories of counties, this category has a greater stock of existing, potentially earthquake vulnerable buildings. These buildings are primarily tilt-up concrete buildings constructed before the mid-1970's. Building officials for these counties rated the likelihood of significant damage from a moderate earthquake (average rating of 48 on the 0 to 100 scale) as twice as likely as the corresponding rating for the other categories of counties. They rated the likelihood of significant damage from a major earthquake (average rating 65) as 1.5 times greater than the other two categories of counties. These counties have large building departments with experience in reviewing complex structures, but the in-house structural-review capacity (that is, the number of structural engineers on staff) is more limited than for the counterpart "pacesetter" cities.

The leading counties have paid more attention to land-use considerations than have "pacesetter" cities. Each county in the "leader" category has some form of landslide land-use controls in effect. King County has an ordinance that is commonly cited as an innovation in regulating land-use practices for risk reduction and preservation of environmentally sensitive areas. Land-use issues have been important considerations in debates about development, and seismic risk was considered in some decisions. For example, seismic factors relating to landslides reportedly were considered in Multnomah County's decision to deny a permit for a metropolitan-area landfill. King County officials have been embroiled in debates over delineation of environmentally sensitive areas. As one means of controlling growth, these counties are moving toward strengthening land-use policies that may also have beneficial side effects for earthquake risk reduction. These improved policies provide the best prospects for addressing earthquake risks in these counties.

[16]Because of the urbanized nature of Multnomah County, building regulation is somewhat different from that of the other two counties in this category. The incorporated areas that make up the county regulate building practices.

TRANSITIONAL COUNTIES

This category (table 48) of 10 counties comprises those unincorporated areas for which growth has entailed the greatest transitions. Large unincorporated areas in these counties are rapidly changing from rural to suburban. The median growth rate in population of unincorporated areas of these counties from 1980 to 1987 was 17 percent. Building and planning departments are trying to catch up with the growth rate by increasing their capacity to address future growth pressures.

For some of these counties, catching up has consisted of establishing building departments and instituting land-use practices. As noted by interviewees:

- "In 1974 over one-half of the county was unzoned and there was no building code."
- "There was no building code until 1971. Since then, enforcement has been progressive. You can't just institute such regulation overnight."
- "Our first major commercial building was built in 1980. There was no county-wide zoning until 1980."

Other counties in this category are much further along in developing building departments and in land-use planning. For these, the main issues have been strengthening building-code enforcement and land-use practices.

Mixed reaction to growth pressures is shown by the variation in the status of current building regulatory and land-use practices. For example, a proposed comprehensive land-use plan for Pierce County that contained zoning and steep-slope provisions was defeated in a county-wide

Table 48. Risk-reduction prospects for counties studied, Oregon and Washington.

Category of counties	Counties	Risk-reduction prospects
"Leading": More heavily populated counties near largest urban areas; established risk-reduction efforts.	King County, Wash.; Multnomah and Washington Counties, Oreg.	Good: Land-use considerations are a key aspect of growth controls; capable and interested building departments.
"Transitional": Counties whose unincorporated areas are changing from rural to suburban, forcing attention to building and planning concerns.	Clackamas, Clark, Island, Kitsap, Pierce, Snohomish, Thurston, and Whatcom Counties, Wash.; Marion County, Oreg.	Mixed: Prospects limited by county-specific factors; some counties are resistant to change.
"Rural": Counties whose unincorporated areas have remained rural; limited population exposure and fewer commercial buildings.	Cowlitz, Grays Harbor, Jefferson, Mason, and Skagit Counties, Wash.; Polk and Yamhill Counties, Oreg.	Poor: Recognize risk and have undertaken some risk reduction for flooding and landslides; further efforts not economically feasible.

referendum in 1986. Many voters apparently thought the plan went too far in regulating land use. Planning officials in three transitional counties specifically mentioned political pressures to go slow in regulating growth.

The future prospects for risk reduction appear to be somewhat mixed for this category of counties. Growth issues will inevitably continue to be an important factor pressing future land-use and building regulatory decisions. However, the political climate, broadly defined, does not necessarily support strong land-use regulation.

RURAL COUNTIES

This category (table 48) consists of seven counties in which growth is occurring but whose unincorporated areas have remained predominantly rural. Officials in these counties have thus not had to confront the growth issues that have affected policies and practices of the other two categories of counties. One building official noted that "we have not had a subdivision of any kind," and another pointed out that "this is a one-man building department." The median population growth rate of unincorporated areas of these counties was 5 percent from 1980 to 1987. The median population of unincorporated areas of these counties was 11,600 in 1987.

Despite the rural nature of these counties, they have had some noteworthy experiences with natural hazards. Grays Harbor County officials evacuated 14,000 people in 1986 in response to a tsunami warning (flooding but no tsunami occurred). Jefferson and Skagit County officials have been involved in lawsuits stemming from deaths caused by landslides in logged areas. Cowlitz County officials have been at the center of a series of negotiations concerning flood and debris control relating to Mount St. Helens. Jefferson County contains Port Townsend, an incorporated area with many unreinforced masonry buildings.

The constraints for future risk-reduction efforts for this category of counties appear to have less to do with recognition of risks than with the costs involved. The exception to this observation are the Oregon counties in this group for which there is little perceived seismic risk. The rural counties simply do not have resources to undertake more extensive risk-reduction efforts.

FUTURE EARTHQUAKE-RISK REDUCTION STRATEGIES

The preceding discussion provides a basis for considering risk-reduction strategies that might be undertaken as new information about earthquake risks is developed for this region. Ongoing research may provide a better understanding of the earthquake hazard in this region. Assumptions about presumed degree of risk will change dramatically if research indicates a high probability of a great (M>8.0) earthquake. Such information is potentially relevant to all jurisdictions studied, especially the "nonplayer" category of cities.

Prospective risk-reduction strategies range from a relatively passive one of hazards-information dissemination to more active efforts to seek policy reforms or to influence practices (table 49). These strategies are not mutually exclusive: pursuing one does not preclude pursuing another. However, because of limited resources, choices must be made as to the strategies to emphasize. Evaluating the strengths and limitations of the strategies entails envisioning the likely responses to the implementation of each strategy. The following assessments are based on the understanding of the political and economic environment described previously.

Table 49. Future earthquake risk-reduction strategies for the Oregon and Washington region studied.

Strategy and examples	Target groups	Strengths	Limitations
Disseminate hazards information: Workshops; publication of hazard maps, loss estimates.	Widely disseminated (targeting possible).	Easily implemented (status quo); information essential for risk reduction.	Only the more capable jurisdictions will act on information; does little for less capable jurisdictions.
Seek mandate revisions: State building-code and land-use mandates.	State agencies, code-writing authorities.	Uniform local policies; few entities to address.	Limited to new buildings or development; practices will still vary among jurisdictions.
Influence local government practices: Workshops, staff funding, demonstration programs, technical assistance.	Local building officials and planners.	Can target jurisdictions with greatest needs; does not require policy changes.	Building officials are restricted by codes (especially Oregon); cities in most need may not want assistance.
Influence private professional practices: Workshops, publication of guidebooks, technical assistance.	Architects, engineers (design and engineering community).	Can target specific groups; does not require State or local endorsement.	Competitive pressures may limit ability to exceed minimum code requirements.

DISSEMINATE HAZARDS INFORMATION

This strategy consists of dissemination of new scientific information about earthquake hazards in the region through professional publications, newsletters, and meetings. The information might be presented as hazards maps prepared at a scale that would show information relevant to at least the major jurisdictions in the region. Demonstration uses of Geographical Information Systems that translate hazards into the risks posed for people or structures might also be undertaken.

One strength of hazards-information dissemination is that it is fairly easy to implement. Several activities are already being jointly undertaken by the Federal Emergency Management Agency and the U.S. Geological Survey. This approach assumes that credible scientific information is essential for making the case for revising building regulatory or land-use policies.

The key uncertainty for this strategy concerns who is likely to act upon the new information. Although the details depend on both the substance and the form of the information, this study suggests that only a few categories of cities and counties are either capable of acting or willing to act upon such information without further external efforts to influence risk-reduction practices. Only the "pacesetter" and "new-sophisticate" cities, and "leading" counties appear to have both the technical in-house capacity and at least some willingness to respond to such information. The "non-player" cities may respond to new information about earthquake risks, but to get them to respond with risk-reduction measures would probably take more than simply providing the information. For the other categories of cities and counties, too many other factors constrain response.

Other potentially responsive audiences are attentive professional groups such as the structural engineers associations of Washington and Oregon. These groups effectively translate the information into new engineering or design practices. Depending on the extent of change in risk assumptions and the credibility of the information, the professional groups might use the information to lobby State building agencies and private code-writing authorities for changes in building standards.

Clearly, better hazards and risk information is necessary. However, this study of risk-reduction prospects suggests that mere dissemination of such information, without other efforts to influence policies or practices, will produce limited reduction of earthquake-hazard risk. The more capable cities and counties may make use of the information, whereas little will likely happen in the remaining jurisdictions. Some structural engineers, geotechnical consultants, and others who design structures may use the new information as part of their practice.

SEEK MANDATE REVISIONS

This strategy consists of directly seeking revisions in State-level building-code or land-use mandates. The specific changes sought will depend upon the nature of the information developed from the scientific research. These revisions might include new seismic-zone delineation, new design standards, special code provisions for particular categories of buildings, or better delineation of seismic hazards within land-use mandates. Building codes could be changed either by State amendments or through the code-revision process of the International Conference of Building Officials. Neither procedure would be easy, and both would require considerable technical justification.

Because State building-code and land-use mandates establish the foundation for local risk-reduction policies, the mandate-revision strategy could lead to desired changes in local policies. Moreover, the changes would be more or less uniform within each of the States. However, this strategy for influencing risk reduction has three main limitations. The first is the difficulty of achieving changes, particularly signficant ones, in State building codes, private codes, or State land-use mandates. The second limitation is that changed policies will only address future development and construction. Even with substantiation of sizeable risks, retroactive State-level policies concerning seismic-risk review or retrofit of existing, potentially hazardous buildings are very unlikely to be enacted in Oregon or Washington. The third limitation is that although local policies closely mirror State mandates, local practices still vary considerably. Implementation of the policies and the discretion used by building and land-use officials depends on the broader political and economic environment.

In sum, appropriate changes will likely be made for new construction (or renovation) throughout the region. To the extent that the new provisions allow discretion in interpretation or implementation, there will be a varied response that reflects differing political and economic factors among the categories of cities and counties. Overall risk reduction in the region can be expected to advance, but the categorization of cities and counties is unlikely to change.

INFLUENCE LOCAL GOVERNMENT PRACTICES

This strategy consists of efforts to influence the practices of building and planning departments in carrying out State mandates and local policies. This influence might entail providing jurisdiction-specific seminars on seismic risk, preparing guidelines for using discretionary building-code and land-use judgments, providing technical assistance in land-use planning or construction-plan review, or funding geologists or structural engineers as part of local staffs. These actions could be targeted to specific jurisdictions or classes of jurisdictions.

This strategy has several strengths. The targeting of assistance would respond to the varied situations of jurisdictions in this region. The emphasis on practice, as opposed to policy, would influence important discretionary judgments concerning such things as renovation of buildings. Also, several model risk-reduction efforts could be developed that could potentially be transferred to other jurisdictions.

The limitations of this strategy result from the constraints imposed by State mandates on local exceptions to those mandates. The Washington State building code allows local jurisdictions to enact stronger provisions than State mandates with appropriate State-level review. The Oregon State building code does not permit exceptions. Therefore, the effectiveness of this strategy is a function of the amount of discretion that exists within existing codes. This strategy would improve risk-reduction efforts the most among those jurisdictions in which current risk-reduction efforts are the weakest. It will do little in the "pacesetter" or "new sophisticate" cities, or in the "leading" counties.

INFLUENCE PRIVATE PROFESSIONAL PRACTICES

This strategy consists of efforts to influence the practices of the private-sector engineering and building-design community. This influence might entail providing special seminars on seismic risk and earthquake engineering, funding creation of special guidelines by professional associations, or providing some other form of professional development opportunities. These actions could be targeted to different types of engineers and building-design professionals.

The strength of this strategy is in the prospective direct influence on the design and engineering recommendations of this community in reducing earthquake risks. The results are likely to be greatest in those sectors that rely extensively on the judgments of design and engineering professionals, such as the utilities and ports in this study. Indirect benefits of changes in practices or knowledge might lead to interest in lobbying for code changes.

Obvious implementation difficulties for this strategy are identifying and reaching appropriate professionals and then convincing them of the need for changes in practice. If these difficulties were overcome, the main limits to the effectiveness of this strategy are the constraints under which the design and engineering community practices its professions. Without code changes, competitive pressures and client desire to reduce costs may restrict the extent to which practices exceed minimum code requirements. The main beneficiaries of this strategy may be the professionals and supportive clients who already are doing the most to address earthquake risks. Insurance companies and financial institutions could potentially be important in endorsing or requiring new seismic-design practices. However, competition and other factors have limited the influence of insurance companies and financial institutions in stimulating stronger risk-reduction efforts.

CONCLUSIONS

The results of this study of earthquake-risk perceptions, existing policies and practices, and the political and economic environment allow substantially different interpretations of the current state of earthquake risk reduction in the region. A positive assessment includes the general awareness of damage potential by building officials, the relatively advanced building and land-use policies in some of the more populous jurisdictions, and the growth in earthquake-engineering experience among private design professionals in this region. A negative assessment might include the seeming indifference of elected officials to earthquake risks, the limited attention to seismic hazards of several categories of cities and counties identified in this study, and the inevitability of a major earthquake that building officials acknowledge will likely lead to significant losses.

Also, any summary evaluation is likely to mask the variation in situations that was discussed in this report. The discussion not only shows the extent to which jurisdictions have different relative risks, but also demonstrates the importance of considering political and economic factors when designing future risk-reduction strategies. The current situation and future prospects for risk reduction are very different between "pacesetter" cities and "restrained" cities, and between "leading" counties and "rural" counties.

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INTEGRATED TSUNAMI-HAZARD ASSESSMENT FOR A COASTAL COMMUNITY, GRAYS HARBOR, WASHINGTON

By Jane Preuss[1] *and* Gerald T. Hebenstreit[2]

ABSTRACT

The Grays Harbor region of southwestern Washington lies at the east edge of the Cascadia subduction zone. This study was conducted to examine the potential hazards to Grays Harbor arising from tsunamis generated just offshore by possible thrust earthquakes involving the Juan de Fuca plate. A series of numerical simulations were conducted to delineate the effects of tsunamis, either in the form of flooding or as high waves, in the populated areas around the shores of Grays Harbor and along the outer coast to the north and south of the harbor. Once the basic tsunami threat potential was identified, the soil structure and land-use patterns in and around Grays Harbor were examined to establish what hazards could arise from secondary tsunami and earthquake effects. These effects include damage to storage containers due to wave impacts, collapse of coastline structures due to wave scour and erosion, and flotation of storage containers (both moored and free standing) due to flooding. Attention was given to the possibility of the coincidence of tsunami waves and riverine flooding due to runoff. In the analysis, the Grays Harbor area was represented by microzones, each characterized by the type of hazard peculiar to its soil and land-use patterns. The study shows that such an integrated hazard-analysis methodology can be of great value in helping communities to plan for specific disasters rather than a broad spectrum of possibilities.

INTRODUCTION

This study was conducted to develop and apply a methodology for making an integrated hazard assessment that treats an earthquake-generated tsunami as the initiator of a suite of interrelated hazards rather than as the sole threat to a community. Through such an integrated approach to hazard assessment, relatively accurate loss estimates and subsequent mitigation efforts can be made effectively.

Because vulnerability to specific risk factors varies from community to community, a risk-based urban planning approach was developed that balances the needs of waterfront activities (industrial and resort) with safety and preparedness requirements in coastal areas vulnerable to tsunamis and earthquake-induced flooding. The study had four objectives:

1. Identify the threat of tsunamis. Characteristics and dimensions of the potential tsunami threat to a coastal community were defined. Numerical simulations of locally generated tsunamis arising from offshore earthquakes were used to define the direction of energy and wave heights.
2. Delineate the vulnerability zone. Patterns of vulnerability to tsunamis were defined based on land use and population distribution. Field work was used to make these determinations.
3. Identify secondary hazards. Secondary hazards that could result from earthquake ground motion and (or) impact of a tsunami or flood were defined. Specific attention was directed to the potential for release of hazardous materials. A combination of field inventory, multidisciplinary data analysis, and an air-dispersion model was used.
4. Microzonation. Primary and secondary hazards were correlated with vulnerability patterns, and a system of microzonation was proposed. Interactive analysis was used.

Grays Harbor, Wash. (fig. 236), was the location used to characterize earthquake-hazard risks along the Washington coast and to calculate the geographic area of vulnerability to earthquake hazards. The study area generally corresponds to an area of sand lenses discovered on the outer Washington coast at Willapa Bay and Grays Harbor (Atwater, 1987; Bourgeois and Reinhart, 1988) that has been interpreted as having been subjected to multiple tsunami impacts from great subduction events in the past.

ACKNOWLEDGMENTS

This study was sponsored by the U.S. Geological Survey (Grant No. 14-080001-G1346) under the Earthquake Hazards

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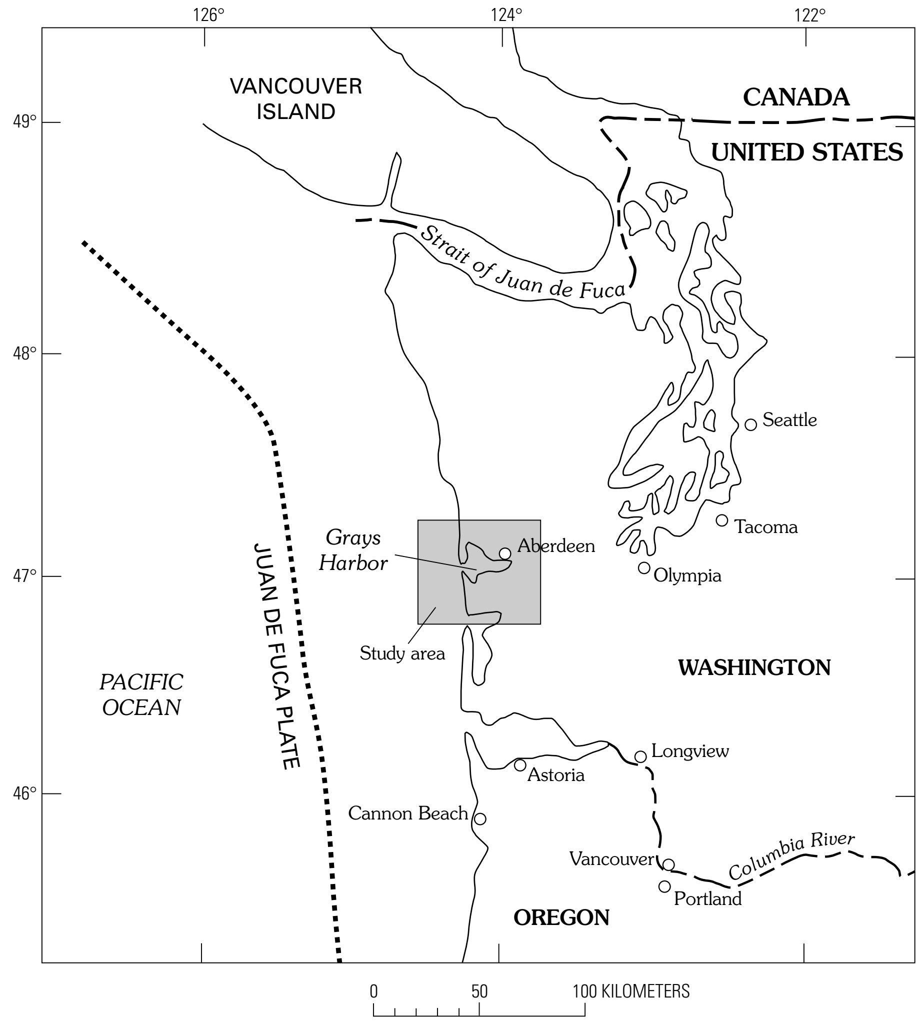


Figure 236. Index map showing the Grays Harbor study area (shaded). Heavy dashed line indicates shoreward boundary of Juan de Fuca plate. The south Cascadia portion of the Cascadia subduction zone extends from just north of Grays Harbor to southern Oregon.

Reduction Program and was based on a project conducted jointly by Science Applications International Corp. and Urban Regional Research. The authors thank their two reviewers, Peter May and James F. Lander, whose comments served to significantly strengthen the presentation of the results of the project.

BACKGROUND OF AND APPROACH TO THE STUDY

In the past decade, considerable interest has developed in the possible occurrence of major subduction-related earthquakes along the Juan de Fuca plate boundary in the Pacific Northwest (for example, see Heaton and Hartzell, 1986, 1987; Heaton and Kanamori, 1984; Rogers, 1988). Evidence from recent investigations (Bourgeois and Reinhart, 1988; Atwater, 1987) and from Indian legends (Heaton and Snavely, 1985) indicates that the coasts of Washington and Oregon are vulnerable to tsunamis. Atwater (1987) reported at least six episodes of coastal subsidence due to earthquakes in the last 7,000 years, with vegetated coastal lowlands being buried by intertidal mud. In three of the episodes, patterns of sand sheets lying atop the buried lowlands could be explained by inundation due to tsunamis and the resulting shoreward transport of sand. Other research (Reinhart and Bourgeois, 1987; Atwater and others, 1987; Johnson, written commun.) cited additional evidence for subsidence and possible tsunami-related flooding in the past 1,000 years.

Although the hazards most commonly expected from major earthquakes are ground movement and failure attributable to the seismic motion, an earthquake occurring offshore in a subduction zone always has the potential to generate a destructive tsunami, which could cause considerable damage to inhabited areas of coastlines. Tsunamis in 1946, 1952, and 1957 originated in the Aleutian Islands region of the North Pacific; a 1960 tsunami originated in Chile; and a 1964 tsunami resulted from an Alaskan earthquake. The recorded data (table 50), although spotty, show that significant waves struck the Pacific coast during these events. The coasts of Washington and Oregon were significantly damanged by the 1964 Prince William Sound, Alaska, earthquake and tsunami (Hogan and others, 1964) (table 51). A wave of about 3 m was observed at Ocean Shores, Wash., just north of the entrance to Grays Harbor.

Analysis of the 1964 Alaska earthquake damage in Seward, Alaska (fig. 237) indicates that there were four relatively distinct causes of tsunami damage. Primary causes were from direct water forces, including hydrodynamic forces, buoyancy, and hydrostatic pressures, and from loss of ground support through subsidence, compaction, erosion, liquefaction, and (or) sand transport. Secondary causes of damage were from direct water forces acting on land uses, including impacts from floating debris (logs, buildings, vehicles, boats), fire, and contamination of land and water from oil, fuel, and other stored materials. Most of the damage was due to the secondary impact of the tsunami. For example, buildings weakened by water-pressure forces were subsequently dislodged when foundations were scoured by the erosive actions of the drawdown following the incoming waves. Thus, even if water levels were not high, damage was still severe.

It is also important to note that considerable tsunami damage in coastal areas can occur away from the shoreline. Spaeth and Berkman (1972) described such damage in Oregon from the 1964 tsunami. The town of Seaside sustained about $275,000 in damage to residential and commercial areas several blocks from the shore. The waves surged up both the Necanicum River and Neawanna Creek, damaging bridges and structures set back from the coast.

These historical data do not establish the likelihood of locally generated tsunamis (source within 200 km of the shore), but they do indicate that the offshore topography of the region does not provide any natural protective barrier to incoming waves. This lack of natural protection means that a locally produced tsunami could indeed be a serious threat.

A recent study (Hebenstreit and Murty, 1989) used numerical modeling techniques to examine the potential threat to the coasts of Washington, Oregon, and British Columbia from tsunamis caused by earthquakes within the Juan de Fuca plate. The results of the study indicated that certain areas of the coastline were more susceptible to concentrated wave energy than others because of variations in offshore topography (similar to a finding by Hebenstreit and Bernard, 1985, for the Hawaiian Islands).

Tsunamis, like earthquakes, vary in magnitude and intensity. In addition, the nature of the tsunami risk is profoundly influenced by characteristics of land use in the inundated areas. The level of risk is examined by combining the likelihood of tsunami impact in a given geographic area with an inventory of the types of land-use-related hazards that could be exposed to that impact. The first step in mitigation-based land-use planning is to develop a clear understanding of scientific criteria for delineation of the hazard. Subsequently, land-use decisions can be based on specific vulnerability to distinct and definable risks.

The hazard analysis for this study consists of two parts. One is the identification of the geographic areas vulnerable to direct tsunami damage. Numerical simulation was used to identify this risk. The second part is the identification of potential secondary hazards caused by the earthquake and (or) the interaction of earthquake effects and tsunami. Identification of these potential hazards was based on secondary sources such as soils data from the Washington State Department of Natural Resources.

Table 50. **Maximum recorded wave heights for five recent tsunamis along the Pacific Northwest coast.**

[Data from U.S. Department of Commerce (1953), Salsman (1959), Symons and Zetler (undated), Berkman and Symons (undated), Wilson and Tõrum (1968), and Spaeth and Berkman (1972). (>), greater than; (---), no data recorded]

Location	Wave height, in feet (meters)				
	1946	1952	1957	1960	1964
Tofino, British Columbia	1.9 (0.6)	2.0 (0.6)	---	4.6 (1.4)	8.1 (2.5)
Port Alberni, British Columbia	---	---	---	---	[1]>17 (>5.2)
Victoria, British Columbia	0.7 (0.2)	1.2 (0.4)	---	---	4.8 (1.5)
Neah Bay, Wash.	1.2 (0.4)	1.5 (0.5)	1.0 (0.3)	2.4 (0.7)	4.7 (1.4)
Friday Harbor, Wash.	---	---	---	0.6 (0.2)	2.3 (0.7)
Seattle, Wash.	---	---	---	---	0.8 (0.2)
Astoria, Oreg.	---	---	0.5 (0.2)	1.0 (0.3)	2.4 (0.7)
Crescent City, Calif.	5.9 (1.8)	6.8 (2.1)	4.3 (1.3)	10.9 (3.3)	[2]>13 (>4.0)

[1]Gauge record incomplete; wave height estimated.
[2]Maximum wave height before gauge was destroyed.

Table 51. Wave heights and damage caused by the March 28, 1964, tsunami along the Pacific coast of Washington.

[Data from Hogan and others (1964), reported by Wilson and Törum (1968). (---), no data reported]

Location	Wave height, in feet, above local tide level (meters)	Amount of damage (in 1964 dollars)	Damage description
La Push	5.3 (1.6)	---	Several boats and floating dock broke loose from moorings
Mouth of Hoh River	1.7 (0.5)	---	None
Tahola	2.4 (0.7)	1,000	Loss of several skiffs and fish nets in inlet at mouth of Quinault River
Wreck Creek Bridge	14.9 (4.5)	500	Erosion of fill at bridge approach; debris on bridge deck and nearby highway
Copalis	---	5,000	Damage to buildings
Copalis River Bridge	---	75,000	Loss of one timber, Joe Creek Bridge bent, and two timber spans near the bridge center and one piling in a four-pile timber bent (Copalis River); loss of five-pile bent, damage to two-pile bents (loss of three pilings) and loss of two 20-ft (6.1 m) reinforced-concrete spans (Joe Creek)
Copalis River Highway	---	5,000	Shoulder erosion and debris on highway
Moclips	11.1 (3.4)	6,000	Damage to ocean side of buildings by floating logs; one building moved off foundation; timber-pile bulkheads and fills extensively damaged; water over some floors from 6 inches to several feet; heavy debris scattered in yards
Ocean Shores	9.7 (3.0)	---	Deposition of debris on streets near Central Motel office; debris in streets and yards near break in sand-dune dike about 3/4 of a mile south of Central Motel office
Pacific Beach	---	12,000	Medium-size house lifted off foundation and partly torn apart (total loss); several sheds moved off foundations; another building partly damaged; yards eroded and covered with debris
Seaview	12.5 (3.8)	---	None
Ilwaco	4.5 (1.4)	---	Minor damage
Cape Disappointment	5.7 (1.7)	---	None

ANALYSIS OF THE TSUNAMI HAZARD

The first step in analyzing the potential tsunami hazard in the study area was to carry out relatively coarse numerical simulations of the likely tsunami propagation patterns due to possible thrust-type earthquakes occurring offshore. These simulations were made in an earlier study (Hebenstreit and Murty, 1989) of the general threat to the Pacific coast from hypothesized subduction-related earthquakes in the Juan de Fuca plate. The plate was subdivided into a number of seismic source regions, including the southern Cascadia subduction zone off the coast of Washington and Oregon. Earthquake-source parameters in each region were postulated from an examination of such factors as the probable length of the fault plane in each section of the plate, the width of the plate, and the depth and dip angle of historical earthquakes in the area. This information was used to produce reasonable depictions of seafloor uplift due to large thrust earthquakes. Several arbitrary vertical-thrust values were used to provide a realistic range of possible tsunami intensities. The various uplift patterns were then translated into resulting sea-surface displacement fields that could be used as the starting point for simulations of wave propagation toward the local coastlines. The wave-propagation simulations were imposed on actual seafloor bathymetric data to include the effects of variations in the ocean bottom on propagation patterns.

These simulations, based on reasonable assumptions concerning the nature of possible earthquakes, formulated a model that helped identify the parts of the Pacific coast most susceptible to tsunamis originating in the different specific sections of the plate. In all the simulations, the model indicated that seafloor uplift would occur offshore and some subsidence would occur on land. Dominant wave-energy distribution would be confined to the immediate source area; that is, the most extreme wave heights would be found along the coastal areas within the source uplift zone. Also, the elevations would tend to decline (although not uniformly) north and south of the immediate area of the uplift. Tsunamis originating in the southern Cascadia subduction zone would likely focus a large part of their energy on the southwestern coast of Washington, including Grays Harbor.

PRIMARY CAUSES OF DAMAGE	BUILDINGS			MARINE STRUCTURES		LIFELINES					OTHER	
	WOOD FRAME	MASONRY/ CONCRETE	STEEL FRAME	WHARVES DOCKS PIERS	JETTIES BREAK WATERS	ROADS AIRSTRIPS	RAIL LINES	BRIDGES	UTILITY PLANTS	UTILITY LINES	BOATS	OIL TANKS
DIRECT WATER FORCES												
Hydrodynamic forces	●			●			●				●	
Buoyancy	●										●	
Hydrostatic pressure	●										●	
LOSS OF GROUND SUPPORT												
Subsidence	○			○			○			○		
Compaction												
Erosion												
Liquefaction												
Sand transport						○	○					
SECONDARY CAUSES OF DAMAGE												
FLOATING DEBRIS												
Cars	○											
Boats	○					○						
Logs/Stored materials	○					○		○				
Buildings	●			○		○						
FIRE AND CONTAMINATION												
Oil and fuel storage	●						●		●		○	●
Vehicular/Railroad	●											○
Electrical												
Stored materials												

EXPLANATION

○ **Least severe**

● **Most severe**

Figure 237. Categories and levels of tsunami damage to structures and other features in Seward, Alaska, due to the 1964 earthquake. From Urban Regional Research (1988).

To characterize the effects of tsunamis on the coast, a series of recording stations were specified in the model grid, and wave elevations at those points in the grid were stored for every simulation time step (fig. 238). The calculated mean value of simulated wave heights in the southern Cascadia subduction zone is just under 6 m above MLLW (mean lower low water—the sea-level datum used by NOAA (National Oceanographic and Atmospheric Administration) bathymetric charts). However, the coast between Newport, Oreg., and Grays Harbor is projected to experience mean wave heights of 8–9 m.

Once the wide-geographic-area simulations had been used to identify likely severe tsunami-impact areas, a more detailed site-specific wave-propagation model was used to investigate wave behavior in regions of high energy concentration. This model, called SURGE II, simulates the behavior of long waves (tsunamis) running toward and onto a coastline and can also delineate flooding in low-lying areas along the shore. The model has been used for many tsunami simulations, including an extensive study for Valparaiso, Chile (Hebenstreit and Gonzalez, 1985). The simulations are obtained by means of an explicit finite-difference algorithm for numerically solving linearized long-wave equations on a Cartesian (x,y as opposed to latitude, longitude) grid. Bottom friction is included in the model by means of a quadratic term. Inundation of coastal areas is computed by means of a weir-overtopping scheme, but wave runup is not calculated. Radiation boundary conditions are applied to open-ocean boundaries to ensure that wave energy leaving the simulation grid is only minimally reflected.

The procedure used in the detailed tsunami simulations is similar to that used in the wide-area simulations:

1. A seismologically realistic earthquake source is developed using historical evidence to specify parameters such as length, depth, width, and dip angle of the fault plane.

2. These parameters are used in the model of Mansinha and Smylie (1971) that predicts the movement of the seafloor that such an earthquake would produce.

3. This seafloor motion is translated directly into a disturbance of the sea surface that propagates toward the shoreline as a long wave (tsunami).

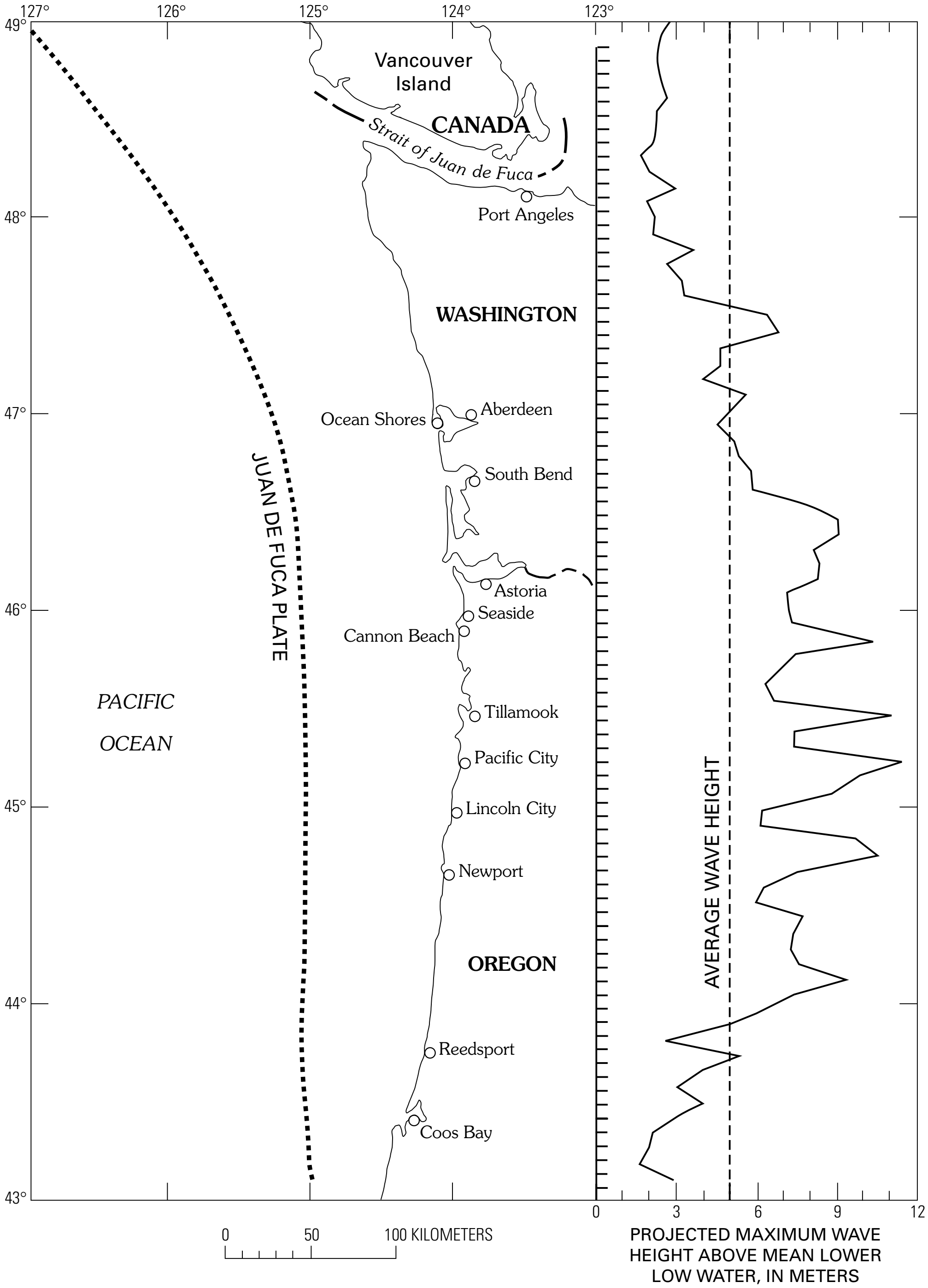


Figure 238. Projected near-shore (about 20 m depth) wave heights calculated for a major thrust earthquake in the southern Cascadia subduction zone of the Juan de Fuca plate (dotted line shows shoreward boundary of plate). Earthquake fault plane extends from north of Aberdeen, Wash., to Coos Bay, Oreg. Line with tick marks indicates model grid recording stations where wave elevations were stored.

4. The long waves are allowed to interact with the coastal area, and water-level time series are recorded at specific points. Locations on the grid where flooding is indicated are noted.

The tsunami sources used in the simulations were offshore of Grays Harbor. One source was located about 200 km from the coast (the approximate location of the surface expression of a fault at depth under the continental slope).

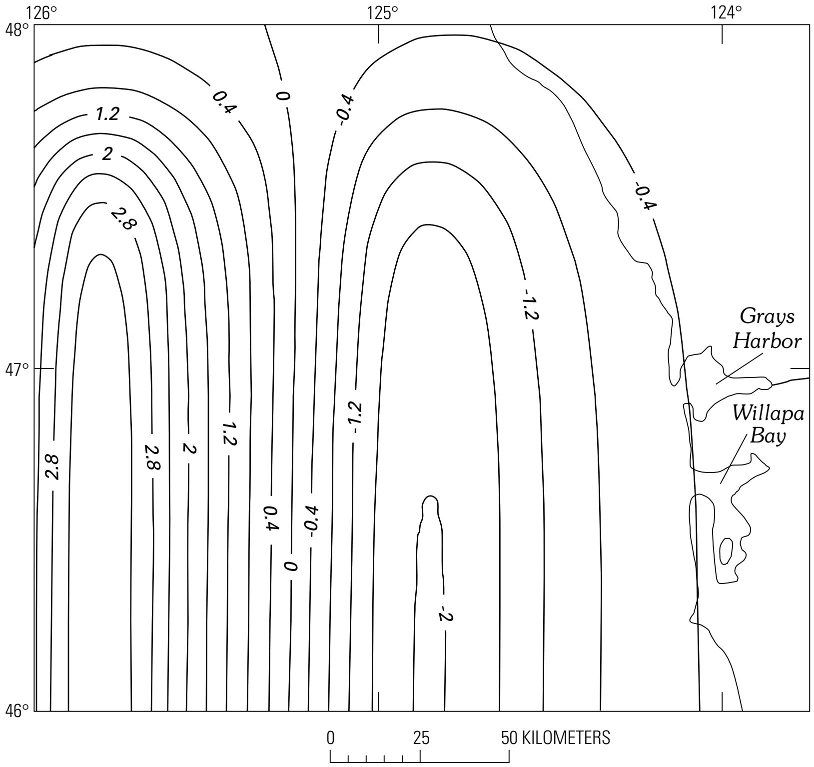


Figure 239. Contours showing relative vertical seafloor response to a possible earthquake in Grays Harbor region. Positive values indicate upward motion of seafloor; negative values indicate downward motion. Irregularities in contours are due to plotting software. Contour interval 0.4 m.

The second was only 100 km offshore, to include possible onshore subsidence effects in the simulation. Because the model is essentially linear, both sources produced about the same results, varying only slightly in the magnitude of wave heights calculated along the coast.

Seafloor (and hence sea surface) uplift from the more distant source (fig. 239) was calculated using the Mansinha and Smylie (1971) source-displacement model with the parameters listed in table 52.

The source zone specified for this earthquake lies in the southern part of the Cascadia subduction zone, along the coast from near Coos Bay, Oreg., to just north of Grays Harbor. This source zone was used in an earlier study (Hebenstreit, 1988) of the generalized tsunami threat from movement of the Juan de Fuca plate. The uplift pattern shown in figure 239 is the north end of a larger pattern from the earlier study.

Table 52. Source parameters used in the source-displacement model to simulate a subduction-zone earthquake off Grays Harbor, Wash.

Source parameter	Parameter value
Source depth	30 km
Fault length	400 km
Fault width	100 km
Dip angle	10°
Maximum vertical displacement	10 m

The site-specific SURGE II model uses a numerical-computation grid with variable seafloor and land topography. A realistic rendition of actual conditions is vital because the process of interaction between long surface waves (tsunamis) and the shoreline is heavily influenced by changes in water depth, as in coastal flooding. Simulated topography in the Grays Harbor model area is shown in figure 240. The contour line labeled “0” marks the approximate location of the shoreline.

One of the dominant landforms in the Grays Harbor area is the extensive mud flats. A large part of the harbor is so shallow that some of the bottom is exposed at low tide. A central channel has been dredged to allow seagoing vessels to reach Hoquiam and Aberdeen.

A series of recording points was identified in the model to facilitate examination of the waves during the course of the simulations (fig. 241*A*). Time series for several sets of these points are shown in figure 241*B* (stations on the outer coast), figure 241*C* (stations roughly along the axis of the main channel in the harbor), and figure 241*D* (stations at the far east end of Grays Harbor).

In the simulation, high-amplitude waves of 7–8 m height strike the outer coast soon after the uplift (fig. 241*B*). The recording stations closest to the mouth of the harbor (stations 14, 15, 19, fig. 241*C*) are initially subjected to high-amplitude waves that rapidly damp down to low-amplitude, high-frequency waves. Farther into the channel, initial amplitudes are greatly reduced. By the time the waves reach the Hoquiam-Aberdeen area (stations 4–9, fig.

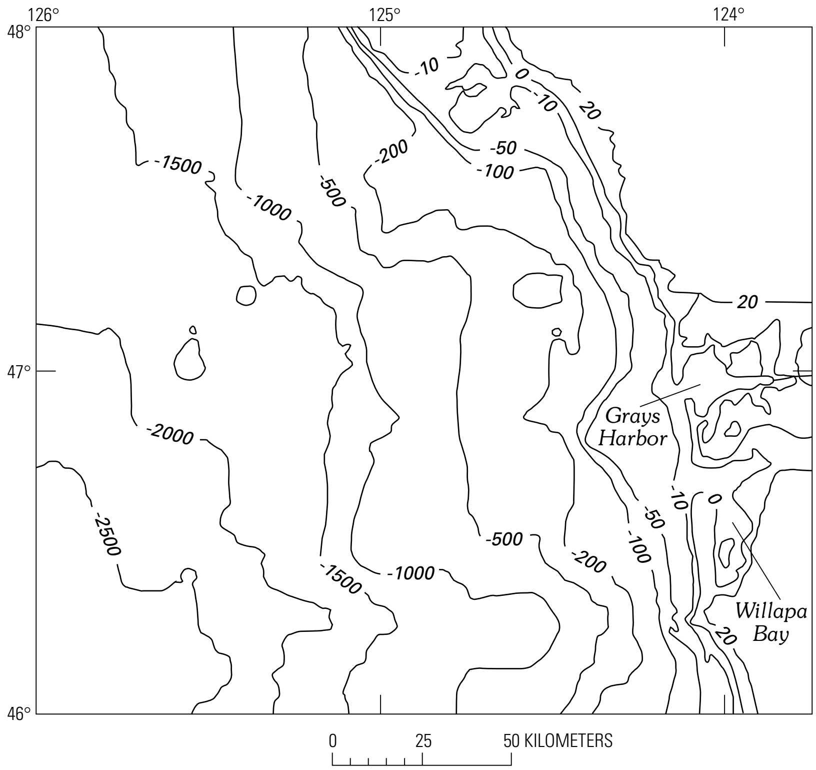


Figure 240. Topography used in numerical simulations of Grays Harbor area. Contour values in meters relative to MLLW (mean lower low water). Small outlines indicate location of small undersea features significantly shallower than surrounding water.

241*D*), there is only a minor variation in water level (about 0.5 m).

Except for some low-lying areas near the mouth of the harbor, especially around Westport, all the areas predicted to be flooded by tsunamis (fig. 242) are on the outer coast, which in this part of Washington is largely sandy beaches with dune barriers on the shoreward side. This simulation seems to be substantiated at Willapa Bay, south of Grays Harbor, where recent sediment-dating studies seem to indicate the possibility of subsidence events and tsunami inundation in the recent geologic past (for example, see Atwater, 1987).

The simulations indicate that the interior of Grays Harbor is relatively well protected from a serious tsunami threat, for several reasons. For example, Grays Harbor is primarily diamond shaped (fig. 241); it is 2.2 km wide at the mouth, widens to about 21 km, and then narrows at the mouth of the Chehalis River at the east end. This configuration is expected to cause the wave to break at the mouth, dissipating its energy. Another factor contributing to the relatively moderate level of tsunami threat is that the extensive shallow mud flats will quickly dissipate a large part of the wave energy, reducing wave height inside the harbor. The wave amplitude would continue to decline as the wave travels inland across the harbor to the Chehalis River. An initial wave amplitude of 2–3 m above the existing tide level at the mouth of the harbor would diminish to 0.5 m by the time the wave reaches Aberdeen. Because other tsunami waves would break at the mouth of the harbor, energy would be considerably reduced. Therefore, the simulation indicates that the wave would have relatively low velocity within Grays Harbor. A wave period of about 20 minutes is anticipated.

However, even relatively small tsunamis can cause considerable damage to coastal areas. The drawdown of the sea surface can expose normally submerged bottom areas to erosion and slumping. Boats and ships moored at coastal installations can be severely damaged by anomalous surface motions such as drawdown or seiching (oscillation at the resonant frequency of the basin). In addition, objects torn from their moorings can become dangerous floating projectiles. If a small tsunami occurs during a time of severe storm seas, anomalously high tides, or river flooding, it can cause greater destruction, because under these conditions, surface waves can propagate much farther inland. Finally, if the surface resonance within the bay coincides with the period of the tsunami, the wave would be amplified by an unknown factor instead of being dissipated.

COASTAL FLOODING CONDITIONS AS AN ADDITIONAL HAZARD

Although the simulations did not factor in river- and rain-induced flood conditions, historical coastal flooding is well documented. Flooding in the Aberdeen area is generally the result of high river flow caused by winter rainfall generated by Pacific weather fronts combining with tidal flows. The tidal influence in Grays Harbor extends

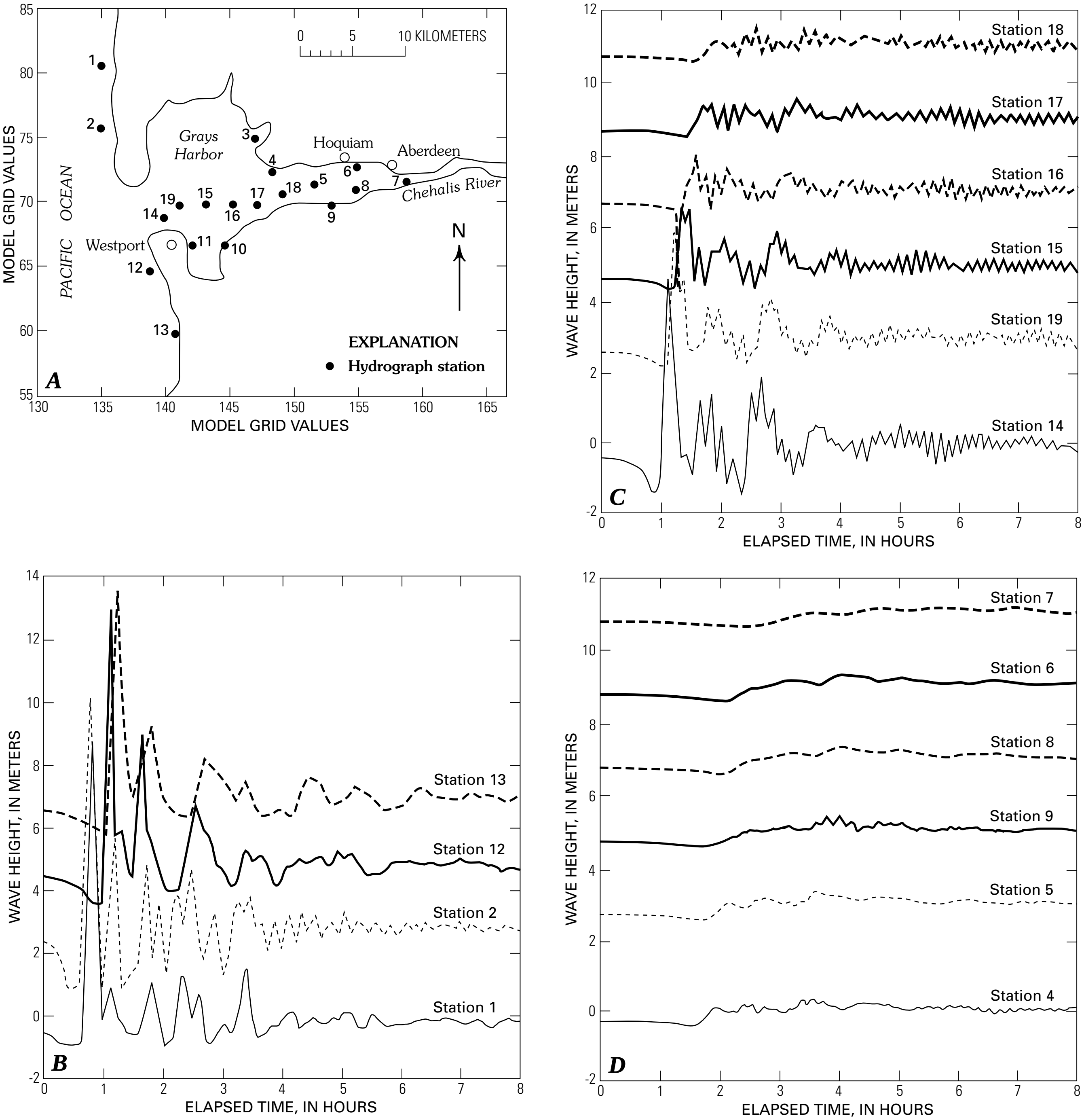


Figure 241. Simulated time-series data for a hypothetical tsunami impacting Grays Harbor area. *A*, Locations of modeled hydrograph recording stations at which time series of waves were recorded. Values on edge of map are part of the model grid. *B*, Time series of computed waves at stations just outside Grays Harbor. *C*, Time series for stations at west end of Grays Harbor. *D*, Time series for stations at east end of Grays Harbor. For clarity, each time-series curve above lowest is vertically offset by +2 m on each graph.

up the Chehalis and Wishkah Rivers and may coincide with high river flows to increase flooding. These conditions can be aggravated during rainstorms by backups in the city's storm-drainage system, when heavy local runoff is prevented from entering the rivers because of high water levels.

The highest river and harbor-water stages in the Aberdeen area result from a combination of anomalous high astronomic tides (which occur frequently), low barometric pressure, strong onshore winds, and heavy rains. This combination of conditions has produced extensive water damage to homes, businesses, and public property many times in the

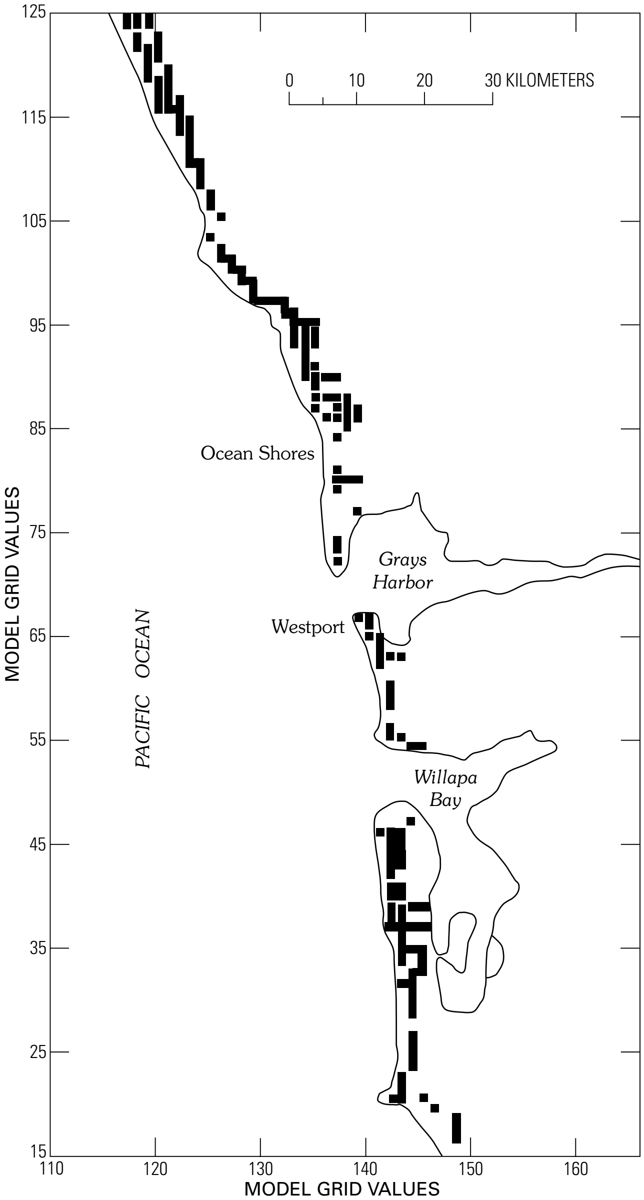


Figure 242. Approximate areas of coastal inundation (rectangles) computed by the tsunami-impact model for Grays Harbor region. Values on edge of map are part of the model grid.

Table 53. Highest known floods in Aberdeen, Wash.

[Floods are listed in decreasing order of magnitude. Information on floods prior to 1971 is based on the June 1971 Flood-Plain Information report by the Corps of Engineers, which reported the highest water levels as recorded at the Port of Grays Harbor staff gauge. Although the port attempted to record the highest tides of any year, the report acknowledged that records are incomplete. Information since 1971 is based on an internal City of Aberdeen Engineering Department memorandum pertaining to recent flooding from Ron Merila to Rudy Balgaroo on December 8, 1983. That information was updated by Bill Langford in 1990. No major river flooding has occurred since November 1983]

Date of flood	Water level, in feet, above mean sea level (meters)[1]
December 17, 1933	10.3 (3.14)
December 1934	10.0 (3.05)
November 1913	9.7 (2.96)
December 1923	9.7 (2.96)
November 14, 1981	9.7 (2.96)
December 3, 1982	9.6 (2.93)
1912	9.5 (2.90)
December 1920	9.4 (2.87)
December 11, 1977	9.4 (2.87)
December 21, 1972	9.3 (2.83)
December 11, 1973	9.3 (2.83)
January 27, 1983	9.3 (2.83)
November 24, 1983	9.3 (2.83)
December 13, 1941	9.2 (2.80)
December 18, 1960	9.2 (2.80)
January 27, 1964	9.2 (2.80)
December 13, 1977	9.2 (2.80)
November 30, 1951	9.1 (2.77)

[1]Measured at the Port of Grays Harbor staff guage. Staff gauge records were converted to mean sea level, National Geodetic Vertical Datum of 1929, using the Flood Plain Information Report, C.O.E. 1971, and the Summary of Tidal Elevations and Datum Planes, Aberdeen, 1981.

past (table 53). Flooding along the lower sections of the small streams in Aberdeen is primarily caused by high water in the rivers backing up into the creeks and inundating adjacent low areas. Also, the Wilson Creek drainage basin was first clearcut in 1974. Additional logging operations have caused an increase in the volume of water that comes down this creek during rainstorms.

On average, Pacific coast tidal action causes the Chehalis River at Aberdeen to vary about 3 m in elevation, from −1.53 m at MLLW (mean lower low water) to 1.56 m at MHHW (mean higher high water). Flooding problems develop first near the southeastern city boundary when the Chehalis River reaches elevations between 2 and 2.3 m above mean sea level. This flooding is primarily on land that is undeveloped. When the water level reaches 2.3 to 2.6 m height, flooding spreads inland to residential and commercial properties in southeastern South Aberdeen along State Highway 101. Also, properties along the Wishkah River in North Aberdeen are affected. A 10-year flood level for this area is estimated to be 2.7 m; at a height of 2.8 m, general flooding occurs because the dikes protecting South Aberdeen are overtopped in many places when the water rises to between 2.6 and 2.8 m. At that level, water enters the downtown area of Aberdeen from the Wishkah River immediately to the east. Above 2.9 m, which is equivalent to a 25-year flood, major flooding occurs throughout the city. Flood-water velocity becomes a problem at this stage because overtopped dikes can fail due to saturation and scouring.

If extraordinarily high tides or tide surges are accompanied by heavy rainfall, flooding likely will occur even earlier than in the previous scenario. Because the peak astronomic tide for Grays Harbor coincides with the greatest threat of winter storm surge and rainfall for the area, the combinations of factors that can potentially result in flooding occur every year between November and February. Ordinary high tides are about 1.6 m at MHHW; an additional 0.5 m of tsunami inundation would raise the level to 2.1 m. Flooding has occurred at 2–2.3 m. The extra 0.5 m of water from a tsunami during winter flood conditions of 2.3–2.6 m would inundate the downtown areas as well as the coastal highway.

Throughout the city, storm-water runoff is directed into adjacent rivers and sloughs. The storm-water-drainage system in North Aberdeen consists of underground drains; in South Aberdeen, the system is open ditches. Storm drains overflow when tide gates at the storm-drain outlets close due to high river levels. This storm-water flooding can occur throughout the area, and storm-water ponding remains as long as high river levels persist. Another problem that can develop is sewer overflow. The dikes protecting the area can be overtopped at a water level of 1.9 m MHHW, which is significantly below the 10-year flood level. If the 0.5 m tsunami flood level is added to the estimated 1.5–2.15 m of potential subsidence (fig. 243) during an earthquake, then the flood level would be raised by roughly 2.3 m, a damaging level even at low tide. These conditions could result in a serious contamination problem.

A tsunami occurring at high tide or during near-flood levels would arrive when the harbor is significantly deeper than normal. Under these conditions it would carry more wave energy into the Hoquiam-Aberdeen area. Thus, if the tsunami occurs during high winter tide conditions, the additional 0.5 m of projected wave height could easily overtop and (or) weaken the dikes protecting Aberdeen. The drawdown from the first tsunami wave can be expected to cause severe scouring of the inland sides of the dikes; the second tsunami wave could destroy them.

VULNERABILITY OF PEOPLE AND PROPERTY

The vulnerability analysis conducted in this study consisted of two primary components. One was the definition of the population at risk within the coastal hazard zone (generally defined as being below 6.1 m above mean sea level, based on the National Geodetic Vertical Datum of 1929). The other was the definition of land-use patterns and specific characteristics of those uses that could result in secondary hazards. For example, the presence of hazardous materials stored at or frequently transported to or through a site could be a secondary hazard.

POPULATION AT RISK

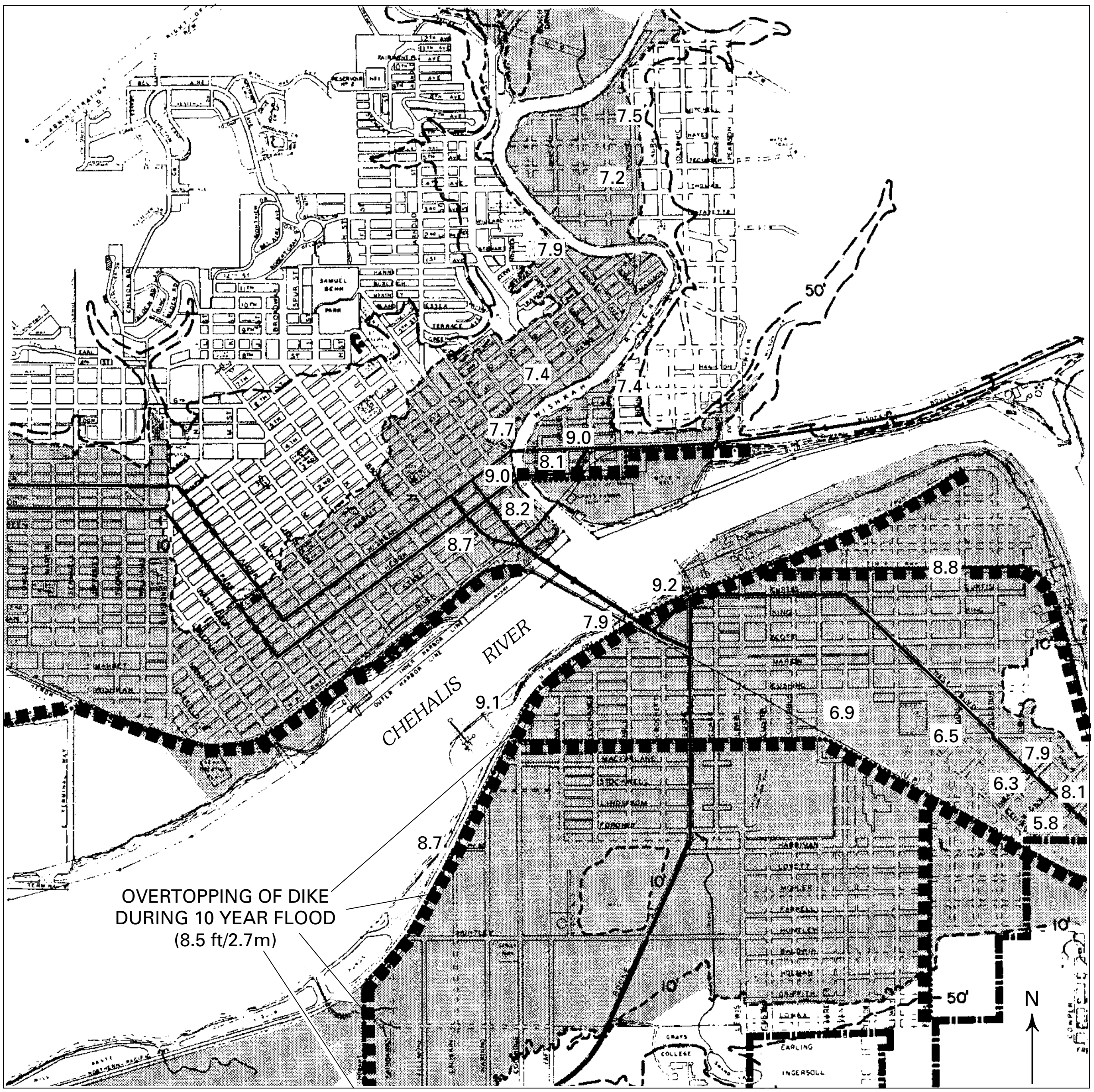
The population at risk from tsunami hazards in the Grays Harbor area varies seasonally. If a tsunami occurs between late October and late March, it could coincide with periods of elevated river heights due to heavy rain, which would magnify the potential for extensive property damage; population levels would, however, be relatively low during that period. If a tsunami occurs during the summer months, the beach and resort communities along the open coasts would have high populations.

The largest year-round population center in Grays Harbor County is the Aberdeen-Hoquiam-Cosmopolis area, with a population of 14,241 (1990 Census of Population and Housing—Washington). This urban complex lies at the east end of Grays Harbor, fed by several rivers (including the Chehalis and the Wishkah) and open to the sea through the channel flanked by Westport on the south and Ocean Shores on the north.

Average year-round population levels of the coastal communities are low, but there are large seasonal fluctuations. Winter populations tend to be below 5,000 residents. During the summer, however, the wide sandy beaches of the Washington and Oregon coast are popular destinations for both Seattle-Tacoma and Portland urban populations. The 1990 population for the greater Seattle-Tacoma consolidated metropolitan area was 2,259,164, and Portland, Oreg.–Vancouver, Wash. had a metropolitan population of 1,286,222. Thus virtually the entire coast can be heavily populated during the summer months by campers and tourists staying in the many beach-front communities, which would make the potential for loss of life from a local tsunami very high. For example, whereas the year-round population of Ocean Shores is about 5,000, about 35,000 people attended a 1-day sand-castle-building contest in a nearby community during the summer. A large number of people in the urbanized Aberdeen-Hoquiam area could also be at risk, even though their residences are within Grays Harbor.

LAND-USE RISKS AND TOPOGRAPHY

Projections of land-use disruption must rely on an estimate of potential flood areas, which to a large extent is a function of ground elevation. This analysis, therefore, encompasses all the area below 6.1 m elevation (above mean sea level), the slope of which is 0–2 percent. A three-dimensional terrain model was used as the basis for the land-use analysis (fig. 244). Correlation of topography with land use permits rapid assessment of geographically based vulnerability to flooding. The urbanized area of Ocean Shores, a community of predominantly second homes, is entirely below 3 m elevation. Land-use patterns indicate that the urban and industrial areas in the central business districts of Hoquiam and Aberdeen are on coastal lowlands, virtually all of which are unconsolidated fills. Grays Harbor has several industrial complexes located along the shore. About 25 percent of the work force in Grays Harbor County is employed in manufacturing activities. ITT-Rayonier and Grays Harbor Paper have a combined pulp and fine-paper production facility on the waterfront in Hoquiam. A large Weyerhauser wood-pulp facility is in South Aberdeen. The harbor has several port



EXPLANATION

Elevations above mean sea level

Dikes

Figure 243. Critical flood levels for Aberdeen (north side of Chehalis River) and South Aberdeen (south side of river). Low-lying areas will be subject to flooding during low tide; during high tide, the entire urbanized area will be subject to extensive flooding that, because of deeper water level, could have relatively high velocity. One hundred year flood boundary defined by FEMA in conjunction with NFIP (National Flood Insurance Program) is the 10-foot contour. From Urban Regional Research (1986).

facilities; in 1985, 5.8 million tons of materials were shipped through the harbor, about 55 percent of which was logs (U.S. Department of the Interior, 1988). In addition, Westport is a commercial fishing center.

In summary, the Grays Harbor area, although not an exceptionally large economic center, contains a significant investment in both commodities handled and infrastructure required to serve the industries present. It is the busiest port in the Pacific Northwest with respect to distribution of regionally produced lumber.

The area of potential flooding encompasses all the industrial areas, many bridges, and the State highway

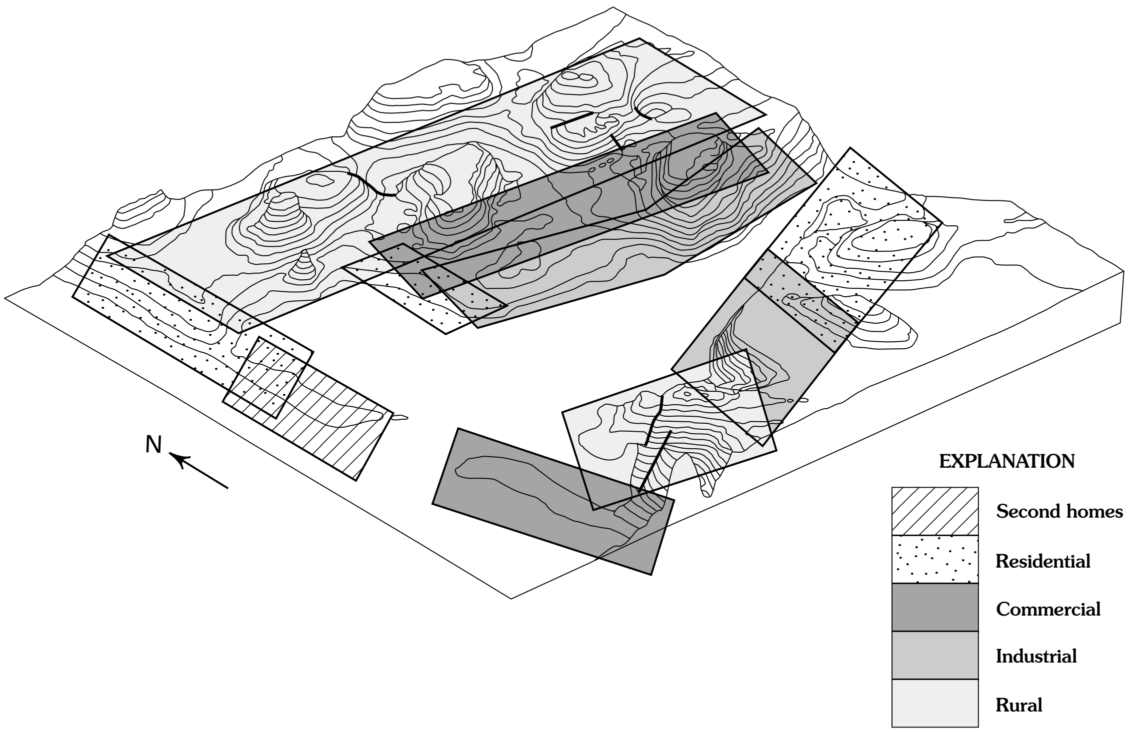


Figure 244. Grays Harbor land-use patterns. Patterns extend past land boundaries for clarity.

linking Grays Harbor with points to the north and south. In addition, the central business districts of both Aberdeen and Hoquiam (fig. 245), as well as residential areas in both communities, are within potential inundation areas. The headquarters of the fire department in Hoquiam and both fire stations in Aberdeen are within the coastal hazard zone.

Two principal highways, State Routes (SR) 12 and 101, serve the area from the east, north, and south. SR 12, a four-lane highway, connects Aberdeen and Hoquiam with the north-south Interstate 5 corridor. SR 101, which is basically a two-lane highway, serves the Olympic Peninsula and southwestern Washington. Two-lane routes connect Ocean Shores and Westport and points north and south along the Pacific coast. Highway routes are characterized by soft soils, so there is a high probability that transportation, such as response and rescue efforts and fire fighting, would be interrupted.

Data collected in conjunction with the analysis of damage from the 1964 Alaska earthquake tsunami specifically mention damage to four bridges in the southern Washington–northern Oregon region. Damage to bridges from a projected tsunami in the Grays Harbor area could be even greater in the industrialized area. Many bridges cross rivers emptying into Grays Harbor, including three drawbridges over the Chehalis and Wishkah Rivers and one drawbridge crossing the Chehalis River between Aberdeen and South Aberdeen–Cosmopolis.

SECONDARY HAZARDS

SUBSIDENCE

An earthquake-related threat that could increase the destructiveness of a tsunami is subsidence caused by compaction of soils under strong ground motion and (or) tectonic displacement. Coastal subsidence commonly accompanies great subduction earthquakes, primarily along an onshore belt flanked by a mostly offshore zone of coseismic uplift (Atwater, 1987). Estuarine deposits of late Holocene age near Washington's outer coast indicate that submergence and shoaling have occurred in cycles that resemble, at least superficially, the known and inferred cycles of coseismic submergence and postseismic shoaling in great-earthquake regions of Alaska and Chile. The amount of subsidence is estimated to be about 1.6–2 m respectively (Curt Peterson, Portland State University, oral commun., 1990).

The seismic effects of the 1964 Alaska subduction earthquake along the Washington coast are well documented. These effects were particularly severe in areas where subsidence was increased by shaking-induced settlement when seismic vibration caused consolidation of loose granular materials. Rearrangement of constituent particles aided by ejection of interstitial water through water spouts or mud spouts caused compaction and local differential subsidence of the ground surface. Lateral spreading, too, caused lowering of the ground surface in places (Plafker,

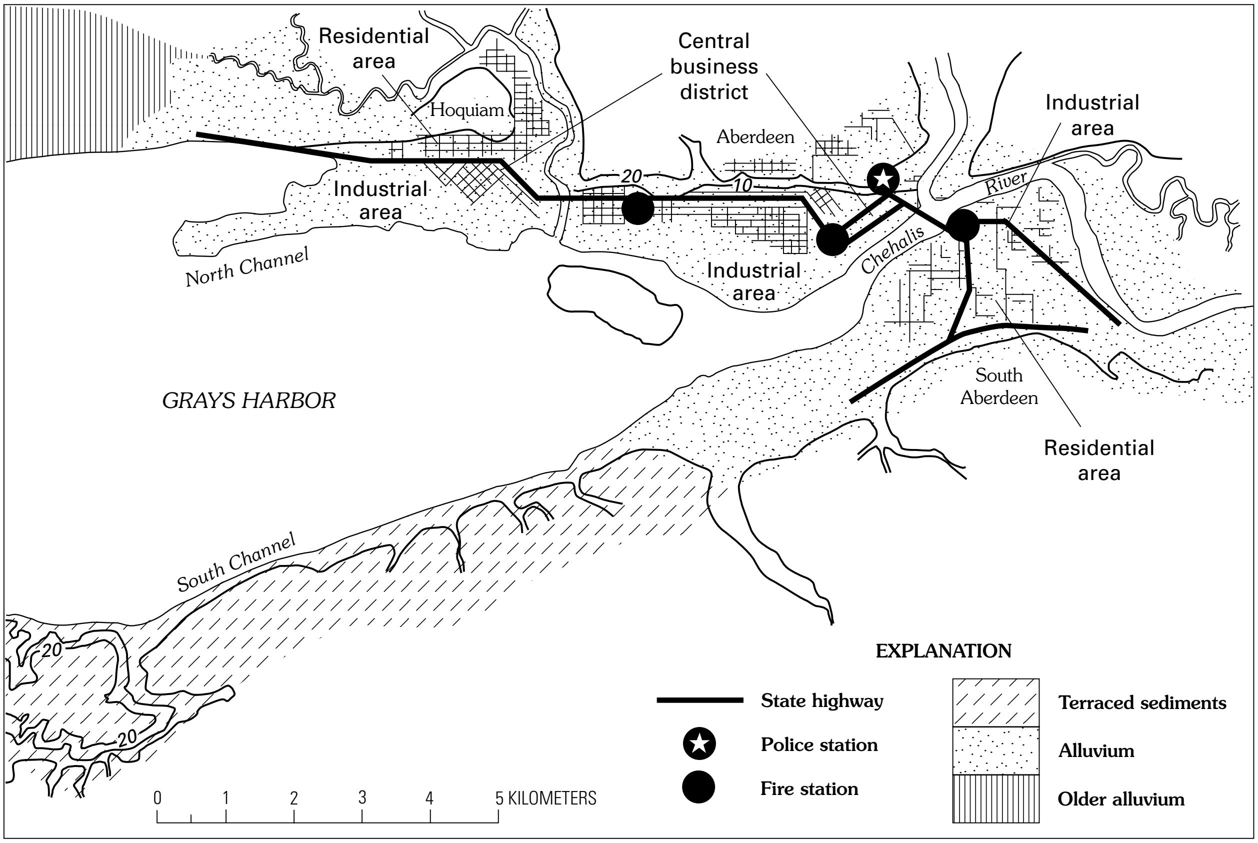


Figure 245. Detailed land use and geology for the Aberdeen (including South Aberdeen) and Hoquiam area of Grays Harbor.

1969). In coastal areas where local subsidence was superimposed on regional tectonic subsidence, the damaging effects were magnified.

Two examples from the 1964 Alaska earthquake illustrate the combined effects of tectonic displacement and subsidence. On Kodiak Island, local subsidence of as much as 3 m was widespread in noncohesive granular deposits through compaction, flow, and sliding that resulted from vibratory loading during the earthquake. Subsidence of more than 1.8 m occurred throughout the northern part of the region. This subsidence, which was largely restricted to saturated beach and alluvial deposits or artificial fill, was locally accompanied by extensive cracking of the ground and ejection of water and water-sediment mixtures. Within the affected area, tectonic subsidence, which was locally augmented by surficial subsidence of unconsolidated deposits, caused widespread inundation of shorelines and damage to intertidal organisms, near-shore terrestrial vegetation, and salmon-spawning areas (Plafker and Kachadoorian, 1966). Subsidence also occurred in the Cook Inlet area, which was downwarped. At the head of Cook Inlet near Portage, estuarine silt buried 18 km^2 of lowland that had subsided 1.6 m and settled an additional 0.8 m, totaling 2.4 m (Atwater, 1987).

As these examples of Alaskan subsidence indicate, a critical variable in projecting inundation and risk is a determination of the areas prone to subsidence. These areas can reasonably be expected to be composed of soft and highly saturated material, such as the alluvium in virtually the entire urbanized Hoquiam and Aberdeen areas (fig. 245) (Washington State Department of Natural Resources, 1987).

Soils in the Grays Harbor flood plain are primarily alluvial silt and fine sand, locally with organic material (fig. 246). Some areas are mantled by artificial fill. These soils are about 1.5–1.8 m deep and range from moderately well drained to somewhat excessively well drained, to excessively well drained on the diked tidelands. This soil type formed in sandy and loamy river dredgings. The other type of soil, found primarily in the flood plain of South Aberdeen, is a silty clay loam. It is a deep, artificially drained soil found on flood plains and deltas that are protected from tidal overflow. This soil type formed in clayey alluvium deposited in quiet waters of coastal bays.

Close to the fairly abrupt boundary between the flood plain and the adjacent uplands are zones of coarse sand and gravel. These zones are probably interbedded with finer grained materials (Washington State Department of Natural Resources, 1987).

Existing soils are predominantly nonengineered fill and (or) highly saturated alluvium; both soil types are prone to compaction. If it is assumed that a combination of tectonic

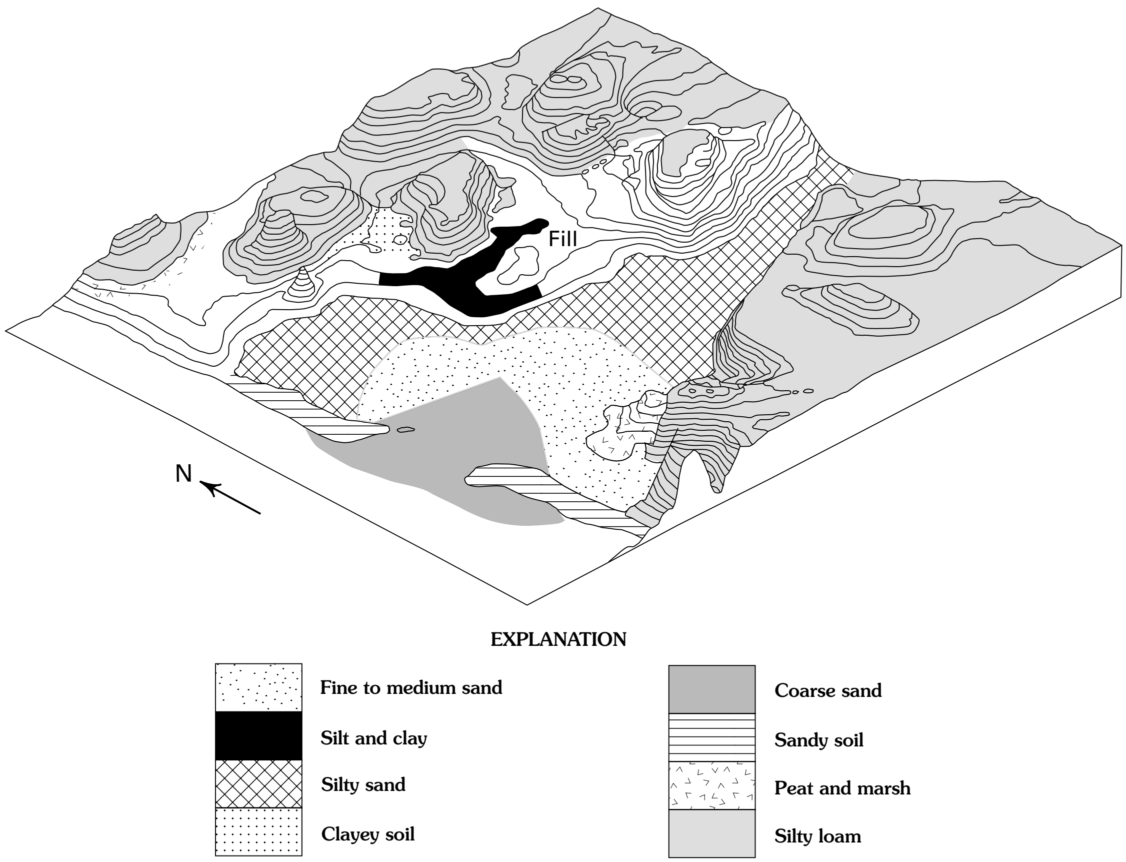


Figure 246. Soil and sediment structure in Grays Harbor area. Source of map data is Grays Harbor Estuary Management Program.

displacement, subsidence, and consolidation will occur to an extent about equivalent to that in the 1960 Chile and 1969 Alaska earthquakes and postulated for Holocene Puget Sound earthquakes, then subsidence of 1.5–2 m would be likely to occur. Under this assumption, all the industrial areas, the majority of the commercial centers, and a significant part of the residential areas are at risk. Loss of the industrial facilities could have a long-term devastating effect on the economy of the area.

In the event of subsidence, wave scouring could further erode foundations and lead to structural failures. Furthermore, much of Grays Harbor and environs consists of sand and sandy clay, which could liquefy under severe shaking, causing foundations to sink differentially and breaking buried pipes and storage structures. Finally, ground saturated by flooding will lose its bearing capacity, and there would be a high incidence of foundation failures and buildings floating off their foundations.

Because subsidence appears to have occurred in the past and seems likely to occur again, a simulation was made to project inundation as a result of subsidence. This simulation found that the flood-prone area would extend somewhat further inland than would occur without subsidence.

BATTERING

A sudden rise in water level can produce extensive damage from flooding and wave action on structures. It can also produce less direct effects such as battering by objects (logs, boats, railway freight cars, vehicles, and storage tanks) which become floating projectiles.

In a fishing enclave, the greatest water-related hazard is the fishing boats themselves. Any dockside complex such as the marina in Westport contains boats that, if torn from their moorings by currents created by rapid rising and falling of sea level, could easily become floating projectiles capable of damaging not only each other but also coastal structures such as industrial and commercial buildings, hotels, and processing plants. Spaeth and Berkman (1972) and Wilson and Törum (1968) cited instances of this type of damage from the 1964 Alaska tsunami.

A wood-pulp facility such as the Weyerhauser plant in South Aberdeen has many types of materials that could become battering hazards. Most notable are the logs piled near the water's edge awaiting processing. Smaller piles could float under high-water conditions and, like the fishing boats, could become projectiles. Vessels moored at the

Table 54. Assumptions of air-dispersion patterns for Hoquiam and Grays Harbor, Wash.

[Ground roughness assumed to be urban; no temperature inversions present]

Period	Wind direction	Average wind speed, in miles/hour (km/hr)	Average temperature
January-March	From the southeast	10.7 (17.2)	35.0°F (1.7°C)
July-September	From the west	11.6 (18.7)	65.0°F (18.3°C)

plant's dock could also become projectiles or could be battered by other vessels and (or) the logs. As it is, every year during storm conditions people are killed by errant logs. Under tsunami conditions, the increased water velocities will turn these log storage areas into highly hazardous areas. In addition, the ITT-Rayonier plant in Hoquiam, at the mouth of the Hoquiam River, is serviced by a railroad. The rail cars on the tracks are also potential floating hazards during flooding.

Another potential industrial hazard is toxic materials stored at plant sites. For example, piles of waste materials on the grounds of a paper plant could be a long-term health and contamination hazard if they were dislodged by water-borne objects and then dispersed by flooding.

AIR CONTAMINATION AND FIRE

The Hoquiam-Aberdeen population is at risk from possible fires and airborne contamination that could originate in the industrial port area and spread to the neighboring residential and commercial areas. Although the precise causes and dimensions of fire or air contamination have not been predicted, it is clear that toxic chemicals could be a devastating hazard if their storage containers were to be breached by ground motion, wave action, or floating.

Grays Harbor is a principal port for Pacific Northwest forest-products industries. Manufacturing of a wide range of wood products (for example, wood shakes) involves the use of an extensive range of chemicals as preservatives, fire retardants, and other related agents. Fire is always a problem when chemical storage tanks are breached; toxic-material storage facilities constitute a major threat to public safety when they are damaged and facilities are disrupted. Surface-water, ground-water, and airborne contamination could occur in the flooded areas.

The U.S. Environmental Protection Agency SERA Title III Program requires mandatory public disclosure of stored hazardous materials exceeding a specific amount for each chemical. Among the toxic substances stored in industrial facilities in the Grays Harbor area are ammonia, chlorine, nitric acid, sulfur dioxide, hydrogen peroxide, propane, and formaldehyde gas. In order to demonstrate vulnerability, the release and spread of selected toxic materials from an industrial site were simulated in the study area. The Computer-Aided Management of Emergency Operations (CAMEO™ II) program, developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) Hazardous Materials Response Branch, was used to project the geographic extent of vulnerability to the spread of toxic materials. This model is designed to help emergency planners and first-response personnel plan for and safely handle chemical accidents.

CAMEO's air-dispersion model can simulate potential dispersion of toxic gases under a variety of wind and weather conditions. It simulates the extent and footprint of a chemical downwind from a chemical spill, using a diagram drawn by the computer from a defined location on a base map. For this analysis, project base maps were used to facilitate correlation of the air-dispersion analysis with land-use patterns. Because concentrations differ for each chemical, the predicted adverse effects vary widely. Two hypotheses were developed by the project to illustrate the pattern of possible air contamination:

Hypothesis 1. Small chemical spill. Release of threshold limits (45 kg or 227 kg) of ammonia and chlorine projected.

Hypothesis 2. Large chemical spill. Release by partial rupture of an average railroad tank-car load (2,270 kg) of chlorine.

Other variables were based on average wind and temperature conditions during summer versus winter (table 54).

Downwind chemical concentrations from a chemical accident were simulated under two base-time conditions:

1. IDLH: Immediately dangerous to life and health. This condition exists in the immediate vicinity of the spill within minutes after it occurs. Under IDLH conditions, the gases remain concentrated and pose a serious threat. Just after a spill, no one should enter an IDLH atmosphere without a self-contained breathing apparatus.

2. TLV-TWA: Threshold limit value—time weight average. This condition occurs within the first 30 minutes after the spill. In TLV-TWA conditions, the gases are more dispersed and pose a less general but still serious threat.

The extent of potential airborne contamination from a release of 45 kg of chlorine gas at the ITT-Rayonier plant under both summer and winter average wind conditions is shown in figure 247. When reviewing the simulation results, it is important to know that the CAMEO program tends to underestimate the dispersal of heavy gases such as chlorine by a factor of about 2. Thus the IDLH is really more extensive than shown in the figure.

Under summer conditions (fig. 247*A*), the threatened areas are primarily residential, and the fire station is within

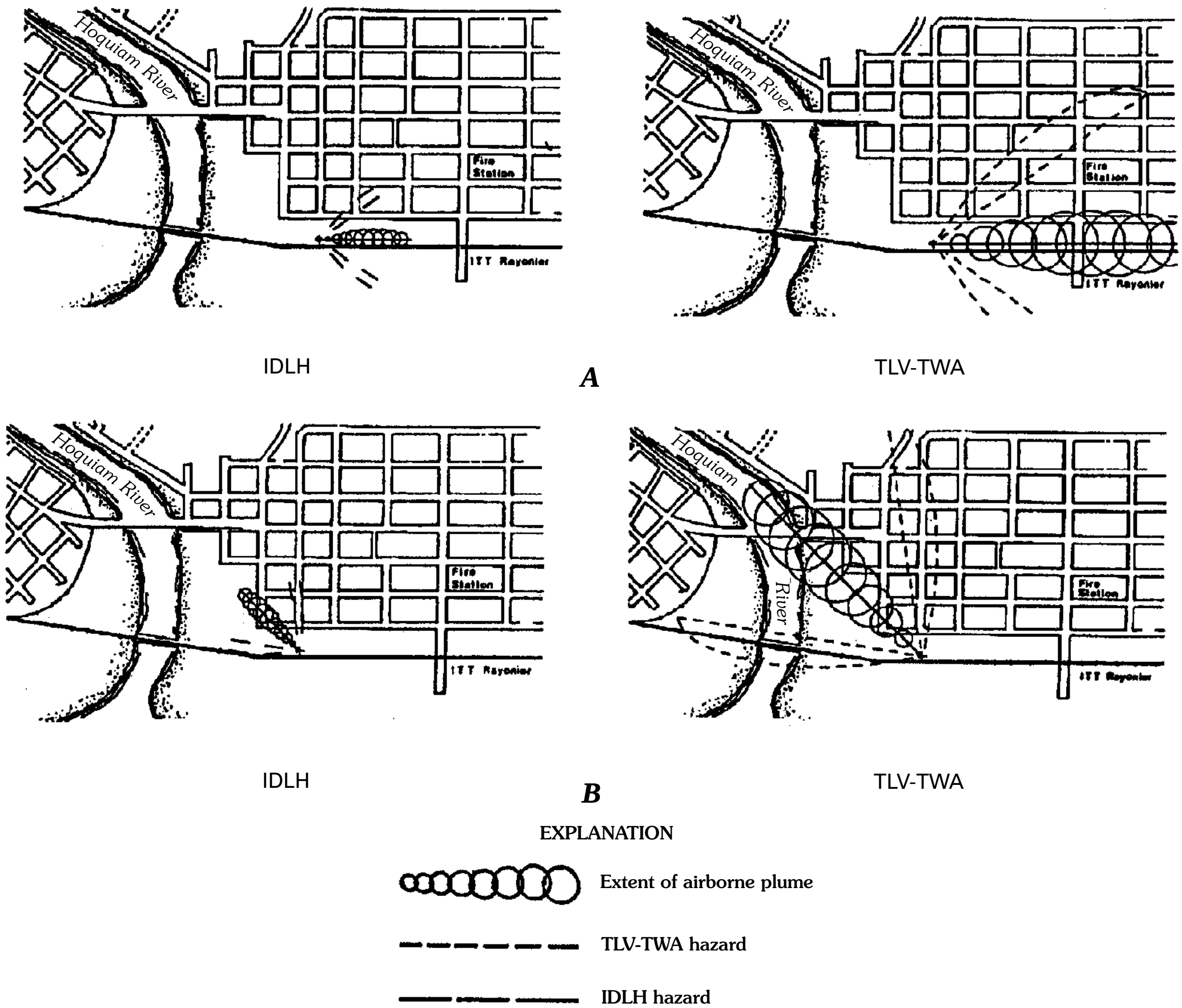


Figure 247. Potential dispersion patterns for chlorine gas spreading from a simulated spill (45 kg) at ITT-Rayonier pulp and paper plant in Hoquiam. Overlapping circles, extent of airborne plume; dashed lines, wider envelopes of potential hazard under IDLH (immediately dangerous to life and health) and TLV-TWA (threshold limit value–time weighted average) scenarios. IDLH concentrations assumed as 30 ppm (parts per million); TLV-TWA concentrations assumed as 1 ppm. *A*, Dispersion under summer temperature and wind conditions. *B*, Dispersion under typical winter temperature and wind conditions.

the potential contamination zone. The threat is exacerbated because when the lives of fire personnel are at risk, the ability of the community to respond to the emergency is reduced.

INTEGRATED HAZARDS MANAGEMENT

Once the base data for delineation of the tsunami threat and the characteristics of vulnerability were developed, it was possible to correlate these two factors. The physical threat, including flooding, strong currents, and potential for ground subsidence, could be correlated with land-use characteristics. An integrated physical-social-economic data base was thereby created for estimating potential damage caused by floating debris, fire, and contamination from hazardous substances. In essence, this integrated methodology treats the tsunami threat as a system rather than a single physical process. The analysis also highlights the reality that hazards are cumulative, that is, whereas the immediate water hazard is dangerous, it can precipitate still other hazards with even greater consequences.

The geographic location, land use, and underlying soils constitute a system of base perimeters of variable vulnerability. Defining tsunami-hazard boundaries can serve two purposes. One is to define possibly vulnerable areas in order to plan for damage mitigation; the other is to define evacuation procedures. Once at-risk locations are defined, a risk-reduction program can be developed that organizes the specific characteristics of vulnerability according to subdivided areas of risk. Analyses of risks in the Grays Harbor area indicate that they are primarily a function of land use. For example, the apparent lack of a high-impact tsunami threat within the harbor indicates that the predominant threat for which Grays Harbor must be prepared is secondary hazards. These secondary hazards include battering, erosion and scouring, loss of soil strength, fire, and air contamination. During high tide and (or) riverine flood conditions, major flooding may exacerbate high-water conditions created by the tsunami.

MICROZONATION OF THE RISK AREA

The specific nature of the tsunami threat is determined mostly by underlying soil conditions and by land-use patterns. Once the soil conditions are clearly defined, an integrated hazard-management system organized into a series of microzones can be applied that reflect these conditions. This hazard analysis constitutes the basis for geographically delineating the risk area. The next step in the hazard-mitigation planning process requires more specific data upon which actual design can be based. The microzones defined by this study (fig. 248) are discussed following.

TSUNAMI HIGH-IMPACT ZONE

Area Delineation.—Based on the flooding simulations, only the outer coastal areas encompassing Ocean Shores and Westport are vulnerable to direct tsunami impact. Because the elevation of both communities is about 3 m above mean sea level, most of the residential areas are within the high-impact hazard zone. The rest of the study area does not appear to be vulnerable to direct high-level, high-velocity tsunami impact.

Preparedness and Mitigation.—In Ocean Shores, the critical planning issues are warning and evacuation. Population levels in this second-home community fluctuate seasonally; a tsunami that occurs in the summer could result in comparatively high life loss, whereas the risks during winter would be considerably less.

In Westport, primary concerns relate to the presence of the fishing fleet. A major cause of destruction from the 1964 Alaska tsunami and earthquake was boats being swamped, battered, and (or) thrown inland against nearby structures. Although boats are normally moored to withstand prevailing currents, tsunami-induced flows may overpower mooring lines. Boat owners who have any warning of an approaching tsunami tend to move their vessels from their anchorage and travel toward the open sea. Of the preventable deaths in Alaska during the 1964 tsunami, many resulted when fishermen tried to save their boats. In Westport, similar damage patterns could be expected to occur. Boat owners and radio-dispatch operators in the Westport area should be informed of proper procedures to be followed in the event of a tsunami warning. It may be necessary to prevent boat owners from entering the marina area if the warning time is not sufficient for evacuation before the first several waves arrive.

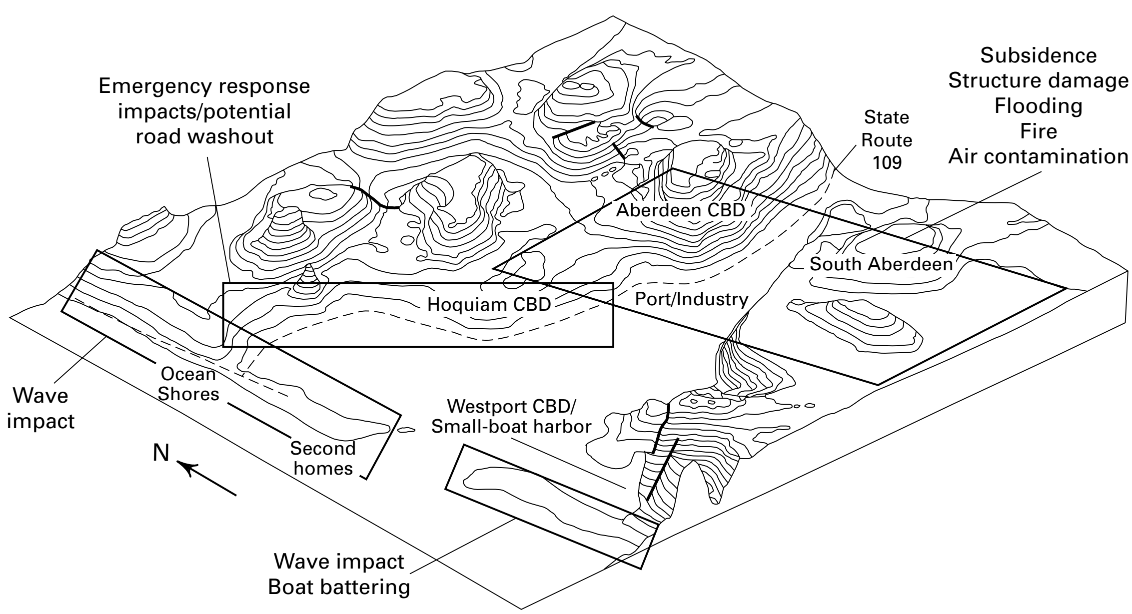


Figure 248. Grays Harbor microzones (polygons) defining hazards arising from tsunamis and earthquakes. Dashed line, major State route. A smaller roadway along south shore of harbor provides local access between Aberdeen and Westport. CBD, central business district. Base prepared by Urban Regional Research.

ZONE OF FLOODING AND HIGH PROBABILITY OF SUBSIDENCE

Area Delineation.—The majority of the urbanized Hoquiam-Aberdeen central business district and port is less than 5.5–6.1 m above mean sea level and is reported to be built on fill and (or) soft alluvial soils. This type of soil may amplify ground motion and is also prone to subsidence. Based on the effects of historical great subduction earthquakes in the Pacific Northwest and elsewhere, about 0.5 m of subsidence from compaction could accompany about 1.5 m of tectonic subsidence, resulting in a total flood elevation of 2 m above the existing MHHW of 1.7 m. Under these assumptions, the land vulnerable to flooding encompasses all the commercial and industrial areas inland to the 6.1 m elevation.

Preparedness and Mitigation.—Two categories of issues based on use have been identified in the urbanized areas. In the commercial zone, preparedness and mitigation must address conditions related to risk from damage and collapse of structures. In the industrial zone, a critical issue is vulnerability of hazardous materials, either transported into or stored on site, which could be dispersed either by flood waters or by wind. Preparedness plans consider two zones of risk: (1) the immediate flooded area, which contains airborne contamination-hazard zones under IDLH conditions; (2) the larger area vulnerable to TLV-TWA (airborne) spread as well as the area disrupted by interruption of major transportation routes.

EMERGENCY PREPAREDNESS PRIORITY AREA

Area Delineation.—The outer coastal areas of Washington and Oregon are linked to the Interstate highway system by State highways. Significant parts of these routes, which include an extensive network of bridges and roads, lie within the zone projected for flooding. Inevitably, coastal routes of the State highway system will be disrupted.

Preparedness and Mitigation Issues.—The preparedness process must assume that in the event of a major earthquake, road access will be disrupted and outside assistance will not be able to reach the area for several days. A self-reliance contingency plan for search and rescue, emergency medical, and repair should assume a delay of 2 days before adequate outside resources through mutual aid can arrive.

CONCLUSIONS

Integrated hazard assessments based on the tsunami threat have not, to our knowledge, been undertaken previously; instead, studies have focused almost exclusively on flooding as a threat. It is clear from this study that an examination of the interconnection of many potential hazards can lead to more fruitful analysis of a multifaceted threat. Additional specific studies should be made, including the following:

1. Collection of more data concerning the foundation design and condition of structures in the flood-hazard zone.
2. Calculations to describe motions of merchant vessels moored in the harbor and subject to tsunami-induced current motions. Such studies should include examination of preventive docking practices.
3. Determination of the location of toxic-material storage facilities in areas prone to tsunami-induced flooding. The design of these facilities must be reviewed because of the potential for breaching of the containers, thereby releasing toxic chemicals into the air and water.
4. Assessment of the impact of the primary (tsunami) and secondary threats on community-response capabilities (immediately after the event and in the postdisaster time frame, both in geographic terms and in terms of response resources (manpower and equipment).

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APPROACHES TO SEISMIC-HAZARD MITIGATION BY LOCAL GOVERNMENTS—AN EXAMPLE FROM KING COUNTY, WASHINGTON

By Derek B. Booth[1] *and* John P. Bethel[2]

ABSTRACT

In areas of rapid urban development, local governments have the opportunity to effectively reduce seismic risk by regulation. Basic risk-reduction strategies in hazardous areas either limit the intensity of land use or apply more stringent building requirements to the development that occurs. These two strategies can be implemented through a combination of methods, including policy-setting comprehensive plans, policy-implementing functional plans, building codes, and hazard-area delineation and regulation.

King County, Washington, has utilized all these methods in addressing seismic hazards. The county's experience with hazard-area delineation and regulation, through its Sensitive Areas Ordinance, is a particularly relevant example for other jurisdictions to study. Major weaknesses in present efforts to address seismic hazards include the poor data available from which to map hazard areas and the uneven quality of site-specific reports by private consultants. Recommendations to any local government contemplating a similar effort include a clear articulation of policies regarding basic strategy; zoning designations that are explicitly derived from functional plans and that reflect the stated policy; regional hazard mapping that is conservative but credible; and sufficient staff geotechnical expertise to adequately establish and implement an effective hazard-reduction program in cooperation with private geotechnical and design consultants.

INTRODUCTION

Local governments are pivotal in the mitigation of seismic hazards. They establish land-use policies, apply zoning, and review all new development within their jurisdictions. Whether intentionally or not, the policies and ordinances administered by these governments determine the vulnerability of all new urban construction to damage from earthquakes. In established cities, the influence over new construction may affect only a small proportion of the total number of structures. Here, risk reduction may require more aggressive efforts to upgrade existing buildings and ensure postearthquake function of utilities and emergency operations. In rapidly growing regions, however, new development may become a significant, or even the predominant, component of the built environment. We focus our attention on these regions because the opportunities for effective risk reduction are most promising and most attainable.

Once seismic hazards are recognized, reducing them for new developments can involve one of two broad strategies. If the seismic risk is perceived as severe and cannot be reduced, then intensive development can be prohibited through zoning regulations. If the risk is perceived as minor or can be mitigated to that level, then development with appropriate conditions may be allowed. The choice of strategies reflects a social rather than a purely technical judgment about the ultimate severity of that risk. That judgment also is likely to be influenced by the size of the area affected, the certainty of the available hazard data, and the economic impacts of the alternative strategies. In general, even in the most hazard-prone areas of North America, only the latter strategy of development modification has been actively pursued.

Within both of the strategies for hazard reduction, four tools are available to local governments. They apply at different stages and in different ways to land development, but each may be part of an overall effort to reduce seismic hazards.

1. Comprehensive Plans. These documents establish land-use and land-development policy throughout a region. They do not regulate land use themselves; indeed, the area of a comprehensive plan developed by a county may include incorporated cities over which the county has no jurisdiction. These plans are intended to establish the policy by which parcel-specific zoning decisions will subsequently be made.

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They therefore define which of the two basic strategies, prohibition or modification, will guide future efforts at seismic-hazard mitigation.

2. Functional Plans. These documents apply zoning regulations over large regions of the issuing jurisdiction. They control allowable land uses and intensity of development for specific parcels within these regions. In theory, functional plans simply implement policies articulated in the comprehensive plan. In practice, they may postdate the relevant policy document to the extent that what is actually implemented reflects subsequent community or political evolution.

3. Building Codes. Most municipalities in the Western United States have adopted the Uniform Building Code (UBC) as the basis for their building regulations. The seismic provisions of the UBC set standards for new structures. Where no other attention to seismic hazards is given, the UBC is implicitly assumed to satisfy any stated (or unstated) policies regarding the minimum acceptable level of safety to be provided to the public. Yet the seismic-design section of the UBC addresses only one element of seismic risk, lateral acceleration. Any seismic hazards other than those related specifically to lateral forces on the structure need to be addressed through other measures.

4. Zoning Overlays. Where a jurisdiction knows of or suspects the existence of specific areas that have an enhanced risk of seismic damage, it may choose to control development in those areas. This approach requires the designation of specific hazard zones by means of an overlay (that is, an area-specific change to established zoning restrictions) and a procedure to evaluate and condition development proposals that lie in the areas so designated. One such effort, King County's Sensitive Areas Ordinance, is discussed in detail in the following section.

ACKNOWLEDGMENTS

We thank our colleagues in King County's Building and Land Development Division, particularly geologist Steve Bottheim, for development of the ideas in this chapter. David Masters, a senior planner in the county's Parks Planning and Resources Department, offered us valuable clarifications of zoning theory and practice, and improved the discussions in the text through his review. Reviewer Martha Blair-Tyler made extensive recommendations that have allowed us to better focus our discussion. We hope that the result will be of value to other jurisdictions contemplating a similar program.

KING COUNTY—A CASE STUDY

INTRODUCTION

In the Puget Sound region, unincorporated King County (fig. 249) has probably progressed furthest in specifically addressing seismic hazards on undeveloped land (May, 1989). The county has used, to varying degrees, each of the four basic approaches to hazard reduction listed in the previous section. The ultimate goal is defined by two policies of the King County Comprehensive Plan, adopted in 1985:

E–308. In areas with severe seismic hazards, special building design and construction measures should be used to minimize the risk of structural damage, fire, and injury to occupants, and to prevent postseismic collapse.

E–309. Prior to development in severe seismic hazard areas, builders should conduct special studies to evaluate seismic risks and should use appropriate measures to reduce the risks.

These policies mandate, at most, modification but not prohibition of development, reflecting the prevailing local attitude towards seismic risk. This approach contrasts with the treatment afforded certain other types of geologic hazards, such as active landsliding or coal-mine subsidence. In areas of such hazards, policies and subsequently adopted restrictions effectively prohibit most development on the constrained parts of the sites. Subsequent functional plans have reiterated these two seismic-hazard policies and do not implement land-use restrictions on the basis of seismic risk.

King County uses both area-wide and site-specific approaches to reduce seismic hazards. These approaches predate the 1985 Comprehensive Plan, and thus the Comprehensive Plan policy does not guide but simply reiterates

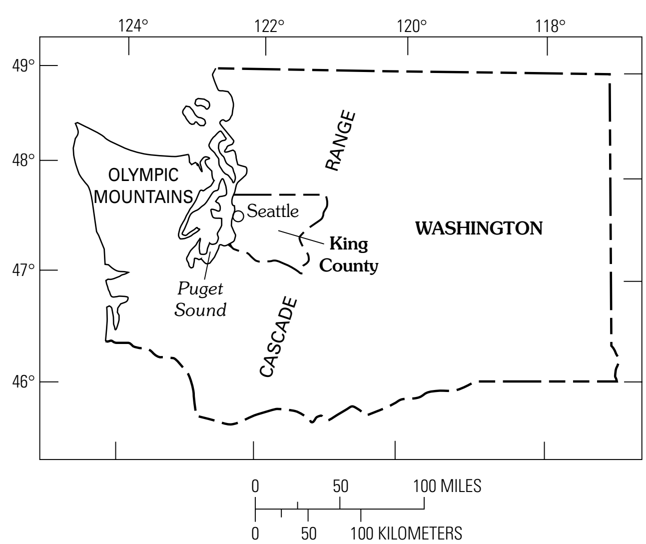

Figure 249. Index map of Washington showing location of King County.

established practice. Area-wide control is provided by the seismic provisions in the UBC. Site-specific risk-reduction measures for hazards not addressed by the UBC have been provided by the county's Sensitive Areas Ordinance, adopted in 1979 and substantially revised in 1990. That ordinance also designates landslide, erosion, and coal-mine-hazard areas and provides for studies and site-specific mitigation to avoid the worst consequences of development in geologically hazardous areas.

The Sensitive Areas Ordinance has proven more complex in its administration and far-reaching in its implications than simple building codes. We therefore describe its elements and its application in some detail, because such an approach to seismic-hazard reduction is probably most feasible for a wide range of local governments.

Several components are necessary for any regulatory effort designed to mitigate any seismic or geologic hazard. These include (1) definition of the hazard; (2) characterization of a set of hazardous site conditions; (3) delineation of the hazard zones on a map; (4) screening of proposed development; and (5) review and conditioning of developments in mapped hazard areas. Each component is described herein, both in a general context and in light of King County's specific experience.

HAZARD DEFINITION

Seismic hazards take a variety of forms. They are generally divided into the direct and indirect effects of earthquakes. Direct effects include immediate ground shaking and displacement, ground rupture, differential settlement, and liquefaction. Indirect effects, often as damaging or more so, include landslides, tsunamis and seiches (ocean and lake waves), floods from damaged dams or levees, and fire.

Planning efforts are typically motivated by past earthquakes; therefore, experience usually guides the choice of relevant concerns in a particular region. In the Puget Sound area, the 1949 and 1965 earthquakes (Thorsen, 1986) indicate that direct effects, particularly shaking-induced ground failure and shaking of buildings, are the primary concerns in this region. The indirect effects of landslides, seiches, and liquefaction were reported in several localities as well but were generally less severe.

CHARACTERIZATION OF HAZARDOUS SITE CONDITIONS

Characterizing hazardous site conditions for seismic hazards primarily involves attempting to recognize those areas where earthquake damage will be anomalously high. Any map of damage after a single earthquake shows some areas where damage is as high as in other areas much closer to the epicenter, and other areas where the effects appear anomalously mild relative to the surrounding region (for example, see Plafker and Galloway, 1989).

Conditions that will control the spatial variability of earthquake-related damage include: (1) proximity to active faults; (2) proximity to, and characteristics of, nearby water bodies; (3) thickness, character, and stratification of surficial deposits; (4) depth to ground water; and (5) site topography.

Any of these factors could in theory be made a part of the basis for seismic zonation of an area (that is, the discrimination of areas of differing seismic hazard or risk). In practice, some of these determinants are more applicable or usable than others.

In King County, only soil conditions and slope angle are presently used to identify hazardous areas; other potential criteria are not applied. Historical earthquakes here have been relatively deep seated, and no surface trace of active faults in this part of the Puget Lowland has been unequivocally identified, so proximity to known faults is not relevant (despite a few local examples of building setbacks from inactive Tertiary-age faults). Tsunamis and seiches have not caused significant damage in historical earthquakes.

Soil and substrate characteristics have long been accepted as primary determinants of earthquake damage. Areas underlain by thick deposits of low-strength, low-density soils have commonly been associated with severe earthquake damage (for example, see Bolt, 1988). Such damage may result from liquefaction or amplification of low-frequency seismic waves. In King County, most of the soil has been consolidated to a high density by multiple glacial episodes. The most extensive low-density deposits are therefore in areas where postglacial sedimentation has filled valleys or depressions in the glaciated ground surface. The Sensitive Areas Ordinance therefore identifies "recent alluvium and organic soils" as indicators of high seismic hazard.

Steep slopes have a potential for landslides during and immediately following an earthquake. Therefore, the seismic provision of the Sensitive Areas Ordinance originally included all slopes steeper than 15 percent as seismically hazardous. Unfortunately, this attempt to include areas of both low-density soil and potential slope instability as a single, undifferentiated hazard area on a single map reduced the usefulness of the hazard mapping. For this reason, the 1990 revision to the ordinance deleted sloping areas and instead treats seismically triggered landsliding as a part of the landslide-hazard review process.

MAPPING OF HAZARD ZONES

Ideally, the representation of seismic-hazard zones would be based on complete topographic, hydrologic, geologic, and seismologic information. The risk from the direct effects of ground shaking might be quantified by the maximum horizontal ground acceleration for an earthquake of given energy release. These data could be mapped and contoured based largely on soil and substrate properties.

Other, indirect effects then could be overlaid on this map where relevant in order to define overall levels of risk.

In practice, the data and the resources are rarely available to make such detailed estimates. New mapping is beyond the means of most local jurisdictions, and existing soils and geologic maps are not specifically prepared to identify seismically hazardous soils. Although a complete data source would show and identify the known types of seismic hazards, including artificial fills, recent alluvial soils, low-density organic soils, thick unconsolidated deposits, and landslide susceptibility, more commonly the information available consists only of surface soil types (for example, county soil surveys) and topography. The result is a much more generalized hazard map, discriminating only relatively "good" land from land that is more likely "bad." King County has this kind of generalized hazard map (fig. 250), where the presence of unfavorable soils (alluvial or organic) solely defines the hazard zones. About 10 percent of the land area within the actively developing parts of the county is so categorized.

Despite these deficiencies, the actual determinants of seismic response in most regions correlate fairly well with soils and slope information. Deep, unconsolidated deposits are most common beneath surfaces of alluvial sediment, which typically include areas of loose organic soil as well. Saturation of these sediments is also common. Steeper slopes correlate fairly well with landslide hazards. Yet, use of soils maps may also identify areas where no increased seismic hazard exists, such as shallow pockets of peat on an undulating till surface or moderate-gradient hillslopes underlain by competent bedrock. Conversely, other seismic hazards may pass unnoticed, such as low-lying shorelines and areas of recent artificial fill.

SCREENING OF DEVELOPMENT PROPOSALS

Once a map is prepared, affected development proposals must be screened. In King County, that authority was created by the Sensitive Areas Ordinance, which requires that virtually all proposals requiring a permit be checked against a map showing so-called hazardous and nonhazardous areas. The process is quite straightforward; the location of the project is checked on a 1:62,500-scale map of hazard areas by the intake permit technician (for building permits) or lead planner (for subdivisions or other large projects). If the project falls within a hazard area, it is referred to a staff geotechnical specialist for further review.

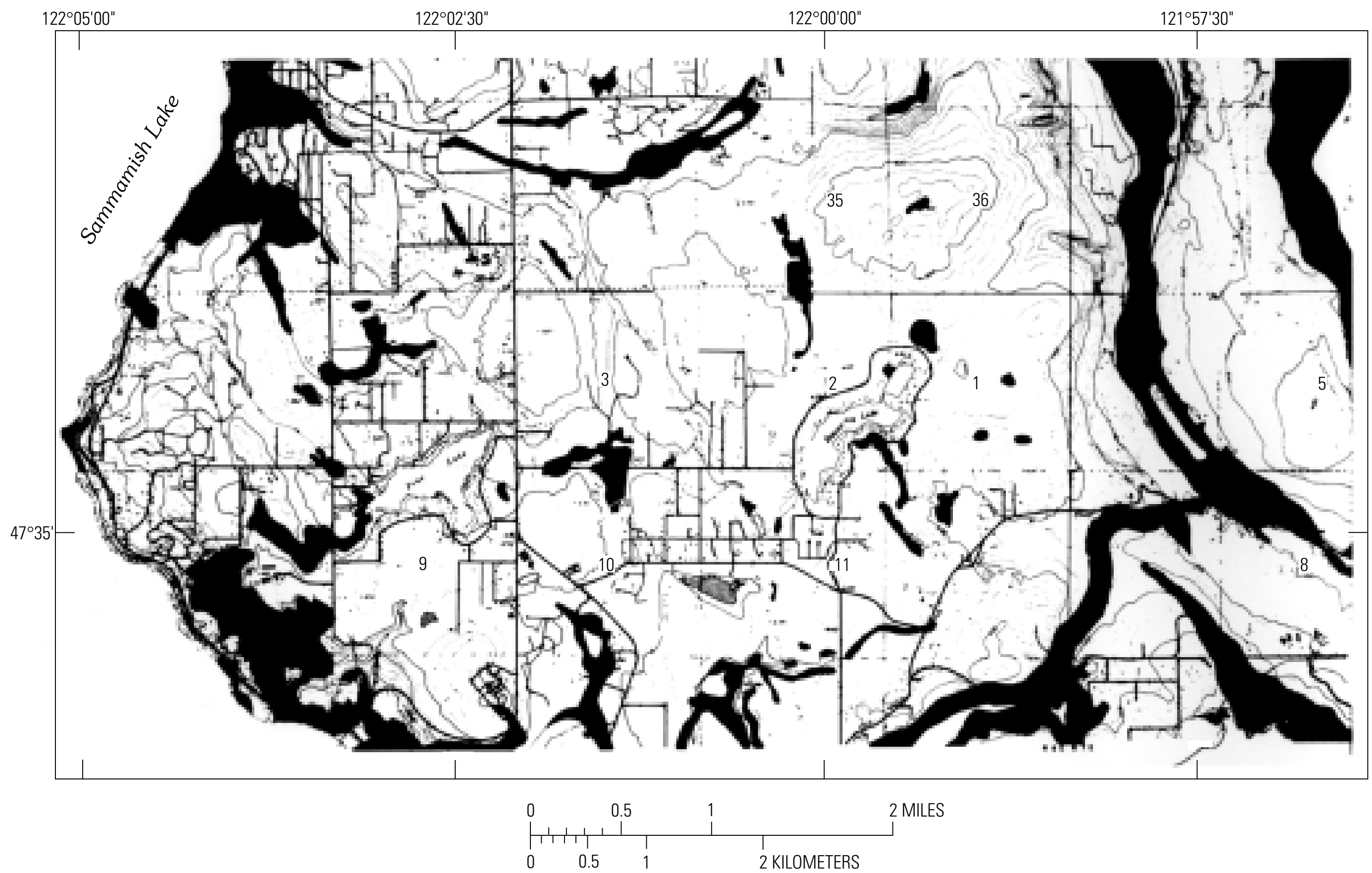

Figure 250. Part of a seismic-hazard map of King County, Washington. Class III areas (dark shade) are defined and regulated under the county's Sensitive Areas Ordinance (King County, 1990). Actual maps are at a scale of 1:62,500.

REVIEW AND CONDITIONING OF PROPOSALS

Once a project has been identified to be in a seismic-hazard zone, the geotechnical specialist must typically choose among the following alternatives to determine if any additional review of the project is needed:

1. Because of the nature of the project, no concern is warranted (for example, kitchen remodeling without any structural change to the building).
2. Despite the project's apparent location within a mapped hazard zone, no concern is warranted (for example, the site is not actually in the hazard zone because of known mapping error or map-reading error).
3. The project lies in a seismic-hazard zone, but the seismicity concerns will be adequately addressed in solving other, more severe, site constraints (such as excessive depth to bearing soil, or active landslide threat). This alternative is most commonly chosen for projects in the seismic-hazard zones in King County.
4. The seismic hazard is in fact a significant concern for the project and requires specific mitigation.

A local government will typically proceed in a similar fashion for either of the last two options, where conditions or requirements beyond the standard zoning and building codes are deemed necessary. The applicant will be directed to hire a professional consultant, normally a geologist or an engineer, to perform a detailed site evaluation and to design an appropriate solution that will be submitted for review (usually) to the local jurisdiction. Detailed site evaluations are routinely required because the existing information regarding site conditions is seldom enough to develop appropriate mitigation. Site evaluations typically characterize the ground-water conditions and address the depth, density, and texture of the subgrade soils. For seismic hazards in King County, proposed mitigations have included subgrade replacement, alternative foundation systems, or improved site drainage. At many sites, these efforts also represent engineering solutions to other nonseismic problems that reduce the seismic hazard to a level equivalent to nonhazardous areas.

EVALUATION OF KING COUNTY'S MITIGATION EFFORTS

King County's primary effort to reduce seismic hazards has several key components. A zoning overlay has been established that defines a method for requiring geotechnical evaluation, thus achieving additional engineering mitigation. No change (that is, no reduction) in the intensity of land use is intended or achieved. Relevant seismic hazards have been identified, namely landsliding and ground failure. A map of these hazard zones has been prepared to screen development proposals. Special engineering studies, prepared by the applicant's consultants, assess any seismic risk and necessary mitigation. Finally, geotechnical review by the county's staff maintains consistency and minimum competency of the mitigation procedures finally adopted.

In this process, two elements are particularly weak. The first is the mapping of hazard areas. Critical because of the sheer volume of development activity (more than 10,000 permits processed in King County in 1989), the seismic-hazard map is imperfectly correlated with zones of actual seismic hazard. King County's current seismic-hazard map displays the extent of several Soil Conservation Services soil types that have been identified as being seismically sensitive (Rasmussen and others, 1974). In practice, it has become apparent that many areas designated as hazardous on this map are not particularly hazardous. Other potentially relevant determinants of seismic hazards have not been fully considered. For example, liquefaction potential is identified only by surface soil types; subregional variability in earthquake intensity because of focusing effects or particularly thick, unconsolidated deposits is nowhere identified. Other potential hazards, particularly seiches or dam breaks, are simply not included in the mapping of any geologic hazard.

The second weak element is the reliance on special engineering studies for specific mitigation strategies. The structural and geotechnical engineering community has a broad range of experience and knowledge in addressing seismic hazards. In the Pacific Northwest, there is little consensus in the geotechnical community on a standard of practice for evaluating site-specific seismic hazards. This lack of consensus is especially apparent in reviewing geotechnical reports for small to moderate-sized projects (residences or small commercial structures). The areas where geotechnical practice is most variable include selection of a design earthquake (namely, the size of the largest earthquake of concern), the scope of adequate subsurface exploration, and appropriate mitigation measures for identified hazards. King County is fortunate in having staff for review, but reliance on these outside studies for design is unavoidable. Currently, the county staff consists of three engineering geologists for all aspects of geotechnical review of development proposals. However, more than 25 years has passed since the last major earthquake in the region. Thus, the experience of local consultants is commonly limited, resulting in reports that vary widely in scope, analytical methodology, and design recommendations.

RECOMMENDATIONS

King County has more than 10 years of experience in implementing a program of seismic-hazard reduction through regulation of land use and building construction. The following recommendations are largely based on this experience and are offered for consideration by other local jurisdictions contemplating a similar program. Their value, however, will be known only after the next large earthquake in the Puget Lowland, followed by a review of developments that were built under this program.

1. Establish Clear Policy. The jurisdiction's comprehensive land-use plan needs to define clearly the policy towards land development in seismically active areas. Without this foundation, subsequent efforts at hazard mitigation will either lack consistency or establish only informal policy. Under the authority of a comprehensive plan, the existence and significance of the seismic threat should be stated clearly, and the types of seismic hazards specific to the jurisdiction should be identified explicitly. Finally, a general framework for hazard mitigation should be established for ultimate implementation through functional plans, building codes, and zoning overlays.
2. Use Policy and Zoning to Minimize Risk. Functional plans, which implement the land-use policies of the comprehensive plan, should reflect both the policy towards and the nature of the seismic hazards. If the hazard can be mitigated during development, then the seismic-hazard delineation should be a factor weighing against intensive land uses but not precluding all uses. This kind of decision would apply to areas subject to liquefaction or settlement of uncontrolled fill, for example. Even hazards that can be mitigated should factor into decisions on locating intensive land uses because of the additional cost of public service to such areas and the potential that mitigation may not be effective. If the hazard (for example, that of potential inundation by tsunamis) cannot be effectively mitigated during development, the hazard should preclude intensive structural land uses (for example, see Nichols and Buchanan-Banks, 1974). Such areas should be set aside for agriculture, recreation, natural-resource production, or other uses that minimize life and property risks.
3. Map Accurately and Conservatively. Although maps associated with zoning overlays are vital to efficient implementation, community-wide seismic-hazard maps are less detailed and less accurate than site-specific studies. For this reason, hazard mapping should be represented and understood as a guideline to the general distribution of seismically sensitive areas rather than as a definitive delineation of such areas. Because the hazard mapping will be approximate, it should err on the side of including too much area in the hazard zone. Errors of this type can be identified during site-specific evaluations. The mapping, however, should not be so conservative that it loses credibility as a useful hazard predictor. It should also seek to incorporate data beyond soil surveys, and it should be updated as new information becomes available.
4. Encourage Uniform Standards for Study Scope and Quality. Jurisdictions should encourage a more uniform approach to seismic-hazard evaluation by working with engineering design professionals and technical experts to establish some baseline hazard-evaluation criteria. In particular, these criteria may include designation of an appropriate design earthquake and establishment of a minimum scope of study for sites in designated seismic-hazard areas. Recent revisions to King County's Sensitive Areas Ordinance provide that authority and also allow more stringent criteria for certain critical structures such as schools, hospitals, and emergency centers.
5. Provide In-House Expertise. Effective implementation of a seismic-hazard-mitigation program requires geotechnical expertise within the jurisdiction as well by the applicant's consultant. Larger governmental bodies, such as the City of Seattle and King County, can justify maintaining a full-time geotechnical staff. This staff is available to assist in all phases of permit processing in seismic-hazard areas, from initial screening to review of construction inspection reports. Smaller municipalities will contract geotechnical review to private consultants, whose overall role in permit processing typically will be more limited. The one step in the permit-review process where geotechnical expertise is most clearly required is the evaluation of geotechnical studies submitted by the applicant. This is the stage at which adherence to a consistent minimum standard of practice must be assured. Yet, without established, well-founded criteria for such a standard, the final results may be far short of needs.

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LIABILITY FOR EARTHQUAKE HAZARDS OR LOSSES AND ITS IMPACTS ON THE CITIES AND COUNTIES OF WASHINGTON

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ABSTRACT

Based on a legal analysis of Washington State tort law, local governments can be held liable for some earthquake losses. The most likely sources of liability are injuries or damage caused by the dangerous condition of governments' own properties. Local governments also have potential liability for injuries on private properties, although the exposure is less than on public property. *Discretionary immunity* is the only defense for losses resulting from the issuing of earthquake warnings or from emergency response activities. The *act of God* defense may prevail in only two very limited situations: (1) if the earthquake was of such type or size as to be unforeseeable, and the local government did not act negligently with respect to dealing with a foreseeable earthquake; or (2) if the earthquake was foreseeable and the local government took all reasonable actions to prevent harm but damage still occurred. Local government employees in Washington, California, Utah, and Alaska rank potential liability as one of the top five factors motivating earthquake-hazard-reduction programs.

THE EXTENT OF LOCAL GOVERNMENT LIABILITY IN WASHINGTON

Local governments can be held liable for some earthquake losses. The Washington Tort Claims Act provides that all political subdivisions and municipal corporations of the State are held liable for damages for their or their employees' tortious conduct to the same extent as if they were a private person or a corporation (Revised Code of Washington, Sec. 4.96.010). Thus, sovereign immunity in Washington is abolished without any statutory exceptions.

The legal defense that earthquakes are an *act of God* will no longer prevail in most circumstances. In the legal sense, an *act of God* is a natural event, causing damage, over which people have no control. Although in one sense an earthquake is beyond our control, the facts are that damaging earthquakes occur in Washington, and scientists are gaining increased knowledge about them and their processes. Earthquakes and the damage resulting from earthquakes may be foreseeable, and under some circumstances the losses can be at least partly mitigated. Therefore, the *act of God* defense to tort liability may prevail in only two very limited situations: (1) if the earthquake was of such type or size as to be unforeseeable, and the local government did not act negligently with respect to dealing with a foreseeable earthquake; or (2) if the earthquake was foreseeable and the local government took all reasonable actions to prevent harm but damage still occurred.

SOME KEY LEGAL CONCEPTS

A tort is a civil (as opposed to criminal) wrong, other than a breach of contract, for which courts award damages. A tort has four elements: (1) A pertinent duty must be imposed on the defendant (local government); (2) the defendant (local government) must have violated that duty; (3) the victim must have been injured or suffered damages; and (4) there must be a causal connection between the negligence and the harm suffered by the victim.

Negligence is the usual standard by which a defendant's actions are judged in order to determine whether a duty was violated. The concept of negligence is commonly based on the rule of reasonableness. How would a reasonable person have acted under similar circumstances? Could the injury or loss have been foreseen? What was the apparent magnitude of the risk? What were the relative costs and benefits of action versus inaction? Has the defendant complied with applicable statutory or regulatory standards?

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If negligence is established, the local government can raise applicable defenses, the most important of which is the discretionary immunity. The discretionary immunity applies to basic policy decisions that have a planning, rather than an operational, character. For example, a city council's decision to enact a law requiring a landowner to disclose geologic and soil conditions prior to selling their property or building on it would be immune to liability as a discretionary function. The city manager's decision to waive the requirement may or may not be immune, depending on the language of the ordinance, the factors used to make the decision, and the State in which the manager is located. The clerk who issues a building permit without requiring the disclosure document is not immune under the discretionary immunity.

The discretionary immunity was created by the Washington judiciary as an exception to the rule of general liability of local governments (see *Evangelical United Brethren* v. *State*, 67 Wn. 2d 246, 407 P.2d 440 (1965)). To avail itself of the immunity, the act of a local government must meet a four-part test. The challenged act must (1) involve a basic governmental policy, program, or objective; (2) be essential to the realization or accomplishment of that same policy, program, or objective; (3) require the exercise of basic policy evaluation, judgment, and expertise; and (4) be performed by the government agency having the requisite authority and duty to perform the act. In addition, the municipality must demonstrate that it actually exercised discretion (see *King* v. *Seattle*, 84 Wn. 2d 239, 525 P.2d 228 (1974)). Finally, Washington appears to give some weight to the position of the decision maker in the governmental hierarchy in assessing whether the decision was truly discretionary (*Chambers-Castanas* v. *King County*, 100 Wn. 2d 275, 869 P.2d 451 (1983)). However, the issue of position in the hierarchy is less important than in some other States, such as California.

A duty may be imposed on the local government under the public-duty doctrine, which applies when a so-called special relationship exists between the local government and the victim. If the enabling statute for the governmental action states a clear legislative intent to protect an identifiable class of persons and a member of the class is injured, then a special relationship exists (see *Baerlein* v. *State*, 92 Wn. 2d 229, 595 P.2d 930 (1979)). A general duty to regulate private-sector activity for the benefit of the general public does not create a special relationship. If a statute obligates a local entity to abate a special known and dangerous condition, failure to do so will create a special relationship between a plaintiff and a defendant (see *Campbell* v. *City of Bellevue*, 85 Wn. 2d 1, 530 P.2d 234 (1975)). If an injured party relies on expressed or implied assurances by a governmental agency with whom the party had direct contact, a special relationship also may be created.

It is also important to understand the role of judges and juries in a jury trial. Questions of fact (concerning whether something is factually true or untrue or whether something did or did not occur) are the province of the jury except under extreme circumstances. Questions of law (requiring that the law be interpreted or applied) are the exclusive province of the judge. However, it is the jury that decides (as a matter of fact) whether or not it would have been reasonable to do more, thereby determining (as a matter of law) that negligence exists. The legal community refers to such questions as mixed questions of fact and law.

LIABILITY VARIES WITH THE CIRCUMSTANCES

The most likely sources of liability for a local government in Washington are injuries or damages caused by the dangerous condition of its own property—its hospitals, city halls, jails, and public works. In most situations, the injured party will rely on traditional tort analysis in establishing liability. The possible use of the discretionary immunity for certain decisions regarding public facilities (such as decisions to build and siting) is undeveloped as of 1992.

Washington's local governments also have potential liability for injuries on private property, although the exposure is less than on public property. Local governments in most States are immune from liability for most actions relating to the issuing of permits or inspection activities. Washington courts, on the other hand, have consistently found liability for building-inspection and permitting activities so long as the injured party can establish a special relationship under Washington's public-duty doctrine.

For losses resulting from emergency-response activities, discretionary immunity is the only defense for local governments in Washington. Emergency-response field decisions are probably not immune. Therefore, the question of whether the public entity owes a duty to the injured party is pivotal. However, this question is difficult to analyze without knowing the specific circumstances of the situation.

In Washington, there is no statute granting immunity for the issuance of an earthquake warning. The discretionary-function immunity is the only defense to liability.

THE IMPACT OF LIABILITY ON LOCAL-GOVERNMENT DECISION MAKING

Using written questionnaires and in-person interviews with local-government staff in Washington, Alaska, California, and Utah during 1978, we arrived at several conclusions about the effects of liability on the creation and motivation of earthquake mitigation programs. Even though a higher risk of earthquakes and earthquake-produced hazards events can trigger the initiation of programs, mere higher risk is an incomplete picture of the motivation process. Local-government staff in the four States ranked 10 factors motivating earthquake-hazard-reduction programs in their jurisdictions. The top five (in order) were:

1. Leadership of a staff member or elected official.
2. The need to maintain local government functions.
3. Concern for potential liability.
4. Improved public safety.
5. A State or Federal government requirement.

The top five of Washington government staff were (there was a tie for third place):

1. A State or Federal government requirement.
2. Leadership of a staff member or elected official.
3. The need to maintain local government functions; Avoiding employee injury.
5. Concern for potential liability.

Liability was ranked even higher among those local governments with most active earthquake programs in the four States surveyed. However, it was listed first by very few local governments when compared to the other top motivators; it ranks high because it is pervasive. There is no single motivator for earthquake-hazard-reduction programs; the motivators are as diverse as the jurisdictions themselves.

More than 90 percent of local governments surveyed in the four-State area (and 80 percent of those in Washington) believe that the law is at least sometimes uncertain. In the four-State area, half of those noting uncertainty think that this has little or no effect on their jurisdiction, one-quarter think that it encourages aggressive hazard-reduction programs, and one-quarter think that it discourages programs. In Washington, about 40 percent think that the uncertainty has little or no effect on their jurisdiction, 30 percent think that it encourages action, and 30 percent think that it discourages action. Managers from jurisdictions that have the most comprehensive earthquake-mitigation programs are more likely to believe that this uncertainty encourages action.

Managers from jurisdictions with active earthquake-hazard-reduction programs do not perceive significantly more or less liability exposure than the entire group surveyed. Thus, there is no indication that any major change in rules governing liability or immunity would result in more active earthquake-hazard-reduction programs. A general concern for liability rather than a specific perception of the degree of liability exposure appears to motivate earthquake-hazard-reduction programs. About two-thirds of those surveyed reported concern for liability for earthquake hazards within their jurisdictions, double the number of a similar survey conducted by ABAG (Association of Bay Area Governments) in 1978.

Jurisdictions with active earthquake-hazard-reduction programs tend to be self insured with active risk-management programs created to control losses associated with general liability claims. However, we concluded that the existence of active risk-management programs and active earthquake-hazard-reduction programs are the result of a progressive top management and stable elected bodies promoting safety awareness, rather than risk management somehow causing the earthquake-hazard-reduction program to be more active.

PROMOTING SAFETY WHILE COPING WITH LIABILITY—SOME ADVICE FOR LOCAL GOVERNMENTS

As a result of this study, the following recommendations are made for local governments to promote public safety and cope with liability:

1. Local governments should comply with any statutory or regulatory standards imposed by State or Federal governments.
2. A program should be developed to inspect, repair, and maintain public buildings and facilities.
3. The local government's risk manager can help promote increased earthquake-hazard safety in all public facilities and buildings.
4. Local-government staff should not assume that liability exposure exists for any mitigation program involving private property. Ask advice from your legal counsel.
5. Act to promote the safety and welfare of the people in your community. If you act reasonably, your liability exposure can be minimized.

The preceding summary highlights the findings of a research project conducted by Perkins and Moy (1989). In addition, a companion document (Perkins and Moy, 1988) contains the background legal research, summaries of case law and statutes, and the results of the survey of local-government behavior.

ACKNOWLEDGMENTS

The authors wish to thank Professor David Jung, Hastings College of the Law, University of California, San Francisco, and Crane Miller, attorney and legal researcher, Washington, D.C., for their thoughtful comments on this report.

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