PB 294686

NATURAL HAZARDS

EARTHQUAKE • LANDSLIDE • EXPANSIVE SOIL LOSS MODELS

j.h.wiggins company

THIS MATERIAL IS BASED UPON RESEARCH SUPPORTED BY THE NATIONAL SCIENCE FOUNDATION UNDER GRANT NUMBERS ERS-75-09998-A01, AND AEN-74-23992. ANY OPINIONS, FINDINGS, AND CONCLUSIONS OR RECOMMENDATIONS EXPRESSED IN THIS PUBLICATION ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF THE NATIONAL SCIENCE FOUNDATION.

50272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO. NSF/PRA-7509998/2

2.

3. Recipient's Accession No. PB294686

4. Title and Subtitle

Natural Hazards: Earthquake, Landslide, Expansive Soil Loss Models

5. Report Date December 1978

6.

7. Author(s) J.H. Wiggins, J.E. Slosson, J.P. Krohn

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

J.H. Wiggins Company
1650 South Pacific Coast Highway
Redondo Beach, California 90277

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.

(C)

(G) ERS7509998
AEN7423992

12. Sponsoring Organization Name and Address

Scientific, Technological, and International Affairs (STIA)
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Natural hazards generally associated with earth movement are considered, namely, earthquake, landslide, and expansive soil. Each hazard was modeled with regard to national and sudden loss projections. Regarding the earthquake hazard, it is estimated that the annualized loss to the nation is about $650 million dollars in damage. Expansive soils, although not dramatic in nature, cause the 1970 building wealth in 1970 dollars to experience losses on the order of 1.1 billion dollars. Landslide caused on the order of 200 million dollars in annualized losses to the 1970 building population at risk in terms of 1970 dollars. From the standpoint of sudden losses (a 100-year event), earthquake dominates the scene for all earth-related hazards. No sudden loss scenarios were computed for landslide and expansive soil losses since their statistical extremes are not very severe. Mitigations were applied to the theoretical national loss, earth hazard models. It was determined that if the most effective mitigations were invoked beginning in the year 1981, approximately 24 percent of the annual loss projected by the year 2000 could be saved. Of all the natural hazards examined, it was determined that earthquake is by far the most extreme type of hazard and also affords the greatest possibility of sudden loss reduction should adequate warning be given and consequent appropriate actions taken to reduce the risk.

17. Document Analysis a. Descriptors

Earthquakes
Hazards
Landslides
Soil erosion
Earth movements
Losses
Cost estimates
Economic analysis

b. Identifiers/Open-Ended Terms

Natural hazards

c. COSATI Field/Group /

18. Availability Statement

NTIS

19. Security Class (This Report)

20. Security Class (This Page)

21. No. of Pages 166

22. Price A08-A01

(See ANSI-Z39.18) *See Instructions on Reverse*

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

NATURAL HAZARDS

- EARTHQUAKE
- LANDSLIDE
- EXPANSIVE SOILS

LOSS MODELS

by

John H. Wiggins
James E. Slosson
James P. Krohn

J.H. Wiggins Company
1650 South Pacific Coast Highway
Redondo Beach, California 90277

December 1978

TABLE OF CONTENTS

SECTION I - EARTHQUAKE SHAKING

SECTION II - LANDSLIDE

SECTION III - EXPANSIVE SOIL

LIST OF TABLES

LIST OF TABLES
(continued)

LIST OF FIGURES

ACKNOWLEDGEMENT

The authors are indebted to the economic modeling conducted by Mr. Joseph Hirschberg for the annual loss and sudden loss estimates as compiled. We are also indebted to the many state geologists, the Soil Conservation Service of the Department of Agriculture and a number of other professionals throughout the country who are individually acknowledged in Appendix A, Sections 2, and to Mr. D. Earl Jones, Jr., with HUD for the invaluable contributions to this effort.

SUMMARY

Those natural hazards generally associated with earth movement are treated in this volume; namely, earthquake, landslide, and expansive soil are Earth hazards which cause damage and loss of life in varying degrees. Each hazard was modeled with regard to national and sudden loss projections for several reasons:

1. In order to test the efficacy of various mitigations, either in the form of building regulation modification or land use, it was necessary to build a computerized simulator which could be used to examine the consequences of invoking those mitigations. These consequences could be evaluated not only for the year 1970, from which the data base line was originally constructed, but also for growth projections of buildings and persons at risk for future time periods.

2. The NSF grants supporting this work involve the study of nine natural hazards which principally affect the damageability of buildings and the safety of persons. In order to give perspective to the specific hazard in question, one must develop models from which damage in terms of dollar losses (constant 1970 dollars were used as a reference throughout the report) and death could be compared. This comparison could be interrelated within the group of hazards examined (earth: earthquake, landslide, expansive soil; water: riverine flood, tsunami, storm surge; and wind: hurricane, severe wind and tornado).

3. An organized, traceable system for treating each hazard is presented in a systematic way. Thus, it can be examined, scrutinized, critiqued, and critically reviewed for the effects of all the parameters which enter into the simulation model. In this way, the sensitive parameters which control loss indicators can be examined by investigators at future dates.

Regarding the earthquake hazard, it is estimated that in terms of 1970 dollars, and 1970 conditions, the annualized loss to the nation is about $650 million dollars in damage. California, with its high seismic zones and considerable wealth exposure makes up about 67% of this loss.

Expansive soils, although not dramatic in nature, cause the 1970 building wealth in 1970 dollars to experience losses on the order of $1.1 billion, with California and Texas accounting for over 35% of the total damage to the nation.

Landslide causes on the order of 200 million dollars in annualized losses to the 1970 building population at risk in terms of 1970 dollars. California and Pennsylvania are leaders with $33 million and $19 million annual loss, respectively, making up about 25% of the total landslide losses to the nation.

From the standpoint of sudden losses (a 100-year event), earthquake dominates the scene for all earth-related hazards. Assuming a sudden loss recurring at San Francisco, California, which was the site of the previous 1906 earthquake, having a magnitude of 8.25, one would compute building damage in the neighborhood of 12 billion 1970 dollars for 1970 conditions. In the year 2000, if the same earthquake occurred, the loss in terms of constant 1970 dollars is estimated to be 23 billion dollars to buildings alone.

No sudden loss scenarios were computed for landslide and expansive soil losses since their statistical extremes are not very severe. Further, the models generated were much simpler than that developed for earthquake in that they did not permit the 100-year event situation to be employed.

Mitigations (those procedures which are invoked through land use planning and/or building regulation) were applied to the theoretical national loss, earth hazard models. It was determined that if the most effective mitigations were invoked beginning in the year 1981, approximately 24% of the annual loss projected by the year 2000 (20 years later) could be saved. No costs, however, for obtaining this reduction were derived for cost/benefit evaluations.

From the standpoint of a sudden loss from earthquake, it was determined that with adequate preparation, money, and cooperation, 59% of the loss could be avoided. Of all the natural hazards examined, it was determined that earthquake is by far the most extreme type of hazard and also affords the greatest possibility of sudden loss reduction should adequate warning be given and consequent appropriate actions taken to reduce the risk (chance of loss).

From the standpoint of landslide, it is estimated that if mitigations such as improved grading ordinances, runoff control and land use control were invoked, approximately 30% of the hazard could be reduced by the year 2000, on an annual loss basis. Virtually all new construction losses could be avoided.

The authors believe that the expansive soils problem could be reduced significantly for new construction, beginning in 1981, but possibly at a cost that the public would not voluntarily buy (possibly \$1.50/ft^2 increase in total cost of structures in 1970\$). Assuming that an acceptable new construction loss reduction would be about 10% after 1980, our building forecast would indicate that the expansive soil problems could be reduced by about 4% in the year 2000. However, since expansive soil losses are so large, even a 4% reduction amounts to about \$200 million 1970 dollars per year. Combined with this loss, reduction would be a corresponding increase in the average half-life of the building population at risk. Put another way, the expansive soil hazard causes structures to have shorter lifetimes due to a more rapid deterioration process. No computation was made on the added loss to the national building wealth caused by this reduction in the nominal life of a building. Therefore, we estimate that the \$200 million saving by the year 2000 is a minimum value achieved at modest or no additional cost, and that greater, intangible savings to the nation could be realized in regions with expansive soil conditions.

INTRODUCTION

The following report documents the construction and operation of building loss natural hazard simulators modeling earth movement (earthquake, expansive soils and landslide). These simulators are constructed in order to evaluate the annualized losses to buildings from each of these hazards as well as to develop an understanding of the sudden loss or maximum regret situation, such as the recurrence of the 1906 San Francisco earthquake in the years 1970, 1980, 1990, and 2000.

The building loss simulators are constructed also to test the usefulness of certain policy decisions in the form of building regulations or land use control that may be invoked in order to reduce annual and sudden losses from these natural hazards. Loss estimates and loss control procedures can therefore be evaluated in a traceable manner to the lowest level within the model; namely, the county. That is to say, the loss simulators model the United States at the county level. No finer level of microzoning was considered; however, the authors believe that this level of accuracy is sufficient to examine federal, state and possibly county policies that may be invoked for controlling natural earth movement hazards.

The authors do not purport the models to be complete; they are, however, <u>first approximations</u> which use a consistent logic to examine each hazard using the following definitions to outline the logic behind each model:

(1) Hazard:
The hazard herein is defined as the proximate earth movement that takes place together with its intensity and occurrence probability for a specific geographical location.

(2) Exposure:
The exposure to the hazard is defined as the number, types, qualities, and monetary values of various types of buildings located in various geographical regions. For example, buildings are divided into categories such as dwellings, commercial, industrial, public and institutional.

(3) Vulnerability:
The vulnerability of the structure describes the as-built damageability of a particular quality and type of structure for each earth hazard.

The vulnerability is described as the capacity of a particular class of structures to resist a certain intensity of earth hazard in terms of percent of total dollar damage in terms of value lost.

(4) Risk:

When one overlays the location of the hazard with the location of the exposure and combines the resultant with the vulnerability of the exposure, the annualized loss (risk) can be computed. Risk, here, is therefore defined as the "chance of loss." The "loss" relates to damage or value lost to buildings, and the "chance" stems from the probability of the occurrence of the hazard.

Using the above logical format for computation, the entire nation was modeled by county in order to develop national loss simulators for each hazard (Table 1).

1970

STATE	TOTAL STRUCTURE VALUE ($BILL.)	POPULATION (MILLIONS)	EARTH HAZARDS (MILLIONS)		
			EARTH-QUAKE	EXPANSIVE SOIL	LAND SLIDE
AL	26.7	3.44	.0	11.6	4.6
AK	3.9	0.27	3.6	-	0
AZ	16.9	1.77	0.7	3.9	2.29
AR	13.6	1.92	3.3	6.5	2.98
CA	228.0	19.96	439.6	226.8	36.83
CO	22.7	2.21	20.2	23.3	6.27
CT	35.0	3.03	0.8	12.9	10.30
DE	5.7	0.55	0.1	1.1	1.59
DC	12.6	0.76	0.1	2.5	.82
FL	61.1	6.79	1.0	17.6	3.91
GA	41.5	4.59	0.5	23.8	5.12
HI	10.0	0.77	0.3	-	0
ID	6.3	0.71	1.5	3.5	1.01
IL	126.8	11.12	1.0	47.3	33.16
IN	48.8	5.20	0.1	10.7	6.80
IA	25.8	2.83	.0	23.2	5.21
KS	21.5	2.25	0.2	28.4	3.41
KY	25.6	3.22	1.3	11.9	5.96
LA	30.3	3.64	1.9	44.1	5.95
ME	8.3	0.99	.0	3.7	2.12
MD	49.2	3.92	0.1	10.8	11.97
MA	63.4	5.69	1.7	12.4	13.21
MI	90.8	8.88	0.9	56.9	19.47
MN	37.7	3.80	.0	9.6	5.52
MS	14.6	2.22	0.4	14.3	2.76
MO	45.1	4.68	15.3	62.9	10.75
MT	6.4	0.69	1.4	5.2	1.18
NE	14.3	1.49	0.2	24.6	2.64
NV	5.8	0.49	2.7	4.2	.64
NH	7.4	0.74	0.2	1.4	1.47
NJ	83.7	7.17	3.4	16.3	10.70
NM	9.1	1.02	1.2	4.8	.82
NY	229.6	18.24	20.2	45.0	29.36
NC	40.0	5.08	0.1	24.0	9.76
ND	4.8	0.62	.0	2.7	1.13
OH	106.3	10.66	1.0	25.3	21.87
OK	23.1	2.56	0.5	20.5	2.16
OR	19.9	2.09	1.7	16.8	4.19
PA	116.1	11.80	0.4	26.1	24.91
RI	9.3	0.95	0.1	1.8	.60
SC	19.6	2.59	1.9	7.2	3.21
SD	5.3	0.67	0.1	3.9	1.31
TN	30.8	3.92	15.1	10.1	2.00
TX	103.7	11.20	0.8	173.8	11.36
UT	10.6	1.06	12.2	7.1	3.13
VT	3.8	0.44	.0	0.9	.54
VA	48.8	4.65	0.4	13.6	8.94
WA	35.6	3.41	96.9	7.9	10.41
WV	14.2	1.74	0.1	5.4	4.88
WI	41.2	4.42	.0	10.9	10.43
WY	3.2	0.33	.0	2.9	.71
U.S.	2064.5	203.24	655.2	1132.1	370.3

2000

STATE	TOTAL STRUCTURE VALUE ($ BILL.)	POPULATION (MILLIONS)	EARTH HAZARDS (MILLIONS)		
			EARTH-QUAKE	EXPANSIVE SOIL	LAND SLIDE
AL	65.0	4.17	.0	27.1	10.8
AK	8.6	0.34	7.1	-	-
AZ	47.8	2.78	1.6	11.0	6.2
AR	32.4	2.18	6.3	14.4	7.4
CA	539.8	26.03	748.8	541.3	88.7
CO	56.1	2.86	44.5	59.3	15.7
CT	82.6	4.05	1.6	30.6	24.4
DE	14.4	0.75	.1	2.8	4.0
DC	42.4	1.49	.1	8.3	2.7
FL	198.8	11.61	2.2	56.1	12.7
GA	116.0	6.32	.9	69.9	14.2
HI	26.2	1.11	.3	-	-
ID	13.5	0.79	3.0	7.6	2.1
IL	286.8	13.60	1.7	108.4	74.9
IN	118.2	6.56	.3	26.2	16.6
IA	53.4	3.03	.1	50.3	11.0
KS	47.0	2.51	.3	65.1	7.8
KY	65.8	4.04	2.6	31.4	15.4
LA	66.4	3.91	3.9	98.4	13.1
ME	17.0	1.05	.1	7.8	4.5
MD	133.3	5.71	.3	28.8	31.0
MA	151.3	7.48	3.3	29.5	31.3
MI	206.6	10.89	1.7	129.0	43.3
MN	91.8	4.80	.0	22.3	13.1
MS	33.0	2.36	.8	34.1	6.4
MO	101.2	5.40	28.2	143.4	24.5
MT	12.3	0.68	2.2	10.0	2.2
NE	31.2	1.67	.3	55.8	6.0
NV	17.7	0.84	7.1	12.9	2.2
NH	18.1	0.97	.4	3.5	3.6
NJ	199.2	9.53	6.5	38.8	25.8
NM	20.2	1.15	2.3	10.9	1.8
NY	511.3	22.55	36.1	100.2	66.2
NC	103.0	6.53	.2	62.7	25.6
ND	8.9	0.57	.0	5.0	2.1
OH	242.5	12.82	2.0	57.9	48.4
OK	55.8	3.08	1.2	54.5	5.2
OR	45.1	2.49	3.2	38.0	9.6
PA	252.0	13.49	.7	56.2	53.2
RI	20.4	1.14	.1	4.0	1.3
SC	48.0	3.20	3.8	17.6	7.8
SD	10.4	0.65	.1	7.5	2.6
TN	80.0	5.04	33.6	26.4	5.2
TX	261.0	14.37	1.4	454.9	28.5
UT	27.2	1.39	27.3	18.5	8.1
VT	8.6	0.51	.0	1.9	1.2
VA	133.0	6.46	.8	36.7	25.3
WA	78.5	3.99	187.7	17.0	23.1
WV	29.5	1.73	.1	11.0	10.1
WI	89.5	5.10	.0	23.8	22.8
WY	6.4	0.33	.1	5.5	1.4
US	4925.2	256.10	1177.0	2734.3	871.28

Table 1. Structure Values Exposed, Population and Annualized Losses by State in 1970$

*These values were computed from Map #2 [see text]. Map #1 gives values of $213.6 million and $502.7 million 1970$ for 1970 and 2000, respectively.

SECTION I

EARTHQUAKE SHAKING

Chapter One

Description of the Hazard

Earthquakes occur in most localities throughout the United States but with different frequencies of occurrence and different upper bound earthquake magnitudes. For example, the 100 year return event in California is an earthquake of magnitude 8.0 or greater. In the Northeast area, the magnitude of the 100-year event is about 5.5 or greater. The difference in energies released between these two events is about 5600 times. That is to say the magnitude 8.0 event is 5600 times larger in terms of energy release than the magnitude 5.5 event. Similarly, the largest credible earthquake possible in California has a magnitude of about 8.5. In the Northeast, the maximum credible earthquake has a magnitude of about 7.1 or about 125 times less than potential energy release in California.

Structural failure or damage from earthquake action can result from any one or combination of ten failure mechanisms. These are listed below in Table 1-1 [Culver, et al, 1975].

Ground Shaking	1. Structural Failure 2. Foundation Settlement 3. Foundation Failure
Gound Breaking	4. Liquefaction 5. Lurching 6. Slope Failure 7. Faulting
Flooding	8. Dam Failure 9. Flooding from Tsunami 10. Flooding from Seiche

Table 1-1. Structural Failure Mechanisms

Only the structural shaking mechanism of failure is considered in our study because: (1) it is estimated to create the greatest amount of damage, (2) the other modes of failure can only be modeled on a microzonation basis, and (3) tsunami is treated in another report of this technology assessment series.

One might ask whether or not earthquakes have been known to cause damage and life loss in places other than California which is commonly thought to be "earthquake country". As Tables 1-2 and 1-3 indicate, there are seven states which have suffered known dead and nine states that have incurred significant damage losses.

Year	Locality	Lives lost
1811	New Madrid, Mo.	Several
1812	New Madrid, Mo.	Several
1812	San Juan Capistrano, Calif.	40
1868	Hayward, Calif.	30
1872	Owens Valley, Calif.	27
1886	Charleston, S.C.	60
1899	San Jacinto, Calif.	6
1906	San Francisco, Calif.	700
1915	Imperial Valley, Calif.	6
1918	Puerto Rico (tsunami from earthquake in Mona Passage)	116
1925	Santa Barbara Calif.	13
1926	Santa Barbara, Calif.	1
1932	Humboldt County, Calif.	1
1933	Long Beach, Calif.	115
1934	Kosmo, Utah	2
1935	Helena, Mont.	4
1940	Imperial Valley, Calif.	9
1946	Hawaii (tsunami from earthquake in Aleutians)	173
1949	Puget Sound, Wash.	8
1952	Kern County, Calif.	14
1954	Eureka-Arcata, Calif.	1
1955	Oakland, Calif.	1
1958	Khantaak Island and Lituya Bay, Alaska	5
1959	Hebgen Lake, Mont.	28
1960	Hilo, Hawaii (tsunami from earthquake off Chile coast)	61
1964	Prince William Sound, Alaska (tsunami)	131
1965	Puget Sound, Wash.	7
1971	San Fernando, Calif.	65

Table 1-2. Lives Lost in Major U.S. Earthquakes, 1811-1971 [Eppley, 1966]

Year	Locality	Damage
1865	San Francisco, Calif.	0.5
1868	San Francisco, Calif.	.4
1872	Owens Valley, Calif.	.3
1886	Charleston, S.C.	23.0
1892	Vacaville, Calif.	.2
1898	Mare Island, Calif.	1.4
1906	San Francisco, Calif.	24.0
	Fire loss	500.0
1915	Imperial Valley, Calif.	.9
1918	Puerto Rico (tsunami damage from earthquake in Mona Passage)	4.0
1918	San Jacinto and Hemet, Calif.	.2
1925	Santa Barbara, Calif.	8.0
1933	Long Beach, Calif.	40.0
1935	Helena, Mont.	4.0
1940	Imperial Valley, Calif.	6.0
1941	Santa Barbara, Calif.	.1
1941	Torrance-Gardena, Calif.	1.0
1944	Cornwall, Canada-Massena, N.Y.	2.0
1946	Hawaii (tsunami damage from earthquake in Aleutians)	25.0
1949	Puget Sound, Wash.	25.0
1949	Terminal Island, Calif. (oil wells only)	9.0
1951	Terminal Island, Calif. (oil wells only)	3.0
1952	Kern County, Calif.	60.0
1954	Eureka-Arcata, Calif.	2.1
1954	Wilkes-Barre, Pa.	1.0
1955	Terminal Island, Calif. (oil wells only)	3.0
1955	Oakland-Walnut Creek, Calif.	1.0
1957	Hawaii (tsunami damage from eathquake in Aleutians)	3.0
1957	San Francisco, Calif.	1.0
1959	Hebgen Lake, Mont. (damage to timber and roads)	11.0
1960	Hawaii and U.S. west coast (tsunami damage from earthquake off Chile)	25.5
1961	Terminal Island, Calif. (oil wells only)	4.5
1964	Alaska and U.S. west coast (tsunami damage from earthquake near Anchorage—includes earthquake damage in Alaska).	500.0
1965	Puget Sound, Wash.	12.5
1966	Dulce, N. Mex.	.2
1969	Santa Rosa, Calif.	6.3
1971	San Fernando, Calif.	553.0
	Total	1,862.1

Table 1-3. Property Damage in Major U.S. Earthquakes, 1865 - 1971 (in millions of dollars (actual)) [Eppley, 1966]

These tables do not tell the story about future losses since the assets and dollar values have changed and the population density has increased so dramatically over the years. Nevertheless, they indicate the problem historically, and the data will be used to project damages into the future.

Chapter Two

Modeling the Hazard, Vulnerability, and Resulting Risk

Development of Intensity Probability

The number of earthquakes of Richter magnitude M or greater, ΣN, affecting a region has been given by Culver, et al, [1975]

$$\log_{10} \Sigma N = A - 0.9M \qquad (1)$$

A is the regional seismicity about a geographical region 1/2° longitude by 1/2° latitude in size. The constant, 0.9, is an empirically determined constant assumed to be valid for the United States. Equation (1) describes the number of earthquakes greater than or equal to magnitude M. The number equal to a specific value of M is required in order to compute damage rates. The relation between ΣN and N is

$$\Sigma N = \sum_{M}^{\infty} N(M)dM \qquad (2)$$

From Equations (1) and (2), N is computed to be

$$\log_{10} N = [A + \log_{10}(2.303x.9)] - .9M \qquad (3)$$

Since damages will be computed in terms of Modified Mercalli Intensity, Equation (3) must be converted into terms of Intensity (I). The frequency of occurrence for intensity at a particular locale may be converted to

$$\log_{10} N = a - .6I \qquad (4)$$

Using Equations (1) through (4), a is defined as the intensity constant reflecting A, the seismicity constant. The value of 0.9 used as a coefficient for M is replaced by the value 0.6 using Richter's conversion equation $M = 1 + \frac{2}{3} I_0$, where I_0 is the maximum epicentral intensity.

Vulnerability Model

The amount of structural damage caused by earthquakes each year can be computed by integrating structural damage algorithms for various types of structures with the exposure and the earthquake intensities expected at a particular geographical locale. The Modified Mercalli Intensity scale (MMI) is the best available for describing intensity, since it represents the local effects of earthquakes, is well understood, and is most closely related to damage.

The lower limit of the intensity scale which may produce monetary loss was selected to be MMI=6. Damage at levels below an MMI=6 is slight and diffucult to define. The upper limit of the intensity scale was chosen as MMI=12. At this severe intensity level, damage is defined to be total.

Since force increases exponentially with intensity, it is reasonable to expect that damage will also increase exponentially with intensity. In all of the investigations referenced in this study, this assumption has been borne out. The damage algorithm therefore takes the general form,

$$\log_{10}D = c + dI \tag{5}$$

where D is the amount of damage done to a structure as a percentage of market value, I is the Modified Mercalli intensity, and c and d are constants to be determined for different intensity ranges using the results of various studies. The only approach used to develop values of c and d was to empirically use damage statistics from all available sources in order to be as objective as possible.

Damage algorithms were derived for two types of construction: (1) single family residential structures and, (2) industrial-commercial construction. These damage algorithms are given for four different relative strengths of construction or Q-factors (Quality). Using the estimates of Moran, Blume, and Wiggins [Whitman, et al, 1973], construction in California built prior to 1933 is assigned Q=1, and construction built in California after 1933 is assigned Q=3. Using these estimates as starting points it was possible to assign quality factors to the available earthquake damage data.

Industrial-Commercial Damage Algorithms

In the derivation of the industrial-commercial damage algorithms, linear regression analyses were performed for quality factors of 1 and 3. The curves for Q=2 and Q=4 were determined by assuming a linear interpolation and extrapolation between the Q=1 and Q=3 curves. The damage data were drawn from the following sources:

(1) C. Pinkham and S. B. Barnes' estimates of the damage occurring to concrete and steel structures having relative Q values of 1 and 3 [1972]. An averaged summary of their estimates is given below:

% Damage	MMI=6	7	8	9
Q=1	0.057	3.4	12.0	33.0
Q=3	0.045	2.0	5.8	11.8

(2) A survey by MIT of damage done to high-rise buildings in the Los Angeles area following the February 1971 San Fernando Valley earthquake [Whitman, et al, 1973]. The data were broken down into construction prior to 1933 and after 1933.

% Damage	MMI=6	7	8
Q=1	0.06	5.86	-
Q=3	0.08	.66	4.24

(3) J. H. Wiggins' regression equation of damage data and estimates made by Donald F. Moran and Roy Johnston [Culver, C. G., et al, 1975]. His equation is given in terms of Q-factor.

% Damage	MMI=6	7	8	9	10	11
Q=1	0.625	3.4	18.5	-	-	-
Q=3	-	-	-	2.23	7.94	28.3

(4) An analysis of data on damage to post-1960 highrise construction drawn from the Pacific Fire Rating Bureau's report on the San Fernando earthquake [Steinbrugge, et al, 1971]. The intensities were computed using hypocentral distance of the damaged structures surveyed and formulas given later in this chapter.

% Damage	MMI=6	7	8
Q=3	0.04	0.33	2.71

The damage curves derived from the above, equally weighted data are shown in Figure 1-1 and the regression coefficients in Equation (5) are given for these curves in Table 1-4.

Q	Modified Mercalli Intensity Range	c	d	
1	6.0 - 7.0	-10.06	1.53	
	7.0 - 9.9	-2.70	0.474	
	9.9 - 12.0	2.0	0.0	
2	6.0 - 7.5	-8.31	1.18	interpolated values
	7.5 11.2	-2.36	0.388	
	11.2 12.0	2.0	0.0	
3	6.0 - 7.6	-6.99	0.962	
	7.6 - 12.0	-2.16	0.332	
4	6.0 - 7.9	-6.34	0.836	extrapolated values
	7.9 - 12.0	-2.03	0.292	

Table 1-4. Damage Coefficients for Industrial-Commercial Structures

Damage Algorithms for Dwellings

Damage curves for residential construction were drawn from California earthquake data. However, since no differentiation of damages for different ages of construction was made, it was necessary to develop one damage curve for the average age of the data base in question. Using this procedure the average Q-factor for the data base was found to be 2.65. The variation between the relative

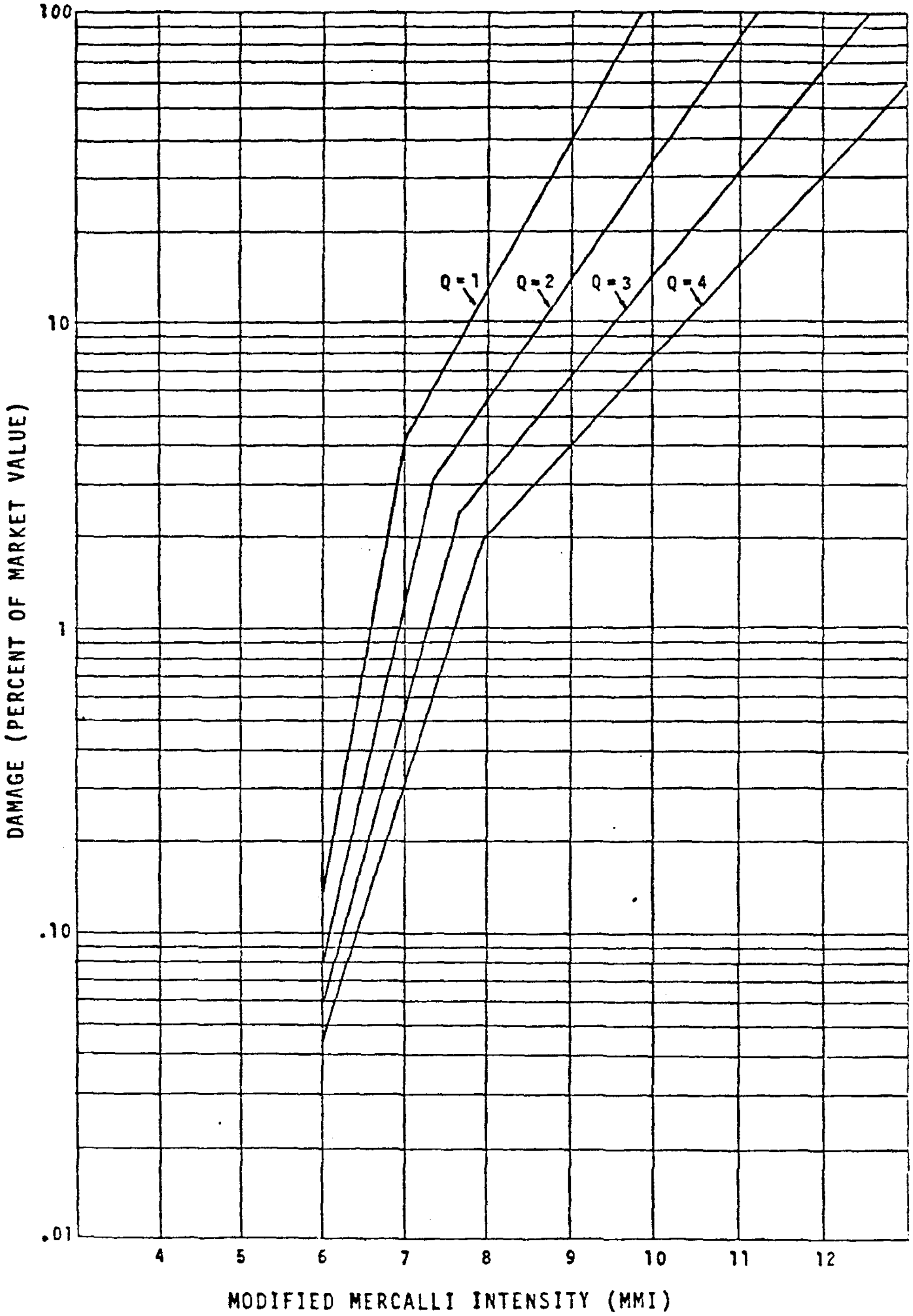


Figure 1-1. Quality of Construction for California and the Rest of the Nation by Date of Construction

damage to intensity for different Q-factors was computed by assuming that Q-factor is proportional to the maximum particle velocity the structure can withstand (i.e., a structure with Q=2 can withstand twice the velocity of shaking of a structure with Q=1 at the same damage level). Data for the regression fit were drawn from the following sources:

(1) Don G. Friedman's [1970] estimate of damage to dwellings if an earthquake were to strike San Francisco in 1960. Twenty six point two (26.2) percent of the residential structures were built prior to 1933 for the damage data base used by Friedman: San Francisco (1957), Kern County (1952), and Long Beach (1933) earthquakes.

% Damage	MMI=6	7	8	9
Dwelling	0.2	0.9	3.8	8.7

(2) Damage estimates for framed dwellings by the Environmental Science Services Administration [1969]. These estimates were obtained from the opinions of several earthquake engineering experts on the amount of damage accruing to each of several construction components. The estimates assumed an earthquake striking the Berkeley area at which time 35.4 percent of the residences were of pre-1933 construction.

% Damage	MMI=6	7	8	9
Dwelling	0.385	1.77	6.74	9.52

(3) An analysis of data on dwelling damage due to the San Fernando earthquake, drawn from the Pacific Fire Rating Bureau report [Steinbrugge, et al, 1971]. The report included maps of the strongly affected portions of the San Fernando Valley which portrayed the percentage loss to wood frame dwellings and also to taxable improvements. These maps were compared to an intensity map of the area compiled by Duke and mapped by Wiggins [1973]. Nine percent of the data base contained pre-1933 construction.

% Damage	MMI=7	8	9
Dwelling	0.5	6.3	18

(4) An analysis of data from the HUD-NOAA report on the San Fernando earthquake [McClure, 1973]. This report gave detailed damage statistics for several affected areas and was combined with intensities computed using known hypocentral distance. All the dwellings surveyed were built after 1950.

% Damage	MMI=8	9	10
Dwelling	14.4	21	30.5

The damage curves derived are given in Figure 1-2 and the results for the coefficients of Equation (5) are tabulated in Table 1-5.

Q	Modified Mercalli Intensity Range	c	d	
1	6.0 - 7.4	-6.01	0.943	
	7.4 - 10.6	-1.48	0.329	
	10.6 - 12.0	2.00	0.0	
2	6.0 - 7.8	-5.32	0.793	
	7.8 - 11.3	-1.55	0.313	
	11.3 - 12.0	2.00	0.0	
3	6.0 - 8.3	-4.84	0.688	
	8.3 - 12.0	-1.63	0.300	
4	6.0 - 8.7	-4.52	0.612	extrapolated values
	8.7 - 12.0	-1.71	0.289	

Table 1-5. Damage Coefficients for Dwellings

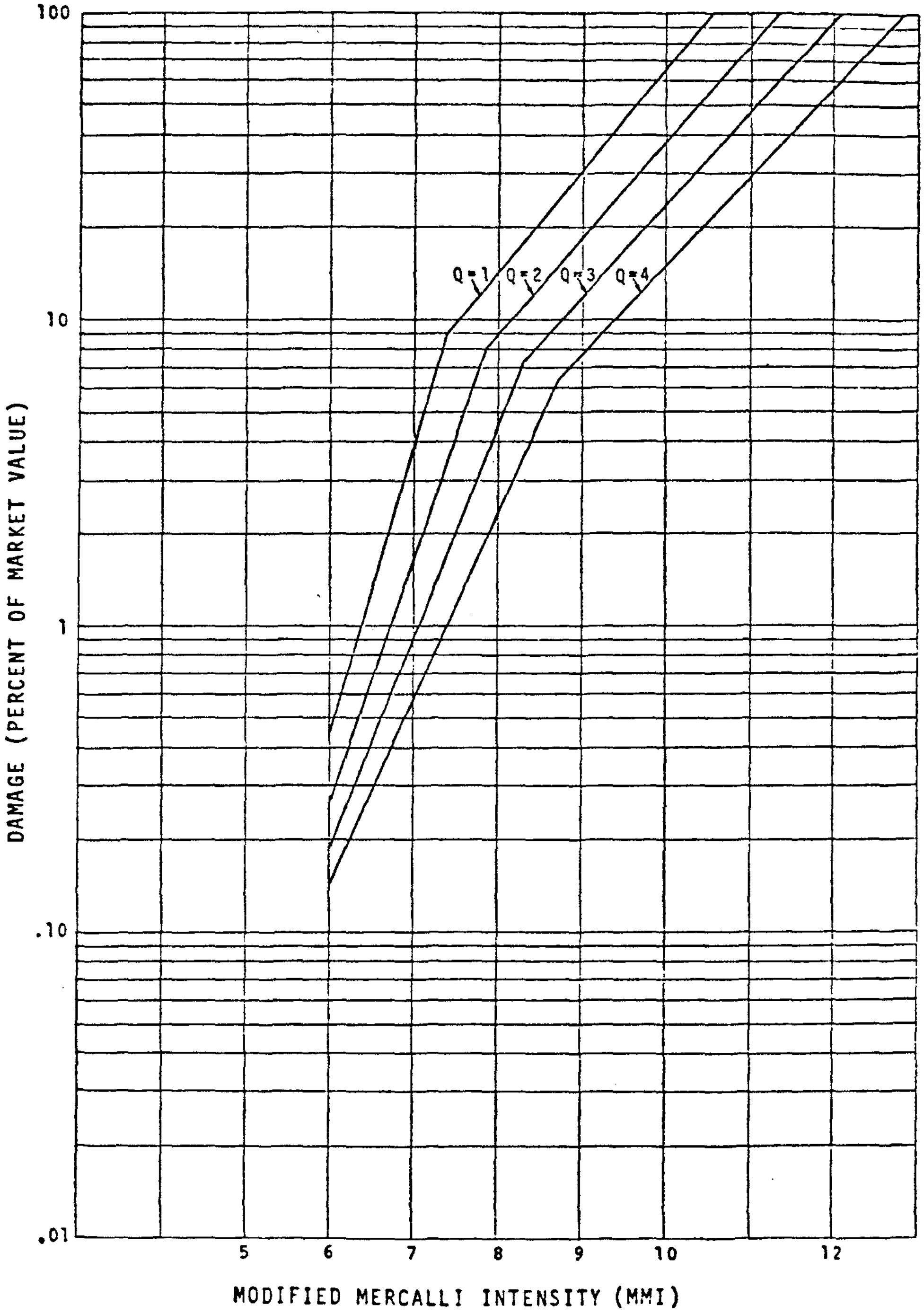


Figure 1-2. Damage Algorithms for Dwellings

Regional Structural Characteristics

Building code specifications in California changed in a number of locations after the 1933 Long Beach earthquake so that the capacity to withstand lateral forces was increased. Using the average relative change after 1933 from estimates by Donald F. Moran, John A. Blume and John H. Wiggins [Whitman, 1973], average descriptors (1 and 3) indicating the quality of construction of pre-1933 and post-1933 structures in California [See Figure 1-3] were used to characterize structure qualities. Calling this descriptor, Q, age distributions for structures built prior to 1933 were estimated in California and prior to 1940 in the remainder of the United States. The derivation of these age distributions are described by Hirschberg, Gordon, and Petak [1978].

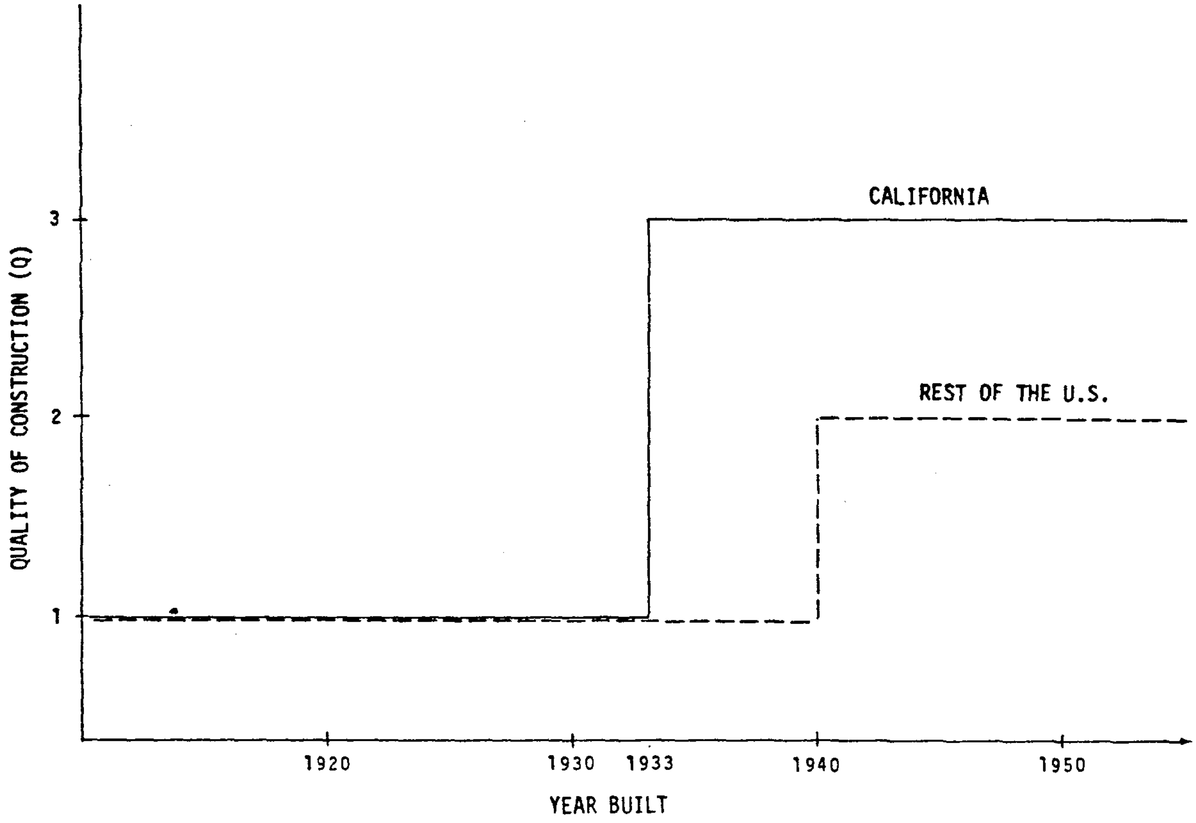


Figure 1-3. Quality of Construction for California and the Rest of the Nation by Date of Construction

Risk Model - Computations of Expected Losses

Having derived the hazard, exposure and the vulnerability of the exposure as a function of geographic location and intensity, it is necessary to determine how different intensities affect a particular region of the country. By combining knowledge of the intensity expectancy with the damage algorithms for the exposure, the determination of a region's Loss Rate can be computed. The Loss Rate (LR) is defined as the average annual percent loss expected to occur to structures.

A functional relationship exists between damage per earthquake and Modified Mercalli Intensity, D(I). Likewise, a relationship exists between the number of earthquake events of a specific intensity to be expected each year and Modified Mercalli Intensity, N(I). The number of earthquakes occurring within an intensity range, ΔI, about some specific intensity, I_i, may thus be given as $N(I_i)\Delta I$ for a specific geographical region. The loss occurring in this intensity range is described as $D(I_i)N(I_i)\Delta I$, Expressing this as a sum,

$$LR = \sum_{I=6}^{I_{max}} D(I)N(I)\Delta I \tag{6}$$

Since the functions are readily integrable this may be written as,

$$LR = \int_{I_1=6}^{I_2 = I_{max}} D(I)N(I)dI \tag{7}$$

Recalling that the expressions for damage and frequency of occurrence are given as,

$$D(I) = 10^{(c + dI)} \tag{8}$$

$$N(I) = 10^{(a + bI)} \tag{9}$$

where b = 0.6 and c and d have been defined, the Loss Rate is derived by computing a and I_{max}.

From Culver et. al. [1975], the following empirical equations were derived which related Modified Mercalli Intensity, I, with surficial particle velocity, V_s; surficial particle velocity with site dynamic amplification factor (DAF) and surficial particle velocity (hard rock), V_r. V_r is a function of hypocentral distance, r, from site to the source of an earthquake of magnitude, M.

$$\log_{10} V_s = -1.973 + 0.375 I \tag{10}$$

The surface velocity can be found from the bedrock velocity by knowing the soil dynamic amplification factor, (DAF)

$$V_s = (DAF) V_r \tag{11}$$

Empirical data indicate that the attenuation equations for V_r in terms of magnitude and hypocentral distance, r, are different on either side of the Rocky Mountains. Thus:

<u>Western United States</u> (longitude ≥ 104°)

$$\log_{10} V_r = -1.625 + 0.563M - 1.403 \log_{10} r \tag{12}$$

<u>Eastern United States</u> (longitude < 104°)

$$\log_{10} V_r = 2.062 + 0.563M - 0.979 \log_{10} r \tag{13}$$

Substituting (13) or (12) into (11) and (11) into (10) and (10) and (1) into (4) yields the following equations. Note that maximum credible magnitude is assumed to be 8.5 in this example and N for the maximum credible event is assumed to be 400 years [Culver, et. al., 1975]. Maximum credible magnitudes varied from 7.1 to 8.5 going from the eastern part of the United States to the western part.

Western United States

$$a = A + 0.56 - 2.243 \log_{10}\bar{r} + 1.598 \log_{10}(DAF) \tag{14}$$

$$I_{max} = 13.7 + 2.67 \log_{10} DAF - 3.74 \log_{10}\bar{r} \tag{15}$$

Eastern United States

$$a = A + 0.139 - 1.565 \log_{10}\bar{r} + 1.598 \log_{10}(DAF) \tag{16}$$

$$I_{max} = 12.5 + 2.67 \log_{10} DAF - 2.61 \log_{10}\bar{r} \tag{17}$$

Note that A is defined as the effective seismicity of a generalized region (in this instance a 1/2° longitude by 1/2° latitude area) while $\bar{r}$ is the effective hypocentral distance of the seismicity for that region [Culver et. al. 1975].

$$\begin{aligned} LR &= \int_6^{I\ max} 10^{(c + dI)} \times 10^{(a - bI)} dI \\ &= \frac{10^{(a + c)}}{2.303\ (d-b)} \left[10^{(d-b)I_{max}} - 10^{(d-b)6}\right] \end{aligned} \tag{18}$$

Derivation of Seismic Intensity Maps

The seismic data used in the computation of the national damage statistics were drawn from Culver et. al. [1975]. That report gave seismic data for Alaska, Hawaii, and the contiguous United States on a 1/2° longitude by 1/2° latitude grid basis. Both the seismicity, A, and effective radius, $\bar{r}$, were computed using two separate data bases. One consisted of all historically recorded earthquakes known to have affected the United States prior to 1961 [Eppley, 1966]. The other data base was supplied by the National Oceanic and Atmospheric Administration (1961 - Present). It consists of all earthquakes having a Richter magnitude of 3.5 or greater through the years 1961 - 1973.

The quantities, a and I_{max}, were computed for each data base and then compared, choosing the combination of A and $\bar{r}$ that gave the maximum basement rock velocity for each grid. The soil amplification data were obtained from the geologic description of the soil using Wiggins' formulas [1961, Barosh, 1964, 1979],

$$(DAF) = \left[\frac{V_o \rho_o}{V_{SH} \rho_s}\right]^{1/2} \tag{19}$$

$$V_{SH} = 41.8\ (ZT)^{1/6} \tag{20}$$

where:

$(DAF) = V_s/V_r$, site dynamic amplification factor,
ρ_s = average density of site soil (124 lb/ft^3),
ρ_o = density of basement rock (158 lb/ft^3)
V_{SH} = average shear wave velocity of site soil (ft/sec),
V_o = shear wave velocity of basement rock (8000 ft/sec),
Z = depth of deposit (10 ft), and
T = age of deposit (years).

The geologic data were taken from a geology map compiled by Kinney [1966]. The surface geology was observed on a 1/2° longitude by 1/2° latitude grid basis and combined with the seismic data to give a and I_{max} for the entire United States. These data were used to construct the United States ground surface velocity contour maps shown in Figures 1-4 through 1-6. The maps represent the acceleration of ground shaking (g) which would have a recurrence interval of 475 years.

Expected Life Loss Estimates

The method for computing life loss due to earthquakes was based on the number of lives lost in past events in relation to the dollar losses for these events. This analysis is described in detail in Hirschberg, Gordon, and Petak [1978]. The resulting formula used for these estimates was:

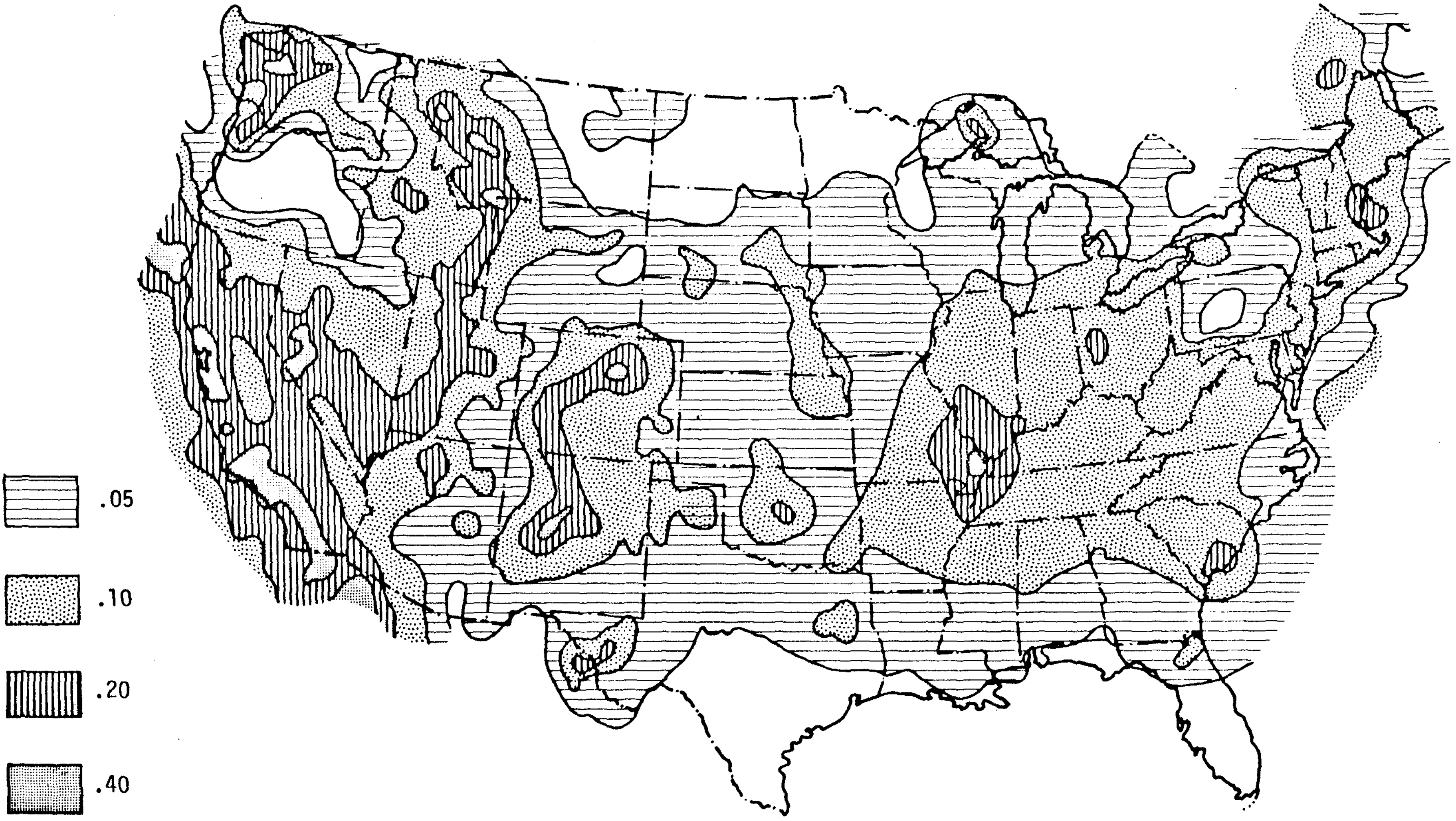


Figure 1-4. Acceleration for "Normal" Soil in 'g's, Contiguous United States of America

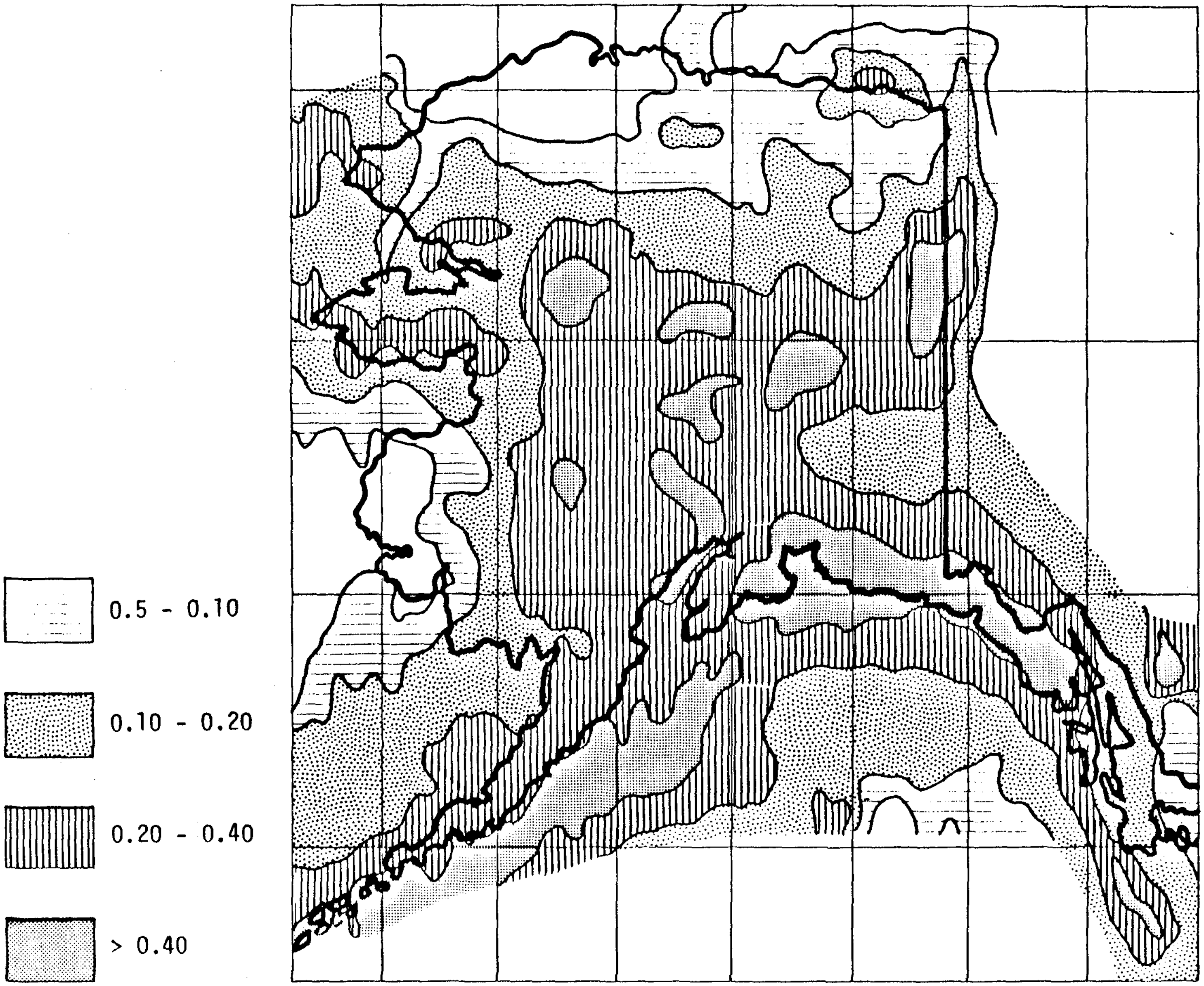


Figure 1-5. Acceleration for "Normal" Soil in 'g's, Alaska

Figure 1-6. Acceleration for "Normal" Soil in 'g's, Hawaiian Islands

$$\text{Life Loss} = 712.88 \begin{pmatrix}\text{building loss}\\ \text{in billions of}\\ \text{1970\$}\end{pmatrix}^{.813} \begin{pmatrix}\text{year of}\\ \text{occurrence}\\ \text{-1900}\end{pmatrix}^{-.288} \qquad (21)$$

Relation of Injuries and Life Loss

The number of injuries and their extent was computed from data available for recent U. S. earthquakes [Table 1-17] giving an average ratio of:

$$(43.0) \cdot LL = \text{all injured} \qquad (22)$$

$$(2.8) \cdot LL = \text{seriously injured} \qquad (23)$$

Neither of these is a very good estimate primarily due to small amount of data and the rather loose definition of "serious" and "injury." In the NOAA Report [1972] the ratios were 4 serious injuries and 30 non-serious injuries to one death.

	LIFE LOSS /100,000	SERIOUS INJURY /100,000	ALL INJURY /100,000
1933 Long Beach	26	NA	1,300
1940 Imp. Valley	18	40	NA
1964 Alaska	9	NA	315
1971 San Fernando	64	180	2,805
ALL INJURY/LIFE LOSS			
1933 Long Beach	50		
1964 Alaska	34		
1971 San Fernando	44		
AVERAGE	43 s		
	43 ± 24.0 (95% confidence)		
SERIOUS INJURY/ LIFE LOSS			
1940 Imp. Valley	2.7		
1971 San Fernando	2.8		
AVERAGE	2.8 s		
	2.8 ± 0.263 (95% confidence)		

Table 1-6. Injury and Life Loss Ratios [NOAA, 1972]

Computation of Isoseismals from the 1906 San Francisco and 1811 - 1812 New Madrid Earthquake

In order to derive some perspective of the earthquake sudden loss problem, we chose two earthquakes for use in damage scenarios. They are the famous 1906 San Francisco and 1811 - 1812 New Madrid earthquakes. These events were first modeled and their intensities mapped. The magnitude of the San Francisco earthquake was taken as M = 8.25 [Eppley, 1966] and the New Madrid as M = 7.5 [Nuttli, 1973]. The energy of the earthquakes was then dispersed along the length of the fault rupture. The fault lines were drawn from a tectonic map of the country [National Atlas, 1966]. The length of fault rupture was related to earthquake magnitude through a regression equation of Bonilla's data [Wiegel, 1970].

$$\log_{10} L = 0.66\,M - 3.1 \qquad (24)$$

where L = fault rupture length (miles)

The energy from the large earthquakes was distributed along the faults by breaking them up into smaller earthquakes every twenty miles along the rupture. The size of the smaller earthquakes was determined using Richter's energy-magnitude relation [Allen et. al., 1965], $\log E = 11.8 + 1.5M$, and was found to be

$$M_i = M_o - \frac{2}{3}\log_{10} N \qquad (25)$$

where M_o = magnitude of the original earthquake,

M_i = magnitude of distributed earthquakes, and

N = number of distributed earthquakes.

The local intensity of these distributed epicenters was found by adding the intensities from each M_i by the root sum square technique and using the hypocentral distance to each M_i. An earthquake depth of 10 miles was assumed for both earthquakes. The hard rock velocity, V_{r_i}, due to each M_i was computed using either equation (12) or (13).

The site intensity was then found using equations (10) and (11). The soil data for the New Madrid sequence were averaged for each 1/2° longitude by 1/2° latitude grid, since the soil conditions do not vary drastically in the Mississippi Valley.

Soil data for the San Francisco Scenario were reduced to a 1/8° longitude by 1/8° latitude grid size in order to give finer detail. Maps of the computed intensity distributions are shown in Figures 1-7 and 1-8. The actual isoseismals (Figures 1-9 and 1-10) may be compared with those derived theoretically.

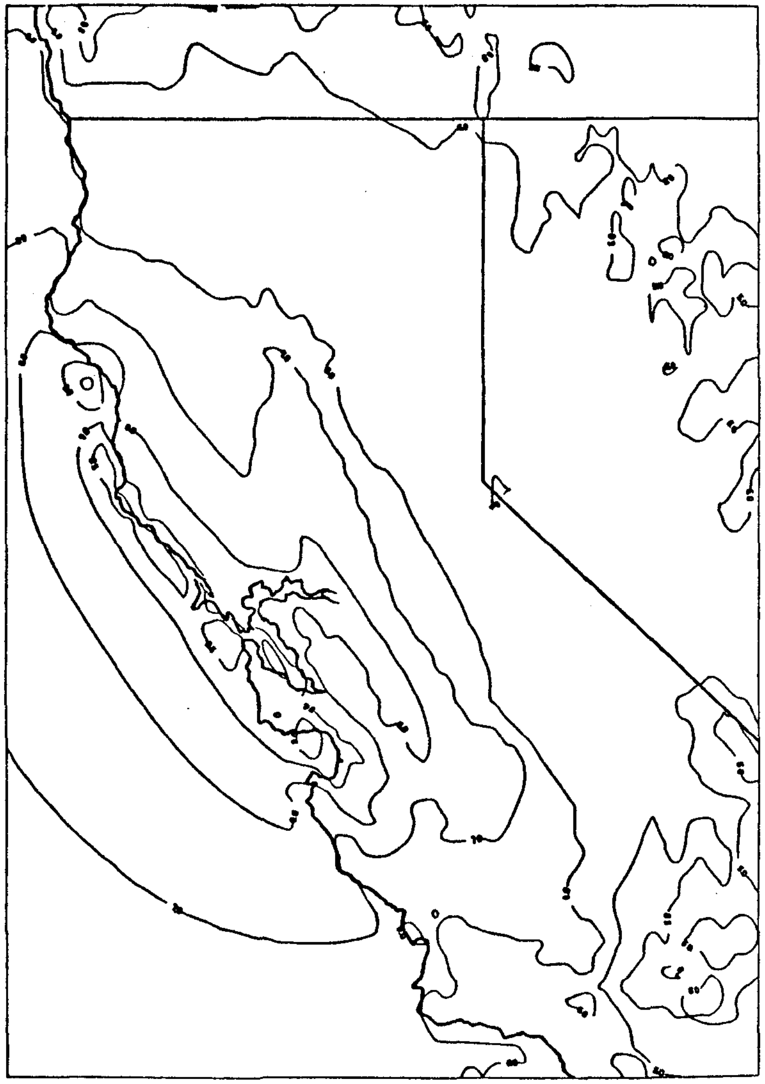


Figure 1-7. San Francisco Scenario, Intensities Due to an M = 8.5 Shock

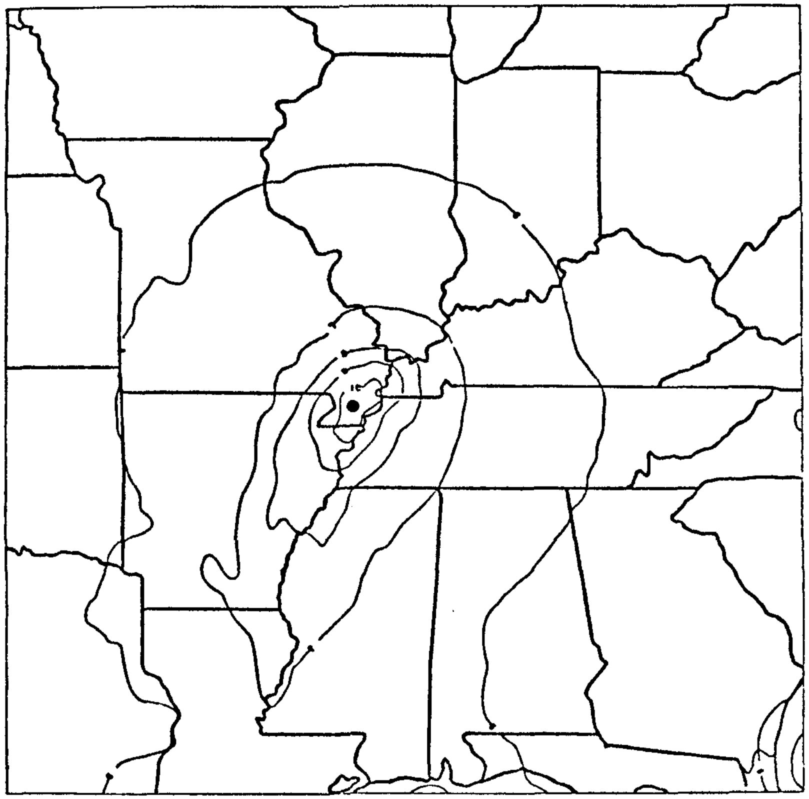


Figure 1-8. The Theoretically Computed New Madrid Earthquake of 1811 - 1812

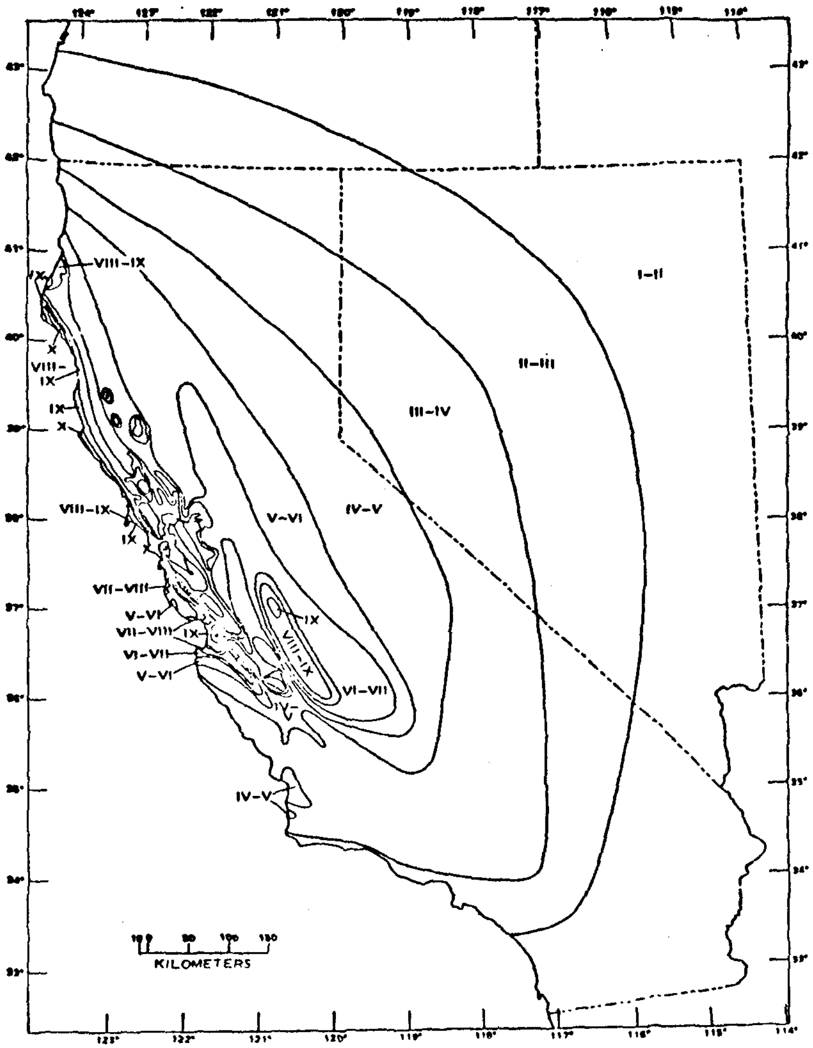


Figure 1-9. The Rossi-Forel Scale Intensity Map of the 1906 San Francisco Earthquake, Redrawn from Essa [1969]

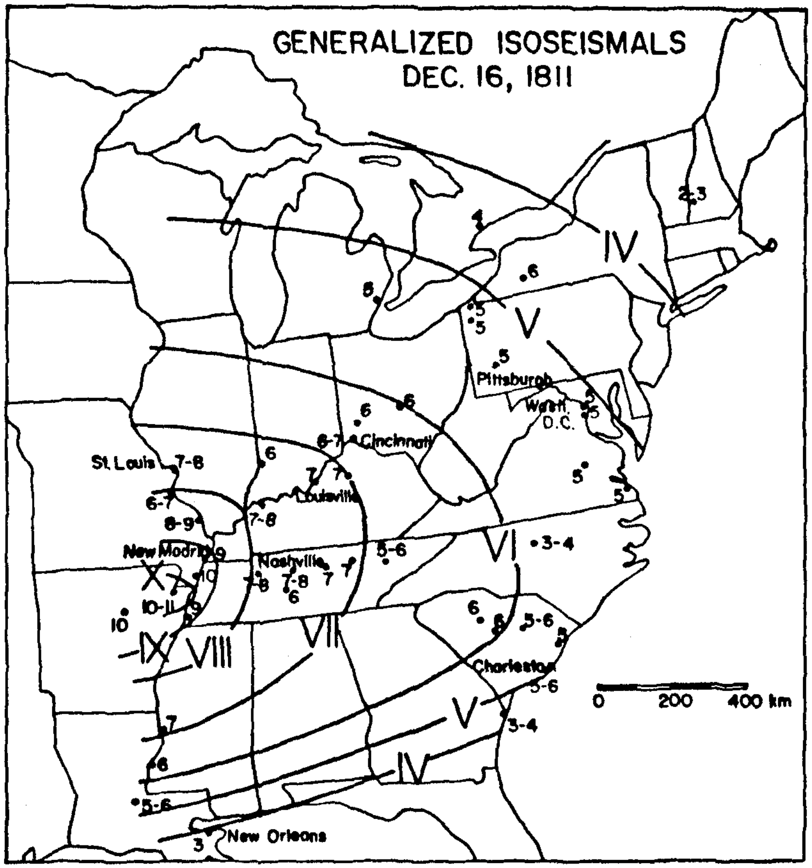


Figure 1-10. The Generalized Isoseismals of the New Madrid Earthquake of December 16, 1811 [Nuttli, 1973]

Chapter Three

Average Annual Earthquake Losses

Annual and Sudden Loss Estimates

Using equation (18) along with the amount, type, and age of construction, losses were computed for each county and added to determine state losses. These totals are listed in Tables 1-7 to 1-10 along with the value of construction exposed to damaging* earthquakes in each state. Tables 1-11 to 1-14 present the regional totals and Tables 1-15 and 1-16 give the regional and national totals with one standard deviation added to the seismicity.

The scenarios chosen for study were the 1906 San Francisco and the 1811 New Madrid, Missouri events. The estimated historic magnitudes were used to derive the damages in the same manner as was done for the national totals. The scenario results are presented in Table 1-17.

Some interesting observations can be derived from the results of these studies.

(1) Even though the loss percentage decreases every year as new, better construction comes on line and the older construction phases out, the annual loss in constant dollars increases because of the increasing amount of dollar exposure.

(2) The San Francisco earthquake was almost the same size as the New Madrid series of shocks, but it would produce more losses because more property is exposed in the epicentral region than that in the New Madrid region.

(3) A greater area is affected by the New Madrid Scenario than the San Francisco event. Losses for New Madrid would be:

	%
Alabama	0.281
Arkansas	5.220
Florida	0.039
Georgia	0.003

---

*areas with damaging earthquake potential were those areas with I_{max} greater than 6.00.

Preceding page blank

Kentucky	0.722
Louisiana	0.608
Mississippi	1.820
Oklahoma	0.003
Tennessee	4.710
Texas	0.028
Illinois	0.255
Indiana	0.096
Missouri	2.200

Losses for the San Francisco event would be:

California	5.210
Nevada	0.003

(4) If the New Madrid event were shifted to the north to include St. Louis in the higher intensity zones, a greater amount of damage could be expected both in the St. Louis and Chicago areas (Figure 1-11).

(5) On an annual loss basis the western region of the country is expected to suffer about 88 percent of the damage even though it contains only 18 percent of the buildings in the country.

(6) The New Madrid scenario results could be quite low, since the computer plots appear to be about 1 MMI lower than the observed plots.

KEY TO TABLES 1-7 TO 1-10

total at risk = the value-in-place of all buildings located in counties with a non-zero* probability of damaging earthquakes in millions of 1970 base year dollars.

total damage = The annual loss in terms of value-in-place in the year of the table in millions of 1970 base year dollars.

total percent damage = the annual damage divided by the value-at-risk x 100

total population = the population in each county with a non-zero probability of a damaging earthquake occurrence.

lives lost = the estimated number of lives lost derived from the dollar losses to buildings.

death rate = the estimated number of lives lost divided by the total population x 100.

percent of damage by type = percentage of total estimated annual damage in each category listed below .

Ratio of Replacement to Repair

NO = none 0.00% - 0.50%

LI = light 0.58% - 1.25%

MOD = moderate 1.25% - 7.50%

HEA = heavy 7.50% - 65.00%

SEV = severe 65.00% - 99.99%

COL = collapse 99.99% -100.00%

*There are some counties that are not expected to experience any damage.

STATE	TOTAL AT RISK	TOTAL DAMAGE	TOTAL PERCENT DAMAGE	TOTAL POPULATION	LIVES LOST	DEATH RATE	PERCENT OF DAMAGE BY TYPE					
							NO	LI	MOD	HEA	SEV	COL
AL	5155.53	.0227	.441E-03	719282.	0.	.536E-05	0.	55.	45.	0.	0.	0.
AZ	16857.38	.7435	.441E-02	1772658.	1.	.390E-04	0.	25.	50.	26.	0.	0.
AR	4184.27	3.2508	.777E-01	655667.	3.	.433E-03	0.	25.	50.	24.	0.	0.
CA	227787.29	439.6156	.193	19935761.	154.	.774E-03	0.	30.	30.	40.	0.	0.
CO	22478.10	20.2387	.900E-01	2182386.	10.	.479E-03	0.	15.	36.	49.	1.	0.
CT	34984.08	.7674	.219E-02	3032217.	1.	.214E-04	0.	54.	46.	0.	0.	0.
DE	5721.53	.0694	.121E-02	548104.	0.	.178E-04	0.	67.	33.	0.	0.	0.
DC	12617.67	.0573	.454E-03	756510.	0.	.920E-05	0.	93.	7.	0.	0.	0.
FL	48006.71	.9489	.198E-02	5193583.	1.	.160E-04	0.	28.	52.	20.	0.	0.
GA	14625.85	.4528	.310E-02	1925636.	1.	.285E-04	0.	32.	49.	19.	0.	0.
ID	5792.37	1.5354	.265E-01	657563.	1.	.212E-03	0.	17.	40.	43.	0.	0.
IL	30920.55	.9548	.309E-02	2926304.	1.	.318E-04	0.	28.	37.	35.	0.	0.
IN	11223.70	.1347	.120E-02	1221265.	0.	.155E-04	0.	59.	37.	3.	0.	0.
IA	6355.07	.0331	.521E-03	683683.	0.	.898E-05	0.	66.	34.	0.	0.	0.
KS	12963.83	.1662	.128E-02	1377462.	0.	.208E-04	0.	36.	56.	8.	0.	0.
KY	5764.57	1.3022	.226E-01	841404.	1.	.147E-03	0.	21.	41.	37.	0.	0.
LA	29489.11	1.8901	.641E-02	3517946.	2.	.496E-04	0.	21.	41.	38.	0.	0.
ME	6972.62	.0323	.463E-03	823851.	0.	.747E-05	0.	98.	2.	0.	0.	0.
MD	30486.01	.1389	.455E-03	2265774.	0.	.952E-05	0.	77.	22.	1.	0.	0.
MA	50020.91	1.6877	.337E-02	4260448.	1.	.316E-04	0.	34.	53.	13.	0.	0.
MI	67761.31	.9454	.140E-02	6464101.	1.	.150E-04	0.	53.	35.	12.	0.	0.
MN	4241.89	.0019	.445E-04	599727.	0.	.123E-05	0.	90.	10.	0.	0.	0.
MS	11525.36	.4190	.364E-02	1686699.	1.	.335E-04	0.	43.	38.	19.	0.	0.
MO	22739.31	15.2595	.671E-01	2214259.	9.	.416E-03	0.	18.	33.	48.	1.	0.
MT	5766.38	1.4403	.250E-01	627717.	1.	.222E-03	0.	15.	42.	42.	0.	0.
NE	14271.01	.1660	.116E-02	1485321.	0.	.219E-04	0.	40.	47.	12.	0.	0.
NV	5793.06	2.6977	.466E-01	487790.	2.	.406E-03	0.	36.	57.	7.	0.	0.
NH	5795.51	.2091	.361E-02	565163.	0.	.440E-04	0.	61.	39.	0.	0.	0.
NJ	83728.33	3.4298	.410E-02	7172164.	3.	.410E-04	0.	41.	59.	0.	0.	0.
NM	8028.13	1.1620	.145E-01	887902.	1.	.122E-03	0.	23.	47.	30.	0.	0.
NY	209387.24	20.2367	.966E-02	16020800.	12.	.734E-04	0.	59.	41.	0.	0.	0.
NC	24632.32	.0781	.317E-03	3256881.	0.	.509E-05	0.	88.	12.	0.	0.	0.
ND	3224.53	.0083	.256E-03	401228.	0.	.550E-05	0.	36.	45.	20.	0.	0.
OH	88663.07	1.0400	.117E-02	8874684.	1.	.142E-04	0.	54.	38.	8.	0.	0.
OK	22307.83	.5157	.231E-02	2445099.	1.	.231E-04	0.	35.	57.	9.	0.	0.
OR	17447.94	1.7062	.978E-02	1807847.	2.	.894E-04	0.	25.	50.	26.	0.	0.
PA	66824.41	.3810	.570E-03	6500033.	0.	.732E-05	0.	67.	22.	11.	0.	0.
RI	8439.58	.0684	.811E-03	864017.	0.	.111E-04	0.	64.	36.	0.	0.	0.
SC	19423.46	1.9364	.997E-02	2556543.	2.	.622E-04	0.	22.	44.	34.	0.	0.
SD	5091.87	.0757	.149E-02	637127.	0.	.228E-04	0.	29.	48.	23.	0.	0.
TN	18332.03	15.1440	.826E-01	2398162.	7.	.308E-03	0.	23.	52.	25.	0.	0.
TX	87076.33	.7542	.866E-03	9075057.	1.	.110E-04	0.	36.	44.	20.	0.	0.
UT	10603.18	12.2015	.115	1059273.	7.	.637E-03	0.	16.	41.	44.	0.	0.
VT	451.42	.0013	.281E-03	55009.	0.	.638E-05	0.	100.	0.	0.	0.	0.
VA	46047.22	.4261	.925E-03	4282881.	1.	.159E-04	0.	54.	41.	4.	0.	0.
WA	34838.53	96.8609	.278	3317835.	40.	.121E-02	0.	16.	41.	43.	0.	0.
WV	9624.81	.0678	.704E-03	1195485.	0.	.930E-05	0.	41.	41.	18.	0.	0.
WI	2142.19	.0203	.949E-03	257938.	0.	.129E-04	0.	59.	41.	0.	0.	0.
WY	2826.69	.0462	.164E-02	294824.	0.	.292E-04	0.	29.	45.	27.	0.	0.
AK	3849.70	3.6247	.942E-01	270801.	3.	.992E-03	0.	29.	55.	16.	0.	0.
HI	1001.77	.2570	.257E-01	109624.	0.	.218E-03	0.	18.	47.	35.	0.	0.

Table 1-7. The Values at Risk and Annual Damages Due to Earthquake in 1970, Valued in Millions of 1970$(by state)

STATE	TOTAL AT RISK	TOTAL DAMAGE	TOTAL PERCENT DAMAGE	TOTAL POPULATION	LIVES LOST	DEATH RATE	PERCENT OF DAMAGE BY TYPE					
							NO	LI	MOD	HEA	SEV	COL
AL	6576.35	.0253	.385E-03	754239.	0.	.536E-05	0.	62.	38.	0.	0.	0.
AZ	24377.17	.8982	.368E-02	2108245.	1.	.368E-04	0.	28.	51.	21.	0.	0.
AR	5161.05	3.5975	.697E-01	662379.	3.	.445E-03	0.	28.	52.	20.	0.	0.
CA	304762.65	444.8183	.146	21956401.	151.	.687E-03	0.	38.	33.	34.	0.	0.
CO	30285.56	24.6223	.813E-01	2402755.	12.	.490E-03	0.	16.	38.	45.	0.	0.
CT	47060.27	.8721	.185E-02	3371325.	1.	.205E-04	0.	62.	38.	0.	0.	0.
DE	7812.41	.0814	.104E-02	616974.	0.	.173E-04	0.	72.	28.	0.	0.	0.
DC	20404.34	.0771	.378E-03	1001025.	0.	.852E-05	0.	96.	4.	0.	0.	0.
FL	73600.72	1.1832	.161E-02	6432974.	1.	.149E-04	0.	32.	53.	15.	0.	0.
GA	19179.53	.5056	.264E-02	2062283.	1.	.281E-04	0.	36.	49.	15.	0.	0.
ID	7371.09	1.7666	.240E-01	684621.	1.	.217E-03	0.	19.	41.	40.	0.	0.
IL	39801.77	1.0306	.259E-02	3091302.	1.	.309E-04	0.	31.	37.	32.	0.	0.
IN	14989.69	.1503	.100E-02	1334399.	0.	.150E-04	0.	63.	34.	2.	0.	0.
IA	7882.89	.0351	.445E-03	693980.	0.	.892E-05	0.	72.	28.	0.	0.	0.
KS	16175.76	.1780	.110E-02	1406730.	0.	.207E-04	0.	41.	53.	6.	0.	0.
KY	7228.90	1.4375	.199E-01	868606.	1.	.148E-03	0.	24.	42.	34.	0.	0.
LA	37093.86	2.2106	.596E-02	3609564.	2.	.521E-04	0.	22.	42.	35.	0.	0.
ME	8685.95	.0358	.412E-03	844345.	0.	.761E-05	0.	98.	2.	0.	0.	0.
MD	46227.29	.1741	.377E-03	2755097.	0.	.901E-05	0.	82.	17.	1.	0.	0.
MA	67729.93	1.9560	.289E-02	4760151.	1.	.308E-04	0.	39.	51.	10.	0.	0.
MI	88353.44	1.0487	.119E-02	6942460.	1.	.147E-04	0.	60.	29.	11.	0.	0.
MN	5246.40	.0020	.391E-04	613339.	0.	.124E-05	0.	92.	8.	0.	0.	0.
MS	14536.58	.4709	.324E-02	1732622.	1.	.343E-04	0.	45.	38.	17.	0.	0.
MO	28807.47	16.4406	.571E-01	2298342.	9.	.410E-03	0.	21.	34.	45.	0.	0.
MT	7016.95	1.5403	.220E-01	625342.	1.	.226E-03	0.	17.	43.	39.	0.	0.
NE	18267.22	.1778	.973E-03	1547752.	0.	.214E-04	0.	45.	45.	10.	0.	0.
NV	8754.40	3.7465	.428E-01	606378.	2.	.407E-03	0.	38.	57.	5.	0.	0.
NH	7853.85	.2431	.310E-02	629533.	0.	.429E-04	0.	68.	32.	0.	0.	0.
NJ	112976.64	3.9236	.347E-02	7957273.	3.	.397E-04	0.	47.	53.	0.	0.	0.
NM	10264.35	1.3340	.130E-01	929114.	1.	.125E-03	0.	25.	49.	26.	0.	0.
NY	276340.02	22.7714	.824E-02	17360590.	12.	.718E-04	0.	67.	33.	0.	0.	0.
NC	32636.61	.0912	.279E-03	3515699.	0.	.510E-05	0.	92.	8.	0.	0.	0.
ND	3827.19	.0084	.220E-03	389936.	0.	.555E-05	0.	39.	44.	17.	0.	0.
OH	115529.54	1.1670	.101E-02	9493150.	1.	.140E-04	0.	58.	35.	6.	0.	0.
OK	29472.29	.6252	.212E-02	2617452.	1.	.239E-04	0.	39.	56.	5.	0.	0.
OR	22766.60	1.9023	.836E-02	1934474.	2.	.878E-04	0.	29.	49.	22.	0.	0.
PA	86702.99	.4350	.502E-03	6938466.	1.	.734E-05	0.	68.	23.	9.	0.	0.
RI	10895.10	.0763	.701E-03	923097.	0.	.109E-04	0.	68.	32.	0.	0.	0.
SC	25507.66	2.2248	.872E-02	2756747.	2.	.620E-04	0.	24.	46.	31.	0.	0.
SD	6189.95	.0797	.129E-02	633426.	0.	.230E-04	0.	32.	47.	20.	0.	0.
TN	24130.06	18.1427	.752E-01	2587490.	8.	.316E-03	0.	26.	54.	20.	0.	0.
TX	118866.52	.8615	.725E-03	10056335.	1.	.106E-04	0.	40.	42.	18.	0.	0.
UT	14427.91	14.7129	.102	1170900.	8.	.642E-03	0.	18.	43.	40.	0.	0.
VT	564.66	.0014	.252E-03	56666.	0.	.653E-05	0.	100.	0.	0.	0.	0.
VA	65576.57	.4853	.740E-03	4865971.	1.	.150E-04	0.	61.	36.	3.	0.	0.
WA	44983.02	111.1633	.247	3513462.	43.	.122E-02	0.	18.	43.	39.	0.	0.
WV	11807.86	.0722	.611E-03	1200838.	0.	.941E-05	0.	44.	40.	16.	0.	0.
WI	2730.93	.0225	.825E-03	271568.	0.	.128E-04	0.	66.	34.	0.	0.	0.
WY	3475.53	.0503	.145E-02	297201.	0.	.299E-04	0.	31.	46.	23.	0.	0.
AK	5007.20	4.3139	.862E-01	287038.	3.	.104E-02	0.	32.	56.	13.	0.	0.
HI	1190.23	.2752	.231E-01	106898.	0.	.227E-03	0.	20.	49.	31.	0.	0.

Table 1-8. The Values at Risk and Annual Damages Due to Earthquake in 1980, Valued in Millions of 1970$(by state)

STATE	TOTAL AT RISK	TOTAL DAMAGE	TOTAL PERCENT DAMAGE	TOTAL POPULATION	LIVES LOST	DEATH RATE	PERCENT OF DAMAGE BY TYPE					
							NO	LI	MOD	HEA	SEV	COL
AL	9077.58	.0344	.379E-03	789196.	0.	.634E-05	0.	62.	38.	0.	0.	0.
AZ	35070.21	1.2129	.346E-02	2443832.	1.	.392E-04	0.	28.	52.	20.	0.	0.
AR	7029.29	4.8952	.696E-01	669090.	4.	.546E-03	0.	28.	52.	20.	0.	0.
CA	414441.45	589.6791	.142	23977041.	184.	.766E-03	0.	39.	35.	32.	0.	0.
CO	42081.28	33.9735	.807E-01	2623124.	15.	.562E-03	0.	17.	38.	45.	0.	0.
CT	63814.25	1.1515	.180E-02	3710433.	1.	.226E-04	0.	63.	37.	0.	0.	0.
DE	10879.00	.1109	.102E-02	685845.	0.	.193E-04	0.	73.	27.	0.	0.	0.
DC	30450.36	.1097	.360E-03	1245540.	0.	.881E-05	0.	96.	4.	0.	0.	0.
FL	111422.63	1.6776	.151E-02	7672365.	1.	.160E-04	0.	32.	54.	14.	0.	0.
GA	26827.44	.6763	.252E-02	2198931.	1.	.324E-04	0.	37.	49.	14.	0.	0.
ID	9853.02	2.3720	.241E-01	711679.	2.	.255E-03	0.	19.	42.	39.	0.	0.
IL	52963.77	1.3446	.254E-02	3256300.	1.	.352E-04	0.	31.	37.	32.	0.	0.
IN	20921.99	.2000	.956E-03	1447533.	0.	.168E-04	0.	64.	34.	2.	0.	0.
IA	10216.41	.0427	.418E-03	704277.	0.	.990E-05	0.	74.	26.	0.	0.	0.
KS	21151.43	.2207	.104E-02	1435998.	0.	.230E-04	0.	43.	51.	6.	0.	0.
KY	10069.15	1.9707	.196E-01	895807.	2.	.179E-03	0.	24.	42.	33.	0.	0.
LA	49959.04	2.9740	.595E-02	3701182.	2.	.622E-04	0.	22.	42.	35.	0.	0.
ME	11478.52	.0454	.395E-03	864838.	0.	.868E-05	0.	99.	1.	0.	0.	0.
MD	67300.11	.2424	.360E-03	3244419.	0.	.966E-05	0.	83.	17.	0.	0.	0.
MA	92961.38	2.6106	.281E-02	5259853.	2.	.341E-04	0.	39.	51.	10.	0.	0.
MI	118571.88	1.3730	.116E-02	7420819.	1.	.166E-04	0.	60.	29.	11.	0.	0.
MN	7027.73	.0026	.370E-04	626951.	0.	.143E-05	0.	93.	7.	0.	0.	0.
MS	20109.41	.6109	.304E-02	1778545.	1.	.396E-04	0.	46.	37.	17.	0.	0.
MO	37905.87	22.0926	.583E-01	2382425.	12.	.485E-03	0.	20.	35.	45.	0.	0.
MT	9025.25	1.8751	.208E-01	622966.	2.	.256E-03	0.	18.	44.	38.	0.	0.
NE	24379.82	.2192	.899E-03	1610182.	0.	.235E-04	0.	46.	45.	9.	0.	0.
NV	12849.55	5.3078	.413E-01	724965.	3.	.438E-03	0.	38.	57.	4.	0.	0.
NH	10930.95	.3273	.299E-02	693902.	0.	.479E-04	0.	69.	31.	0.	0.	0.
NJ	153580.25	5.1783	.337E-02	8742382.	4.	.437E-04	0.	48.	52.	0.	0.	0.
NM	13748.61	1.7876	.130E-01	970326.	1.	.146E-03	0.	25.	49.	26.	0.	0.
NY	368067.48	29.3406	.797E-02	18700380.	15.	.792E-04	0.	67.	33.	0.	0.	0.
NC	46043.94	.1256	.273E-03	3774516.	0.	.594E-05	0.	92.	8.	0.	0.	0.
ND	4861.14	.0094	.194E-03	378645.	0.	.607E-05	0.	41.	43.	15.	0.	0.
OH	156672.53	1.5437	.985E-03	10111617.	2.	.159E-04	0.	58.	36.	6.	0.	0.
OK	40881.26	.8738	.214E-02	2789806.	1.	.282E-04	0.	39.	56.	5.	0.	0.
OR	30885.77	2.5389	.822E-02	2061101.	2.	.101E-03	0.	29.	49.	22.	0.	0.
PA	116287.08	.5761	.495E-03	7376900.	1.	.836E-05	0.	68.	23.	9.	0.	0.
RI	14507.94	.0993	.684E-03	982177.	0.	.123E-04	0.	69.	31.	0.	0.	0.
SC	35608.95	2.9657	.833E-02	2956951.	2.	.707E-04	0.	24.	46.	30.	0.	0.
SD	8006.60	.0939	.117E-02	629724.	0.	.255E-04	0.	34.	48.	18.	0.	0.
TN	34024.69	25.3354	.745E-01	2776818.	10.	.372E-03	0.	26.	54.	20.	0.	0.
TX	167251.71	1.1305	.676E-03	11037612.	1.	.116E-04	0.	41.	42.	17.	0.	0.
UT	20310.30	20.5382	.101	1282527.	9.	.740E-03	0.	18.	43.	39.	0.	0.
VT	775.28	.0019	.247E-03	58322.	0.	.782E-05	0.	100.	0.	0.	0.	0.
VA	93491.54	.6542	.700E-03	5449060.	1.	.165E-04	0.	62.	35.	3.	0.	0.
WA	60118.45	147.6803	.246	3709090.	52.	.141E-02	0.	18.	43.	38.	0.	0.
WV	15863.01	.0918	.579E-03	1206191.	0.	.111E-04	0.	46.	40.	14.	0.	0.
WI	3647.72	.0294	.806E-03	285198.	0.	.146E-04	0.	66.	34.	0.	0.	0.
WY	4519.52	.0629	.139E-02	299578.	0.	.342E-04	0.	32.	46.	22.	0.	0.
AK	6636.74	5.6487	.851E-01	303276.	4.	.118E-02	0.	32.	56.	12.	0.	0.
HI	1463.38	.3104	.212E-01	104172.	0.	.248E-03	0.	22.	50.	28.	0.	0.

Table 1-9. The Values at Risk and Annual Damages Due to Earthquake in 1990 Valued in Millions of 1970$(by state)

STATE	TOTAL AT RISK	TOTAL DAMAGE	TOTAL PERCENT DAMAGE	TOTAL POPULATION	LIVES LOST	DEATH RATE	PERCENT OF DAMAGE BY TYPE					
							NO	LI	MOD	HEA	SEV	COL
AL	11951.97	.0446	.373E-03	824154.	0.	.727E-05	0.	62.	38.	0.	0.	0.
AZ	47834.87	1.5642	.327E-02	2779419.	1.	.412E-04	0.	28.	52.	20.	0.	0.
AR	9085.24	6.3216	.696E-01	675802.	4.	.644E-03	0.	28.	52.	19.	0.	0.
CA	539352.31	748.7506	.139	25997681.	217.	.834E-03	0.	39.	36.	31.	0.	0.
CO	55662.12	44.5304	.800E-01	2843493.	18.	.627E-03	0.	17.	39.	44.	0.	0.
CT	82591.01	1.4547	.176E-02	4049541.	1.	.243E-04	0.	64.	36.	0.	0.	0.
DE	14391.93	.1439	.100E-02	754715.	0.	.211E-04	0.	73.	27.	0.	0.	0.
DC	42386.32	.1454	.343E-03	1490054.	0.	.899E-05	0.	97.	3.	0.	0.	0.
FL	157362.40	2.2499	.143E-02	8911756.	2.	.170E-04	0.	32.	54.	14.	0.	0.
GA	35646.32	.8667	.243E-02	2335578.	1.	.364E-04	0.	37.	49.	14.	0.	0.
ID	12667.49	3.0374	.240E-01	738737.	2.	.290E-03	0.	19.	42.	39.	0.	0.
IL	67557.65	1.6907	.250E-02	3421299.	1.	.392E-04	0.	31.	38.	32.	0.	0.
IN	27727.73	.2545	.918E-03	1560667.	0.	.184E-04	0.	64.	33.	2.	0.	0.
IA	12699.12	.0503	.396E-03	714574.	0.	.107E-04	0.	75.	25.	0.	0.	0.
KB	26540.58	.2654	.100E-02	1465267.	0.	.252E-04	0.	44.	50.	6.	0.	0.
KY	13307.53	2.5755	.194E-01	923009.	2.	.209E-03	0.	25.	43.	33.	0.	0.
LA	64741.43	3.8500	.595E-02	3792799.	3.	.722E-04	0.	23.	43.	35.	0.	0.
ME	14525.18	.0555	.382E-03	885332.	0.	.966E-05	0.	99.	1.	0.	0.	0.
MD	92112.87	.3196	.347E-03	3733742.	0.	.102E-04	0.	83.	16.	0.	0.	0.
MA	121580.23	3.3211	.273E-02	5759556.	2.	.367E-04	0.	40.	51.	9.	0.	0.
MI	152899.33	1.7329	.113E-02	7899178.	1.	.183E-04	0.	60.	29.	11.	0.	0.
MN	8930.72	.0032	.354E-04	640563.	0.	.159E-05	0.	94.	6.	0.	0.	0.
MS	26371.92	.7602	.288E-02	1824468.	1.	.445E-04	0.	46.	36.	18.	0.	0.
MO	47922.75	28.1788	.588E-01	2466507.	14.	.554E-03	0.	20.	35.	45.	1.	0.
MT	11212.71	2.2341	.199E-01	620591.	2.	.286E-03	0.	19.	44.	37.	0.	0.
NE	31162.48	.2616	.840E-03	1672613.	0.	.253E-04	0.	48.	44.	8.	0.	0.
NV	17685.38	7.0749	.400E-01	843553.	4.	.461E-03	0.	39.	57.	4.	0.	0.
NH	14488.20	.4201	.290E-02	758272.	0.	.521E-04	0.	70.	30.	0.	0.	0.
NJ	199247.52	6.5226	.327E-02	9527490.	4.	.470E-04	0.	49.	51.	0.	0.	0.
NM	17771.81	2.3050	.130E-01	1011538.	2.	.166E-03	0.	25.	49.	26.	0.	0.
NY	467536.94	36.1238	.773E-02	20040170.	17.	.850E-04	0.	68.	32.	0.	0.	0.
NC	61612.73	.1644	.267E-03	4033334.	0.	.669E-05	0.	93.	7.	0.	0.	0.
ND	5929.93	.0103	.174E-03	367353.	0.	.654E-05	0.	44.	43.	13.	0.	0.
OH	203190.09	1.9543	.962E-03	10730083.	2.	.176E-04	0.	59.	36.	6.	0.	0.
OK	54045.74	1.1601	.215E-02	2962159.	1.	.321E-04	0.	40.	56.	4.	0.	0.
OR	40099.28	3.2410	.808E-02	2187728.	2.	.112E-03	0.	29.	49.	22.	0.	0.
PA	149484.02	.7314	.489E-03	7815333.	1.	.928E-05	0.	67.	24.	9.	0.	0.
RI	18536.28	.1241	.669E-03	1041257.	0.	.134E-04	0.	69.	31.	0.	0.	0.
SC	47245.60	3.8007	.804E-02	3157155.	2.	.786E-04	0.	24.	46.	30.	0.	0.
SD	9944.57	.1079	.109E-02	626023.	0.	.278E-04	0.	36.	48.	16.	0.	0.
TN	45713.63	33.6391	.736E-01	2966145.	13.	.425E-03	0.	26.	55.	19.	0.	0.
TX	224019.18	1.4294	.638E-03	12018890.	1.	.124E-04	0.	42.	41.	17.	0.	0.
UT	27243.39	27.2900	.100	1394154.	12.	.830E-03	0.	18.	44.	38.	0.	0.
VT	1010.55	.0025	.243E-03	59979.	0.	.901E-05	0.	100.	0.	0.	0.	0.
VA	126062.28	.8425	.668E-03	6032150.	1.	.177E-04	0.	62.	35.	3.	0.	0.
WA	76979.18	187.7317	.244	3904717.	62.	.158E-02	0.	19.	44.	38.	0.	0.
WV	20369.73	.1122	.551E-03	1211543.	0.	.126E-04	0.	47.	41.	12.	0.	0.
WI	4678.39	.0370	.790E-03	298828.	0.	.163E-04	0.	67.	33.	0.	0.	0.
WY	5676.80	.0768	.135E-02	301955.	0.	.385E-04	0.	33.	46.	21.	0.	0.
AK	8480.39	7.1353	.841E-01	319513.	4.	.132E-02	0.	32.	56.	12.	0.	0.
HI	1740.26	.3439	.198E-01	101445.	0.	.269E-03	0.	23.	52.	25.	0.	0.

Table 1-10. The Values at Risk and Annual Damages Due to Earthquake in 2000, Valued in Millions of 1970$(by state)

KEY TO TABLES 1-11 TO 1-14.

Census Regions

NE	Northeast
NC	North Central
SO	South
WT	West
US	National Total
UR VL	SMSA Value of structures at risk in 10^6 1970$
RR VL	Non-SMSA Value of structures at risk in 10^6 1970$
UR DR	[Damage/Value of Structure] x 100. SMSA
RR DR	[Damage/Value of Structure] x 100. NON-SMSA
TOT VL	Regional Total Value of Structures at risk 10^6 1970$
TOT DM	Regional Total Damage Estimate 1970$
TOT DR	Regional [Damage Total/Value of Structures Total] x 100.

Note: The data in the population column are in number of people.

REGIONAL AND NATIONAL TOTALS

REGIONS		HOUSEHOLD STRUCTURES	FARM+MINES STRUCTURES	CONSTRUCT STRUCTURES	MANUFACTOR STRUCTURES	TRAN+UTILY STRUCTURES	W+RTRADE STRUCTURES	FINANCE STRUCTURES	SERVICES STRUCTURES	FEDGOV STRUCTURES	ST+LOCGOV STRUCTURES	POPULATION IN NUMBER	TOTAL
NE	UR VL	228551,36	468,32	5278,49	22464,01	53078,07	17741,22	30683,94	23566,02	17566,51	30778.81	35106566,	430176,75
	UR DR	7,662E-03	3,409E-03	3,883E-03	3,436E-03	4,776E-03	4,337E-03	5,202E-03	4,505E-03	3,906E-03	4.491E-03	4,886E-05	,617E-02
	RR VL	21294,99	288,74	548,44	1951,15	2929,42	1397,26	1142,81	1420,27	2151,25	3303.01	4187136,	36427,35
	RR DR	9,417E-04	2,680E-04	4,553E-04	3,489E-04	4,190E-04	4,645E-04	4,362E-04	4,637E-04	9,875E-04	4.591E-04	1,040E-05	,761E-03
	TOT VL	249846,35	757,06	5826,93	24415,16	56007,50	19138,48	31826,75	24986,29	19717,76	34081,82	39293702,	466604,10
	TOT DM	1,771E+07	1,674E+04	2,075E+05	7,787E+05	2,548E+06	7,760E+05	1,601E+06	1,068E+06	7,074E+05	1.398E+06	18,	2,681E+07
	TOT DR	7,090E-03	2,211E-03	3,561E-03	3,190E-03	4,549E-03	4,055E-03	5,030E-03	4,275E-03	3,588E-03	4,100E-03	4,476E-05	,575E-02
NC	UR VL	106421,57	555,24	2660,36	15143,03	22521,87	8436,87	9335,63	8739,03	9584,17	13013,69	18014973,	196411,45
	UR DR	1,850E-03	9,506E-04	8,375E-04	8,548E-04	8,815E-04	8,504E-04	8,249E-04	8,300E-04	9,245E-04	7,711E-04	1,446E-05	,139E-02
	RR VL	43192,39	2125,95	872,44	4112,88	6598,27	2864,80	1974,51	2421,47	2606,47	6417.70	9128126,	73186,88
	RR DR	2,533E-02	1,899E-02	1,657E-02	1,651E-02	1,631E-02	2,012E-02	1,899E-02	1,719E-02	1,862E-02	1,517E-02	1,187E-04	,220E-01
	TOT VL	149613,96	2681,19	3532,80	19255,91	29120,14	11301,67	11310,14	11160,50	12190,64	19431.39	27143099,	269598,33
	TOT DM	1,291E+07	4,090E+05	1,669E+05	8,084E+05	1,274E+06	6,482E+05	4,519E+05	4,888E+05	5,740E+05	1.074E+06	13,	1,881E+07
	TOT DR	8,629E-03	1,525E-02	4,723E-03	4,198E-03	4,376E-03	5,735E-03	3,996E-03	4,379E-03	4,708E-03	5,526E-03	4,951E-05	,698E-02
SO	UR VL	128885,78	3351,07	3752,45	9554,31	31947,21	10965,72	13846,60	11886,20	33234,97	16458.56	24066946,	263882,86
	UR DR	9,973E-03	1,563E-03	6,689E-03	6,953E-03	6,028E-03	7,664E-03	6,449E-03	6,263E-03	4,524E-03	6.977E-03	5.033E-05	,791E-02
	RR VL	76397,19	4378,69	1596,78	7818,63	11558,19	4798,99	3696,54	4238,11	6134,37	10520.25	19253767,	131137,74
	RR DR	6,101E-03	3,238E-03	3,468E-03	4,120E-03	3,350E-03	4,029E-03	3,681E-03	3,492E-03	3,367E-03	3,292E-03	3,931E-05	,503E-02
	TOT VL	205282,97	7729,75	5349,23	17372,94	43505,40	15764,71	17543,14	16124,31	39369,33	26978.82	43320713,	395020,61
	TOT DM	1,751E+07	1,942E+05	3,064E+05	9,864E+05	2,313E+06	1,034E+06	1,029E+06	8,924E+05	1.710E+06	1.495E+06	20,	2,747E+07
	TOT DR	8,532E-03	2,512E-03	5,727E-03	5,678E-03	5,317E-03	6,558E-03	5,866E-03	5,534E-03	4,344E-03	5.540E-03	4,543E-05	,696E-02
WT	UR VL	158864,45	1769,48	3785,74	12597,72	36253,09	12829,38	16558,85	15068,76	21176,17	24501.35	26752876,	303404,98
	UR DR	,181	,254	,162	,172	,192	,176	,183	,172	.191	.172	7,465E-04	,181E+00
	RR VL	31249,07	2363,49	789,29	1619,07	5945,17	2081,66	1551,42	2078.57	5166.56	6821.25	6659105,	59665,54
	RR DR	6,008E-02	2,555E-02	4,369E-02	3,937E-02	3,734E-02	4,392E-02	4,239E-02	3.758E-02	5,870E-02	5.187E-02	3.455E-04	,528E-01
	TOT VL	190113,51	4132,97	4575,04	14216,78	42198,27	14911,04	18110,26	17147.33	26342,73	31322.59	33411981,	363070,52
	TOT DM	3,061E+08	5,093E+06	6,481E+06	2,227E+07	7,177E+07	2,350E+07	3,103E+07	2,666E+07	4,351E+07	4,574E+07	223,	5,821E+08
	TOT DR	,161	,123	,142	,157	,170	,158	,171	,156	,165	.146	6.666E-04	,160E+00
US	UR VL	622723,16	6144,10	15477,04	59759,06	143800,24	49973,19	70425,02	59260.00	81561.82	84752.41	103941361,	1193876,04
	UR DR	5,133E-02	7,427E-02	4,274E-02	3,881E-02	5,161E-02	4,857E-02	4,677E-02	4,685E-02	5,242E-02	5,289E-02	2,228E-04	,503E-01
	RR VL	172133,63	9156,87	3806,96	15501,74	27031,06	11142,71	8365,27	10158,43	16058,64	27062.21	39228134,	300417,53
	RR DR	2,009E-02	1,256E-02	1,438E-02	1,061E-02	1,367E-02	1,517E-02	1,403E-02	1,331E-02	2,333E-02	1.801E-02	1.067E-04	,181E-01
	TOT VL	794856,79	15300,98	19284,01	75260,80	170831,30	61115,90	78790,29	69418,43	97620,46	111814.62	143169495,	1494293,56
	TOT DM	3,542E+08	5,713E+06	7,162E+06	2,484E+07	7,790E+07	2,596E+07	3,411E+07	2,911E+07	4,650E+07	4,970E+07	273,	6,552E+08
	TOT DR	4,456E-02	3,734E-02	3,714E-02	3,301E-02	4,560E-02	4,248E-02	4,330E-02	4,194E-02	4,764E-02	4,445E-02	1.910E-04	,438E-01

Table 1-11. The Values at Risk and Annual Damages Due to Earthquake in 1970, Valued in Millions of 1970$ (regional and national totals)

```
REGIONAL AND NATIONAL TOTALS
R      H S        F S        C S        M S        T S        W S        F S        S S        F S        S S        P
 E      O T        A T        O T        A T        R T        + T        I T        E T        E T        T T        O I
  G      U R        R R        N R        N R        A R        R R        N R        R R        D R        + R        P N        T
   I      S U        M U        S U        U U        N U          U        A U        V U          U        L U          U        O
    O      E C        + C        T C        F C        + C        T C        N C        I C        G C        O C        L N        T
     N       T        M T        R T        A T        U T        R T        C T        C T        O T        C T        A U        A
      S      H U        I U        U U        C U        T U        A U        E U        E U        V U          U        T M        L
             O R        N R        C R        T R        I R        D R          R        S R          R        G R        I B
              L E        E E        T E        O E        L E        E E          E          E          E        O E        U E
               D S        S S          S        R S        Y S          S          S          S          S        V S        N R
=====================================================================================================================================
NE UR VL | 291016,97     753,65    6623,67   33053,00   78200,48   21944,60   42642,91   31942,33   24198,94   41752,81 38410087,| 572129,36|
   UR DR | 6,804E-03 2,703E-03 3,146E-03 2,786E-03 3,875E-03 3,513E-03 4,207E-03 3,645E-03 3,175E-03 3,635E-03 4,754E-05|  ,524E-02|
   RR VL |  26293,43     436,55     669,88    2773,72    4158,89    1680,60    1546,83    1867,06    2935,91    4317,18  4431358,|  46680,04|
   RR DR | 8,751E-04 2,384E-04 3,889E-04 2,971E-04 3,615E-04 3,976E-04 3,723E-04 3,980E-04 8,503E-04 3,952E-04 1,053E-05|  ,683E-03|
         +----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+
   TOT VL| 317310,40    1190,21    7293,54   35826,72   82359,36   23625,21   44189,73   33809,38   27134,85   46069,99 42841445,| 618809,40|
   TOT DM| 2,003E+07 2,141E+04 2,110E+05 9,290E+05 3,045E+06 7,777E+05 1,800E+06 1,172E+06 7,932E+05 1,535E+06        19,| 3,031E+07|
   TOT DR| 6,313E-03 1,799E-03 2,892E-03 2,593E-03 3,697E-03 3,292E-03 4,072E-03 3,466E-03 2,923E-03 3,332E-03 4,371E-05|  ,490E-02|
=====================================================================================================================================
NC UR VL | 133055,98     832,37    3278,36   21854,05   32619,01   10245,55   12787,49   11627,66   13045,56   17465,14 19371654,| 256811,17|
   UR DR | 1,644E-03 8,062E-04 6,801E-04 6,958E-04 7,160E-04 6,913E-04 6,678E-04 6,738E-04 7,485E-04 6,235E-04 1,417E-05|  ,119E-02|
   RR VL |  51502,63    3180,18    1025,97    5745,92    9101,50    3312,02    2566,13    3067,66    3342,23    8146,87  9344731,|  90991,10|
   RR DR | 2,247E-02 1,817E-02 1,386E-02 1,363E-02 1,370E-02 1,689E-02 1,594E-02 1,442E-02 1,574E-02 1,273E-02 1,184E-04|  ,190E-01|
         +----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+
   TOT VL| 184558,60    4012,54    4304,33   27599,97   41720,52   13557,56   15353,62   14695,32   16387,80   25612,01 28716385,| 347802,27|
   TUT DM| 1,376E+07 5,844E+05 1,645E+05 9,354E+05 1,480E+06 6,302E+05 4,945E+05 5,206E+05 6,238E+05 1,146E+06        14,| 2,034E+07|
   TOT DR| 7,456E-03 1,456E-02 3,823E-03 3,389E-03 3,548E-03 4,649E-03 3,221E-03 3,543E-03 3,806E-03 4,474E-03 4,809E-05|  ,585E-02|
=====================================================================================================================================
SO UR VL | 176801,74    4898,07    5087,73   14694,45   50803,04   14542,75   20884,07   17519,63   51305,22   23995,94 28123364,| 380532,65|
   UR DR | 8,640E-03 1,451E-03 5,458E-03 5,853E-03 4,927E-03 6,308E-03 5,254E-03 5,075E-03 3,542E-03 5,728E-03 4,803E-05|  ,659E-02|
   RR VL |  92340,24    6235,53    1908,84   10952,85   16174,81    5642,72    4901,36    5460,56    8115,41   13553,64 19972929,| 165285,98|
   RR DR | 5,429E-03 3,050E-03 2,882E-03 3,430E-03 2,799E-03 3,352E-03 3,057E-03 2,905E-03 2,790E-03 2,745E-03 3,913E-05|  ,435E-02|
         +----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+
   TOT VL| 269141,98   11133,61    6996,57   25647,30   66977,85   20185,47   25785,43   22980,20   59420,63   37549,58 48096293,| 545818,62|
   TOT DM| 2,029E+07 2,613E+05 3,327E+05 1,236E+06 2,956E+06 1,107E+06 1,247E+06 1,048E+06 2,043E+06 1,747E+06        21,| 3,227E+07|
   TOT DR| 7,538E-03 2,347E-03 4,755E-03 4,818E-03 4,413E-03 5,482E-03 4,836E-03 4,559E-03 3,439E-03 4,652E-03 4,433E-05|  ,591E-02|
=====================================================================================================================================
WT UR VL | 205286,85    2751,41    4837,93   18811,73   54229,50   16093,90   23379,28   20760,08   29681,46   33705,89 29751461,| 409538,03|
   UR DR |  ,136      ,200       ,129       ,138       ,153       ,141       ,147       ,137       ,152       ,138      6,781E-04|  ,141E+00|
   RR VL |  37525,56    3433,05     938,20    2242,55    8271,45    2425,30    2037,84    2687,82    6831,62    8751,28  6871368,|  75144,68|
   RR DR | 5,288E-02 2,469E-02 3,742E-02 3,369E-02 3,202E-02 3,700E-02 3,601E-02 3,185E-02 5,003E-02 4,387E-02 3,457E-04|  ,455E-01|
         +----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+
   TOT VL| 242812,41    6184,46    5776,13   21054,28   62500,95   18519,20   25417,12   23447,90   36513,08   42457,17 36622829,| 484682,71|
   TUT DM| 2,989E+08 6,349E+06 6,614E+06 2,665E+07 8,579E+07 2,361E+07 3,499E+07 2,933E+07 4,867E+07 5,027E+07       226,| 6,111E+08|
   TOT DR|  ,123      ,103       ,114       ,127       ,137       ,127       ,138       ,125       ,133       ,118      6,158E-04|  ,126E+00|
=====================================================================================================================================
US UR VL | 806161,54    9235,51   19827,69   88413,23  215852,03   62826,80   99693,74   81849,70  118231,19  116919,79115656566,|1619011,20|
   UR DR | 3,923E-02 6,063E-02 3,415E-02 3,148E-02 4,119E-02 3,894E-02 3,735E-02 3,739E-02 4,055E-02 4,228E-02 2,043E-04|  ,392E-01|
   RR VL | 207661,86   13285,31    4542,89   21715,04   37706,65   13060,65   11052,16   13083,09   21225,17   34768,97 40620386,| 378101,80|
   RR DR | 1,765E-02 1,217E-02 1,213E-02 8,855E-03 1,157E-02 1,265E-02 1,175E-02 1,119E-02 1,977E-02 1,514E-02 1,061E-04|  ,156E-01|
         +----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+----------+
   TOT VL|1013823,40   22520,82   24370,58  110128,27  253558,68   75887,44  110745,90   94932,79  139456,36  151688,76156276952,|1997113,01|
   TOT DM| 3,529E+08 7,216E+06 7,322E+06 2,975E+07 9,328E+07 2,612E+07 3,853E+07 3,207E+07 5,213E+07 5,470E+07       279,| 6,941E+08|
   TOT DR| 3,481E-02 3,204E-02 3,004E-02 2,702E-02 3,679E-02 3,442E-02 3,479E-02 3,378E-02 3,738E-02 3,606E-02 1,788E-04|  ,348E-01|
=====================================================================================================================================
```

Table 1-12. The Values at Risk and Annual Damages Due to Earthquake in 1980, Valued in Millions of 1970$
~~(regional and national totals)~~

REGIONAL AND NATIONAL TOTALS

REGIONS		HOUSEHOLD STRUCTURES	FARM+MINES STRUCTURES	CONSTRUCT STRUCTURES	MANUFACTUR STRUCTURES	TRAN+UTILY STRUCTURES	W+R TRADE STRUCTURES	FINANCE STRUCTURES	SERVICES STRUCTURES	FED GOV STRUCTURES	ST+LOC GOV STRUCTURES	POPULATION IN NUMBER	TOTAL
NE	UR VL	376466.63	1249.01	8428.82	47831.82	116758.12	27771.78	61576.90	43931.65	30482.63	55284.04	41713609.	769781.41
	UR DR	6.652E-03	2.568E-03	3.047E-03	2.696E-03	3.758E-03	3.404E-03	4.084E-03	3.531E-03	3.077E-03	3.518E-03	5.238E-05	.505E-02
	RR VL	34255.08	707.53	858.09	4013.30	6263.27	2145.66	2260.99	2589.52	3784.02	5744.26	4675579.	62621.72
	RR DR	8.880E-04	2.470E-04	3.918E-04	2.971E-04	3.649E-04	4.007E-04	3.744E-04	4.017E-04	8.617E-04	3.995E-04	1.217E-05	.682E-03
	TOT VL	410721.71	1956.53	9286.91	51845.12	123021.39	29917.44	63837.90	46521.17	34266.65	61028.30	46389188.	832403.12
	TOT DM	2.535E+07	3.382E+04	2.602E+05	1.302E+06	4.411E+06	9.540E+05	2.523E+06	1.562E+06	9.707E+05	1.968E+06	22.	3.933E+07
	TOT DR	6.171E-03	1.729E-03	2.801E-03	2.510E-03	3.586E-03	3.189E-03	3.953E-03	3.357E-03	2.833E-03	3.224E-03	4.833E-05	.472E-02
NC	UR VL	172333.69	1320.34	4173.56	31535.40	48894.17	12985.73	18611.57	16029.33	16504.98	23310.77	20728335.	345699.53
	UR DR	1.615E-03	8.133E-04	6.642E-04	6.813E-04	6.994E-04	6.757E-04	6.507E-04	6.580E-04	7.296E-04	6.071E-04	1.587E-05	.114E-02
	RR VL	65742.62	5159.12	1288.57	8269.88	13423.69	4130.16	3664.10	4162.69	4136.00	10650.52	9561336.	120627.36
	RR DR	2.286E-02	2.020E-02	1.405E-02	1.372E-02	1.395E-02	1.720E-02	1.625E-02	1.466E-02	1.610E-02	1.291E-02	1.413E-04	.192E-01
	TOT VL	238076.30	6479.46	5462.13	39805.28	62317.86	17115.88	22275.67	20192.02	20640.98	33961.29	30289670.	466326.89
	TOT DM	1.781E+07	1.053E+06	2.087E+05	1.349E+06	2.215E+06	7.983E+05	7.165E+05	7.159E+05	7.863E+05	1.517E+06	17.	2.717E+07
	TOT DR	7.482E-03	1.625E-02	3.821E-03	3.390E-03	3.554E-03	4.664E-03	3.216E-03	3.545E-03	3.809E-03	4.466E-03	5.548E-05	.583E-02
SO	UR VL	246608.29	7566.61	6984.12	22466.45	81950.33	19796.63	32758.71	26131.96	71100.20	34289.25	32179782.	549652.55
	UR DR	8.400E-03	1.560E-03	5.263E-03	5.756E-03	4.773E-03	6.126E-03	5.075E-03	4.888E-03	3.344E-03	5.537E-03	5.281E-05	.634E-02
	RR VL	122090.60	9934.59	2487.34	16228.85	24730.53	7305.38	7284.61	7692.59	10516.35	18365.73	20692092.	226636.55
	RR DR	5.370E-03	3.262E-03	2.833E-03	3.372E-03	2.755E-03	3.305E-03	3.008E-03	2.860E-03	2.743E-03	2.700E-03	4.622E-05	.426E-02
	TOT VL	368698.89	17501.20	9471.46	38695.30	106680.85	27102.00	40043.32	33824.55	81616.55	52654.98	52871873.	776289.11
	TOT DM	2.727E+07	4.421E+05	4.381E+05	1.840E+06	4.593E+06	1.454E+06	1.881E+06	1.497E+06	2.666E+06	2.394E+06	27.	4.448E+07
	TOT DR	7.397E-03	2.526E-03	4.625E-03	4.756E-03	4.305E-03	5.366E-03	4.699E-03	4.426E-03	3.267E-03	4.547E-03	5.023E-05	.573E-02
WT	UR VL	271443.85	4484.81	6304.81	27697.42	82750.42	20800.38	34566.69	29209.40	38416.46	45665.24	32750045.	561339.48
	UR DR	.132	.193	.125	.134	.149	.137	.142	.133	.148	.134	7.536E-04	.137E+00
	RR VL	47964.18	5355.55	1182.30	3193.30	12224.17	3031.12	2924.71	3692.36	8603.29	11493.07	7083631.	99664.05
	RR DR	5.270E-02	2.674E-02	3.717E-02	3.351E-02	3.170E-02	3.652E-02	3.567E-02	3.144E-02	4.947E-02	4.331E-02	4.023E-04	.448E-01
	TOT VL	319408.03	9840.36	7487.11	30890.72	94974.58	23831.51	37491.41	32901.76	47019.75	57158.30	39833676.	661003.54
	TOT DM	3.827E+08	1.011E+07	8.332E+06	3.805E+07	1.271E+08	2.959E+07	5.017E+07	3.996E+07	6.104E+07	6.596E+07	275.	8.130E+08
	TOT DR	.120	.103	.111	.123	.134	.124	.134	.121	.130	.115	6.911E-04	.123E+00
US	UR VL	1066852.46	14620.77	25891.32	129531.10	330353.03	81354.51	147513.87	115302.34	156504.27	158549.31	127371770.	2226472.98
	UR DR	3.805E-02	6.043E-02	3.300E-02	3.071E-02	3.992E-02	3.777E-02	3.622E-02	3.619E-02	3.848E-02	4.098E-02	2.268E-04	.380E-01
	RR VL	270052.48	21156.78	5816.29	31705.33	56641.65	16612.31	16134.42	18137.17	27039.66	46253.58	42012638.	509549.68
	RR DR	1.747E-02	1.324E-02	1.194E-02	8.717E-03	1.139E-02	1.245E-02	1.157E-02	1.104E-02	1.939E-02	1.486E-02	1.241E-04	.153E-01
	TOT VL	1336904.93	35777.55	31707.61	161236.43	386994.69	97966.83	163648.29	133439.51	183543.93	204802.89	169384408.	2736022.66
	TOT DM	4.531E+08	1.164E+07	9.239E+06	4.254E+07	1.383E+08	3.280E+07	5.529E+07	4.373E+07	6.547E+07	7.184E+07	341.	9.240E+08
	TOT DR	3.389E-02	3.252E-02	2.914E-02	2.638E-02	3.575E-02	3.348E-02	3.378E-02	3.277E-02	3.567E-02	3.508E-02	2.014E-04	.338E-01

Table 1-13. The Values at Risk and Annual Damages Due to Earthquake in 1990, Valued in Millions of 1970$
(regional and national totals)

```
REGIONAL AND NATIONAL TOTALS
R       H S       F S       C S       M S       T S       W S       F S       S S       F S       S S         P
 E       O T       A T       O T       A T       R T       + T       I T       E T       E T       T T         O I
  G       U R       R R       N R       N R       A R       R R       N R       R R       D R       + R         P N         T
   I       S U       M U       S U       U U       N U         U       A U       V U         U       L U         U           O
    O       E C       + C       T C       F C       + C       T C       N C       I C       G C       O C         L N         T
     N         T       M T       R T       A T       U T       R T       C T       C T       O T       C T         A U         A
      S       H U       I U       U U       C U       T U       A U       E U       E U       V U         U       T M         L
               O R       N R       C R       T R       I R       D R         R       S R         R       G R         I B
                L E       E E       T E       O E       L E       E E         E         E         E       O E         O E
                 D S       S S         S       R S       Y S         S         S         S         S       V S         N R

====================================================================================================================================
NE UR VL | 467269,78   1986,00  10179,44  65615,89 163793,18  33223,75  83383,09  56553,34  36882,05  69894,71 45017130,| 988781,23|
   UR DR | 6,501E-03 2,450E-03 2,948E-03 2,607E-03 3,643E-03 3,296E-03 3,962E-03 3,419E-03 2,980E-03 3,403E-03 5,618E-05|  ,488E-02|
   RR VL |  42744,95   1103,23   1041,27   5498,22   8842,65   2584,55   3092,99   3355,82   4667,40   7287,61  4919801,|  80218,69|
   RR DR | 8,978E-04 2,529E-04 3,923E-04 2,961E-04 3,663E-04 4,014E-04 3,744E-04 4,029E-04 8,636E-04 4,013E-04 1,362E-05|  ,679E-03|
          +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+----------+
   TOT VL| 510014,73   3089,23  11220,71  71114,11 172635,83  35808,30  86476,07  59909,16  41549,45  77182,32 49936931,|1068999,92|
   TOT DM| 3,076E+07 5,145E+04 3,042E+05 1,727E+06 5,999E+06 1,105E+06 3,315E+06 1,947E+06 1,139E+06 2,408E+06       26,| 4,876E+07|
   TOT DR| 6,031E-03 1,665E-03 2,711E-03 2,429E-03 3,475E-03 3,087E-03 3,833E-03 3,250E-03 2,742E-03 3,119E-03 5,198E-05|  ,456E-02|
====================================================================================================================================
NC UR VL | 214891,93   2034,03   5058,83  43300,13  69074,02  15610,81  25477,62  20754,71  20115,15  29788,88 22085015,| 446106,12|
   UR DR | 1,590E-03 8,158E-04 6,495E-04 6,676E-04 6,842E-04 6,613E-04 6,353E-04 6,436E-04 7,125E-04 5,921E-04 1,736E-05|  ,111E-02|
   RR VL |  80460,63   7975,52   1534,58  11267,24  18591,01   4865,56   4903,44   5283,55   4909,56  13286,12  9777941,| 153077,21|
   RR DR | 2,304E-02 2,173E-02 1,411E-02 1,367E-02 1,408E-02 1,736E-02 1,640E-02 1,478E-02 1,631E-02 1,299E-02 1,627E-04|  ,193E-01|
          +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+----------+
   TOT VL| 295352,56  10009,55   6593,41  54567,37  87665,03  20476,37  30381,06  26038,26  25024,71  43075,01 31862956,| 599183,33|
   TOT DM| 2,195E+07 1,750E+06 2,494E+05 1,830E+06 3,090E+06 9,478E+05 9,660E+05 9,144E+05 9,442E+05 1,902E+06       20,| 3,455E+07|
   TOT DR| 7,433E-03 1,748E-02 3,783E-03 3,353E-03 3,525E-03 4,629E-03 3,180E-03 3,512E-03 3,773E-03 4,416E-03 6,198E-05|  ,577E-02|
====================================================================================================================================
SO UR VL | 326374,84  11470,40   8994,71  32326,83 122836,81  25211,02  47609,45  36036,54  93102,13  46281,03 36236200,| 750243,76|
   UR DR | 8,220E-03 1,649E-03 5,112E-03 5,676E-03 4,651E-03 5,982E-03 4,935E-03 4,742E-03 3,197E-03 5,387E-03 5,694E-05|  ,614E-02|
   RR VL | 154108,69  15263,60   3059,78  22657,78  35353,80   8897,37  10099,14  10092,25  13008,85  23641,80 21411254,| 296183,06|
   RR DR | 5,315E-03 3,420E-03 2,789E-03 3,325E-03 2,715E-03 3,259E-03 2,964E-03 2,818E-03 2,699E-03 2,659E-03 5,287E-05|  ,417E-02|
          +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+----------+
   TOT VL| 480483,54  26734,00  12054,49  54984,61 158190,61  34108,39  57708,60  46128,79 106110,99  69922,83 57647454,|1046426,82|
   TOT DM| 3,502E+07 7,111E+05 5,452E+05 2,588E+06 6,673E+06 1,798E+06 2,649E+06 1,993E+06 3,327E+06 3,122E+06       32,| 5,843E+07|
   TOT DR| 7,288E-03 2,660E-03 4,523E-03 4,707E-03 4,218E-03 5,271E-03 4,590E-03 4,321E-03 3,136E-03 4,465E-03 5,543E-05|  ,558E-02|
====================================================================================================================================
WT UR VL | 344449,19   7068,10   7793,55  38691,75 118683,34  25424,84  47955,36  38479,54  47668,00  59079,71 35748630,| 735293,38|
   UR DR |   ,128      ,188      ,121      ,130      ,145      ,133      ,138      ,129      ,144      ,130     8,173E-04|  ,133E+00|
   RR VL |  59034,81   8111,63   1418,45   4327,55  17039,06   3594,78   3949,11   4760,17  10422,19  14454,87  7295894,| 127112,61|
   RR DR | 5,239E-02 2,811E-02 3,681E-02 3,324E-02 3,137E-02 3,600E-02 3,526E-02 3,096E-02 4,876E-02 4,270E-02 4,551E-04|  ,440E-01|
          +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+----------+
   TOT VL| 403484,00  15179,72   9212,00  43019,30 135722,40  29019,62  51904,48  43239,71  58090,18  73534,58 43044524,| 862405,99|
   TOT DM| 4,706E+08 1,555E+07 9,980E+06 5,164E+07 1,773E+08 3,515E+07 6,761E+07 5,108E+07 7,354E+07 8,281E+07      325,| 1,035E+09|
   TOT DR|   ,117      ,102      ,108      ,120      ,131      ,121      ,130      ,118      ,127      ,113     7,559E-04|  ,120E+00|
====================================================================================================================================
US UR VL |1352985,75  22558,53  32026,54 179934,60 474387,35  99470,42 204425,52 151824,12 197767,33 205044,33139086975,|2920424,50|
   UR DR | 3,698E-02 5,997E-02 3,201E-02 3,003E-02 3,881E-02 3,675E-02 3,524E-02 3,516E-02 3,675E-02 3,984E-02 2,458E-04|  ,369E-01|
   RR VL | 336349,07  32453,98   7054,08  43750,79  79826,52  19942,25  22044,69  23491,79  33008,00  58670,41 43404890,| 656591,57|
   RR DR | 1,726E-02 1,398E-02 1,174E-02 8,569E-03 1,122E-02 1,223E-02 1,137E-02 1,087E-02 1,901E-02 1,458E-02 1,408E-04|  ,150E-01|
          +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+----------+
   TOT VL|1689334,82  55012,50  39080,61 223685,39 554213,87 119412,68 226470,21 175315,91 230775,33 263714,74182491865,|3577016,07|
   TOT DM| 5,584E+08 1,807E+07 1,108E+07 5,778E+07 1,931E+08 3,900E+07 7,454E+07 5,593E+07 7,895E+07 9,024E+07      403,| 1,177E+09|
   TOT DR| 3,305E-02 3,284E-02 2,835E-02 2,583E-02 3,484E-02 3,266E-02 3,291E-02 3,190E-02 3,421E-02 3,422E-02 2,209E-04|  ,329E-01|
====================================================================================================================================
```

Table 1-14. The Values at Risk and Annual Damages Due to Earthquake in 2000,Valued in Millions of 1970$
(regional and national totals)

REGION	VALUE OF STRUCTURES (MILLION 1970 $) AT RISK TO DAMAGING EARTHQUAKES	AVERAGE LOSS (%)	AVERAGE PLUS ONE STANDARD DEVIATION LOSS (%)	AVERAGE LOSS (MILLION 1970 $)
NORTHEAST				
1970	466,087	.00575	.00820	26.8
1980	618,809	.00490	.00698	30.3
1990	832,403	.00472	.00674	39.3
2000	1,069,000	.00456	.00651	48.8
NORTH CENTRAL				
1970	269,341	.00698	.03310	18.8
1980	347,802	.00585	.02755	20.3
1990	466,327	.00583	.02886	27.2
2000	599,183	.00577	.02675	34.6
SOUTH				
1970	395,113	.00696	.02940	27.5
1980	545,819	.00591	.02495	32.3
1990	776,289	.00573	.02416	44.5
2000	1,046,427	.00558	.02346	58.4
WEST (including CA)				
1970	363,875	.16000	.30160	582.1
1980	484,683	.12600	.23698	611.1
1990	660,975	.12300	.23101	813.0
2000	862,406	.12000	.22504	1,035.0

Table 1-15. Annualized Losses to Structures by Census Region

NATIONAL YEAR	BILLION 1970 $ EXPOSED	BILLION 1970 $ AT RISK	MILLION 1970 $ LOSS	AVERAGE LOSS (%)	AVERAGE PLUS ONE STANDARD DEVIATION LOSS (%)
1970	2,064.5	1,494.2	655	.04380	.09043
1980	2,754.4	1.947,1	694	.03480	.07209
1990	3,779.8	2,736.0	924	.03380	.06890
2000	4,925.2	3,577.0	1,177	.03290	.06712

Table 1-16 . Annualized Losses to Structures Nationally

NATIONAL YEAR	VALUE AT RISK IN AREA MMI>6 BILLION 1970 $	POPULATION AT RISK IN AREA MMI≥6	BUILDING LOSS IN BILLION 1970 $	TOTAL VALUE AT RISK LOST (%)
SAN FRANCISCO SCENARIO				
1970	76.5	7,795,137	10.2	13.4
1980	113.3	9,252,058	13.7	12.1
1990	157.3	10,708,978	17.6	11.2
2000	208.4	12,165,899	20.8	10.9
NEW MADRID SCENARIO*				
1970	118 1	19,525,116	3.1	2.6
1980	165.5	21,683,916	3.9	2.3
1990	220.2	23,842,716	4.7	2.1
2000	282.0	26,001,515	5.8	2.0

*The numbers in the value at risk and population at risk columns could easily be doubled whereas the losses could be quadrupled if an average DAF equal to 4+ were used uniformly for the site amplification factor. The uncertainty of DAF in areas east of longitude 104° gives rise to uncertainty in this scenario

Table 1-17. Losses Due to the Recurrence of the New Madrid and San Francisco Earthquakes

The De Facto Value of a Lost Life and an Injury

Using techniques determined by Wiggins [1973], the de facto value of a human life in 1970 dollars ranges between $75,000 and $250,000 depending on the mode of calculation. The mean value is $150,000. Using the figures cited by the National Safety Council [1971] for 1970, 10,800,000 injuries cost $16 billion in wage loss, medical expense and insurance administration costs. An additional $4 billion was accounted for as time lost by workers. Thus, the average cost of an injury is $1,852.

Table 1-18 gives the dollar costs associated with life loss and injury from the predicted annualized damages for 1970, 1980, 1990 and 2000.

YEAR	LIFE LOSS	ALL INJURIES	ANNUAL LOSSES IN MILLIONS OF 1970$		
			DUE TO INJURIES AND DEATHS	DUE TO BUILDING LOSSES	DUE TO LIFE LOSS, INJURY, AND BUILDING LOSS
1970	273	11739	63	655	718
1980	279	11997	64	694	758
1990	341	14663	78	924	1002
2000	403	17329	93	1177	1270

Table 1-18. Total Annual Losses Including Life Loss and Injury Costs

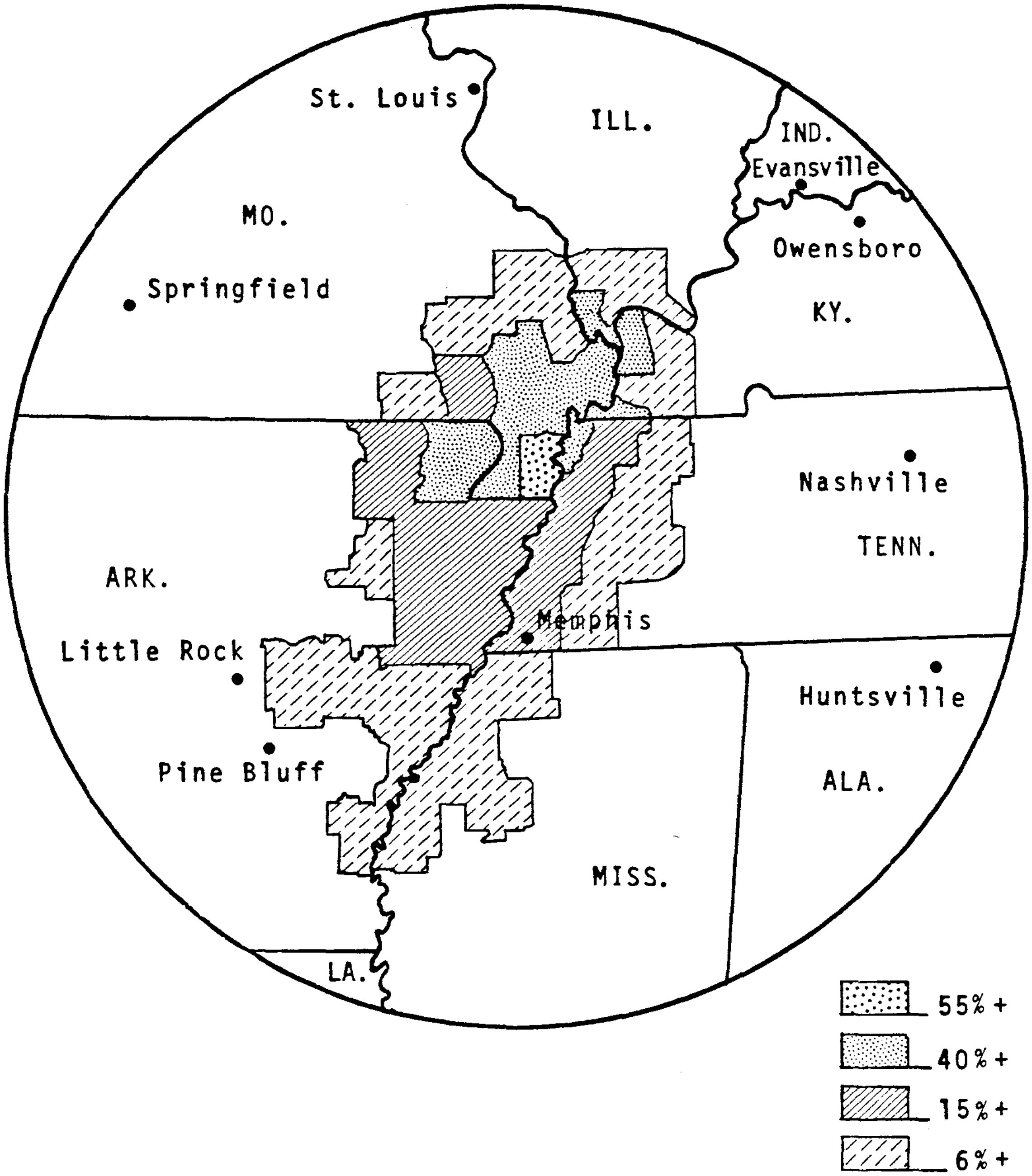


Figure 1-11. Percent Damage for Counties in the Epicentral Region of the New Madrid Scenario [1974]. A Higher DAF Assigned to the Surrounding Soil Could Double the Cross-Hatched Area and Increase Percentages by about 1.5 Times

Chapter Four

Effects of Mitigations on Earthquake Losses

The Types of Earthquake Mitigations Considered for the Adjustments

An indication of the effect various mitigations have on earthquake losses may be studied by simulating changes in the physical relationship of seismically active areas and the structures at risk. A list of potential mitigations has been constructed in Table 1-19 to present a perspective on the various types of mitigations possible. Although the study is not charged with the responsibility of investigating the effect of mitigating the "hazard" part of the hazard-exposure-vulnerability-risk situation, it is examined in order to demonstrate the simulator.

MITIGATION	APPLICATION TIME	REQUIREMENTS
(1) Warning System (WS)	PRE-DISASTER	Prediction Tools & Administrative Policies
(2) Earthquake Prevention (EP)		Earth Strain Relief
(3) Earthquake Insurance (EI)		Earthquake Loss Simulators
(4) Structural Protection (SP)		Building Codes, Standards of Practice & Enforcement
(5) Land Use Planning (LP)		Zoning and Subdivision Regulations
(6) Hazardous Building Rehabilitation (BR)		Favorable Taxation Laws Rehabilitation Monies and Legislation
(7) Disaster Relief (DR)	POST-DISASTER	Government Plans
(8) Reconstruction (RE)		Repair Money
(9) Loss Bearing or Inaction (LB)		Nothing

Table 1-19. A Perspective on Various Earthquake Mitigations

National Loss Reduction Due to Various Hypothesized Mitigations

(1) The first mitigation considered was limited to California, reflecting a policy which could be enacted at the state level. It involves a type of earthquake prevention wherein the potential strain energy is conserved. The maximum credible earthquake magnitude was lowered by one Richter magnitude unit. In order to conserve energy, however, the number of earthquakes below the new maximum credible, M, was increased.

The Magnitude-frequency-of-occurrence relationship is

$$\log N = A - bM \qquad (26)$$

where N is the number of earthquakes equal to or greater than Richter magnitude M to be expected each year, b is a constant empirically determined to to be 0.9 and A is one measure of the seismicity (see Chapter Two for the differentiation between a and A). The series of earthquakes in Denver which were allegedly triggered by water pumping were found to obey this relation rather closely. Using Richter's energy equation, $\log E = 11.8 + 1.5M$, and decreasing the maximum credible magnitude as stated above implies that, in order to conserve energy released, the seismicity, A, and thus, a, must be increased by 0.4. The number of earthquakes experienced is increased although the maximum credible magnitude is decreased. Arbitrarily selecting a value of $a > 2.8$ as a cutoff limit which potential mitigation measures could be applied to the nineteen counties affected [Figure 1-12], the following results are derived. These counties represent 64 percent of the population at risk.

YEAR	NO ADJUSTMENT* (% VALUE LOST/YR)	WITH ADJUSTMENT* (% VALUE LOST/YR)	(%) DIFFERENCE*
1970	.17	.24	+40
1980	.14	.21	+42
1990	.13	.19	+43
2000	.12	.17	+44

* California losses only. Values to two significant figures.

Figure 1-12. California Counties with a >2.8

The results are obvious in that this mitigation would cause more and not less damage. The damage caused by the more frequent earthquakes having magnitudes less than 7.5 (the maximum credible magnitude was lowered from 8.5 to 7.5) is more important than the less frequent, large earthquakes. Although the sudden loss impact of the large earthquakes would be more traumatizing than a number of smaller, less damaging earthquakes, no comparison of the relative impacts is made within the scope of this study.

(2) The second mitigation reflects a national policy involving seismicity reduction or control of the outcome from earthquake action. Specifically, in all national counties where the seismicity is equal to or greater than $a \geq 2.8$, the intensity, I, is reduced by one unit. One interpretation of this mitigation would include renovation of old structures and construction of all new structures so that they can withstand one greater MMI intensity level for the same damage level. Another is that a is reduced from 2.8 to 1.0 by some currently unknown means developed through research. Results follow.

YEAR	NO ADJUSTMENT* (% VALUE LOST/YR)	WITH ADJUSTMENT* (% VALUE LOST/YR)	(%) DIFFERENCE
1970	.031	.024	-24
1980	.028	.022	-24
1990	.026	.020	-24
2000	.025	.019	-24

*California losses only. Two significant figures only.

It is obvious that this mitigation could be very effective, however, the costs of achieving the results, which may be considerable, must be balanced against the loss savings.

(3) Three different code changes were considered:

CODE	SEISMICITY ZONE (a)	FOR 400 MAXIMUM CREDIBLE EVENT g-EQUIVALENT (%)	BUILDING QUALITY REQUIREMENT
(a)	$a < 2.77$	< 40	Q = 2
	$a \geq 2.77$	≥ 40	Q = 3
(b)	$a < 2.1$	< 20	Q = 2
	$2.1 \leq a \leq 2.73$	$20 \leq g \leq 40$	Q = 3
	$a > 2.73$	> 40	Q = 4
(c)	$a < 2.0$	< 18	Q = 2
	$2.0 \leq a \leq 2.5$	$18 \leq g \leq 32$	Q = 3
	$a > 2.5$	> 32	Q = 4

(This is an arbitrary requirement aimed at giving perspective to each of the other codes.)

Year	LOSS REDUCTION (%) AFTER 1976 IMPLEMENTATION		
	(a)	(b)	(c)
1970	0.0	0.0	0.0
1980	-1.3	-1.7	-2.9
1990	-3.2	-4.2	-7.3
2000	-4.9	-6.3	-10.8

The efficacy of the latter, more stringent code (c) can be deduced by examining the amount of the new value added after 1976 in the various zones. It is necessary to first compute the values added after 1976 contributed by appreciation of new structures, appreciation of existing structures, and the value of new construction. This is cited below.

	INCREASE IN VALUE (MILLIONS OF 1970$)			
YEAR	2.0 < a < 2.5 OUTSIDE CALIF. Q = 3	a > 2.5 CALIFORNIA Q = 4	a > 2.5 OUTSIDE CALIF. Q = 4	% OF NATIONAL VALUE AT RISK
1970	0	0	0	-
1980	32,410	38,100	10,880	5.03
1990	107,880	129,290	36,730	12.3
2000	197,130	235,450	66,600	14.0

Since the appreciation of existing construction is not affected by a building code, this contribution must be subtracted from the above totals and the savings computed. The following lists only the values of construction built after 1976 and the associated loss reduction computed at a zero discount rate.

YEAR	2.0 ≤ a ≤ 2.5 OUTSIDE CALIF. Q = 3 (MILLION 1970$)	a > 2.5 CALIFORNIA Q = 4 (MILLION 1970$)	a > 2.5 OUTSIDE CALIF. Q = 4 (MILLIONS 1970$)	SAVED TO DATE (MILLIONS 1970$)
1970	0	0	0	0
1980	2,240	3,640	990	60
1990	22,330	37,040	10,030	562
2000	68,010	112,430	30,300	1,655

This mitigation reduces property loss by about 0.8 percent over a 24-year period. If this saving were increased by a factor of 1.103, which includes life loss and injury (0.88 percent), an allowable construction cost increase can be computed assuming an average structure life of 60 years. The resulting balance between loss and construction cost increase would be 0.35 percent (0.88 x 24-years/60-years). Consequently, if the added damage reduction capacity cannot be provided for a total of 0.35 percent of construction cost, it cannot be justified without assigning a higher value to life loss and injury. This move would only be warranted if all hazards were treated in a balanced and equitable manner.

(4) A fourth mitigation involves an increased rate at which older buildings are replaced by new buildings. Replacement of the pre-1940 buildings for the nation (except California) and the pre-1933 buildings in California was increased to a 10 percent faster rate than the de facto level. The difference is then added to the post-1940 or 1933 building stock for every county with a ≥ 2.0. This adjustment was simulated to begin in 1976 and reflects a national policy.

YEAR	NO ADJUSTMENT (% VALUE LOST/YR)	WITH ADJUSTMENT (% VALUE LOST/YR)	(%) DIFFERENCE
1970	0.0438	0.0438	0.0
1980	0.0348	0.0338	-2.9
1990	0.0338	0.0320	-5.2
2000	0.0329	0.0305	-7.2

Decisions about the efficacy of this mitigation must be made by balancing the loss reduction with the extrinsic and intrinsic costs of phasing structures out earlier. Obviously, tax depreciation schedules, insurance rates, loan policies, etc., are all involved with the resolution of this question.

Loss Reductions for Scenarios

(1) The first scenario mitigation simulated the efficacy of possible warning systems. Once the warning was received, a strengthening of the existing structures and a revision of the building code for new structures would take place. Obviously the amount of strengthening that can be done is dependent

upon the time element available between warning and earthquake. However, the savings can be predicted for the recurrence of a San Francisco earthquake as a scenario. The general rationale assumed was that the longer the time period from warning to occurrence, the greater the possibility for reducing the "effective" MMI. This adjustment reflects a state policy.

INTENSITY REDUCTION (MMI)	CALIFORNIA DAMAGE (% AT RISK)	DIFFERENCE (%)
0	5.21	0
0.25	4.19	-20
0.50	3.35	-36
0.75	2.67	-49
1.00	2.12	-59

This warning adjustment affects all of the structures in California. Listed below are the savings possible in 2000:

REDUCED EARTHQUAKE INTENSITY (MMI)	AMOUNT SAVED (BILLION 1970 $)
0.25	5.5
0.50	10.0
0.75	13.7
1.00	16.7
NON-ADJUSTED	DAMAGE
0	28.1

Value of Structures in State at risk to earthquake = 539 Billion 1970$

Calculated below is the approximate value of construction in the counties affected by the following intensity ranges:

VALUE IN 2000 AFFECTED BY A RECURRENCE
OF A 1906 SAN FRANCISCO TYPE EARTHQUAKE

MMI	VALUE AT RISK (BILLION 1970 $)
MMI $\geq$ 9	103.0
9 > MMI $\geq$ 8	38.9
8 > MMI $\geq$ 7	45.3
7 > MMI $\geq$ 6	23.2
10 > MMI $\geq$ 6	210.4

Comparing the above listings it can be seen that a 25 percent reduction in intensity is worth 2.6 percent investment of all values at risk at a zero discount rate. A one intensity reduction factor is worth 7.9 percent investment for this one-time event.

From the damage algorithm cited earlier in Figures 1-1 and 1-2, the average amount of damage occurring from MMI 6 to MMI 8 is about 3.6 percent, (given the age distribution of structures in California). Thus, $5.1 billion is lost in areas with MMI $\geq$ 8.0 (18.2% of the total damage). Treating only the area where MMI > 8.0, the following investments in a warning system, stronger codes and strengthening results in an equal return on the investment.

REDUCED EARTHQUAKE INTENSITY (MMI)	MILLION 1970 $ VALUE AT RISK (MMI >1980)	SAVINGS MILLION 1970 $	INVESTMENT (%)
0.25	141,900	4.5	3.2
0.50	141,900	8.2	5.8
0.75	141,900	11.2	7.9
1.00	141,900	13.7	9.7

(2) The next mitigation relating to the San Francisco scenario limits population growth (beginning in 1970) in counties which experience MMI $\geq$ 9.0 resulting from the recurrence of the 1906 San Francisco earthquake. This adjustment reflects a state policy.

YEAR	BEFORE ADJUSTMENT (BILLION 1970 $)	AFTER ADJUSTMENT (BILLION 1970 $)	DIFFERENCE (%)
1970	11.9	11.9	0.0
1980	15.9	13.9	-12.8
1990	21.6	16.8	-22.0
2000	28.1	21.4	-24.0

YEAR	CHANGE IN POPULATION	CHANGE IN THE VALUE OF STRUCTURES MILLION 1970 $	CHANGE IN AMOUNT OF DAMAGE MILLION 1970 $	% OF PREVIOUS TOTAL
1970	0	0	0	0
1980	-738,938	-9,101.2	-1,760	-12.8
1990	-1,477,877	-21,819.56	-3,864	-22.0
2000	-2,216,813	-38,155.1	-5,001	-24.0

By 2000 this adjustment would cause a reduction of 38 billion dollars in building value and a 2.2 million person drop in the anticipated population growth. It would eventually yield a 24 percent decline in damage, life loss and injury.

It is clear from the discussion above that no real price tag can be applied to this policy because the counties experiencing intensities lower than 9 may grow faster than predicted, thus, compensating for the no-growth in the affected areas and cause the differences to be smaller. Also, values may not all increase or decrease in the same way. The property values in the affected areas may decline leading to problems of a greater magnitude than earthquake. Obviously, mitigations and their application are <u>not</u> solely a technical process.

Chapter Five

Conclusions

1. A sudden loss such as a recurrence of the San Francisco earthquake could cause 20 times the annualized national loss. A sudden loss such as a recurrence of the New Madrid earthquake could also cause from 6 to 20 fold increase in annual national loss.

2. Annualized losses in constant 1970$ are $655 million (1970), $694 million (1980), $924 million (1990), and $1.77 billion (2000).

3. The construction value at risk in the United States in constant 1970$ is $1.494 trillion (1970), $1.997 trillion (1980), $2.736 trillion (1990), and $3.577 trillion (2000). These values represent about 72.5 percent of the total construction value in the United States implying that 27.5 percent is unaffected by earthquake.

4. The New Madrid scenario affects 13 states and $423,850 million (1970) in construction assets and does .722 percent damage to those affected construction assets, whereas the San Francisco scenario affects principally one state with $196,477 million (1970) in construction assets and does 5.2 percent damage to the affected construction assets.

5. If the epicenter of the New Madrid scenario were shifted to the north by 100 miles, the damage could easily be trebled.

6. On an annual basis, the western region of the country is expected to experience 89 percent of the damage even though it contains only 24 percent of the construction value exposed to damaging earthquakes. It is, therefore, 26 times as prone to seismically-induced damage as the rest of the nation.

7. The current de facto value of a death due to accident is $150,000 (1970) and the cost of injury is $1,852 (1970). Thus, deaths and injuries raise earthquake losses by about 10.3 percent in addition to construction losses.

Preceding page blank

REFERENCES

Allen, C.R., P. St. Amand, C.F. Richter and J.M. Nordquist. "Relationship Between Seismicity and Geologic Structure in the Southern California Region." Bulletin Seismological Society of American, 1965.

Barnes, S.B. and C. Pinkham. Damage Probability Matrix. Prepared for M.I.T., Cambridge, Massachusetts, 1972.

Barosh, P.J. "Use of Seismic Intensity Data to Predict the Effects of Earthquakes and Underground Nuclear Explosions in Various Geologic Settings." Geological Survey Bulletin 1279, 1969.

Culver, C.B., H.S. Lew, G.C. Hart and C.W. Pinkham. Natural Hazards Evaluation of Existing Buildings. Building Science Series 61, U.S. Department of Commerce, National Bureau of Standards, 1975.

Environmental Science Services Administration. Studies in Seismicity and Earthquake Damage Statistics. Prepared for the Department of Housing and Urban Development, 1969.

Eppley, R.A. Earthquake History of the United States, Parts 1 and 2. U.S. Department of Commerce, Coast and Geodectic Survey, 1966.

Friedman, D.C. Insurance and the National Hazards. Presented at the 9th ASTIN Colloquium, International Congress of Actuaries. Randers, Denmark, 1970.

Gutenberg, B. and C. Richter. "Earthquake Magnitude, Intensity, Energy and Acceleration." Bulletin of the Seismological Society of America. 46:105-145, 1956.

Hirschberg, J.G., Peter Gordon and W.J. Petak. "Natural Hazards: Socioeconomic Impact Assessment Model." Prepared under NSF Grants #ERP-75-09998 and #AEN-74-23993. J.H. Wiggins Company: Redondo Beach, California, 1978.

McClure, Frank E. Performance of Single Family Dwellings in the San Fernando Earthquake of February 9, 1971. Prepared for the Department of Housing and Urban Development and National Oceanic and Atmospheric Administration, 1973.

National Safety Council. Accident Facts (1970). Chicago, Illinois, 1971.

Nuttli, O.W. "The Mississippi Valley Earthquakes of 1811 and 1812: Intensities, Ground Motion and Magnitudes." Bulletin of the Seismological Society of America, 1973.

Steinbrugge, Carl et al. "San Fernando Earthquake, February 9, 1971." The Pacific Fire Rating Bureau. Bulletin of the Seismological Society of America, 1971.

U.S. Department of Commerce. Office of Emergency Preparedness, National Oceanic and Atmospheric Administration. A Study of Earthquake Losses in the San Francisco Bay Area. Washington, D.C.: Government Printing Office, 1972.

Preceding page blank

U.S. Department of Commerce. National Oceanic and Atmospheric Administration. "World Earthquakes, 1961-1972." NOAA.

U.S. Department of the Interior. USGS. U.S. National Atlas, Geology Map. Compiled by Douglas M. Kinney, 1966.

Whitman, Robert V., S-T Hange and J.W. Reed. Damage Statistics for High-Rise Buildings in the Vicinity of the San Fernando Earthquake. School of Engineering, MIT, Cambridge, Massachusetts, 1973.

Wiggins, J.H. "Balanced Risk: An Approach to Reconciling Man's Need with His Environment." First International System Safety Society Symposium. Denver, Colorado, July, 1973.

Wiggins, J.H. "Earthquake Risk Analysis of the West Wing, California State Capitol Building." Bulletin of the Association of Engineering Geologists, Volume XI, No. 2. pp. 147-159, Spring 1974.

Wiggins, J.H. The Effects of Soft Surficial Layering on Earthquake Intensity. Civil Engineering Studies, Structural Research Series, No. 216. University of Illinois, 1961.

Wiggins, J.H. "Effects of Site Conditions on Earthquake Intensity." Journal of the Structural Division, ASCE, 1964.

SECTION II

LANDSLIDE

Chapter One

Description of the Hazard

Landslides are not uncommon nor do they represent fortuitous events. They occur in diverse environments and can be found scattered throughout the United States. Areas affected by landslides may range in size from several square feet up to several square miles.

The term "landslide" denotes the downward and outward movement of slope-forming materials reacting to the force of gravity. The slide materials may be composed of natural rock, soil, artificial fill or combinations of these materials [Varnes, 1958]. Landslides vary both in type and movement rate. Terminology used to define particular landslide types generally refers to landforms as well as the process responsible for the landform. The word "landslide" is a very generalized term and may encompass such terms as: rockfall, rockslide, block glide, debris slide, earth-flow, mudflow, slump and rotation slide - to name a few [AGI, 1972]. Movement of landslide material may be rapid or slow, ranging in velocities of tens of miles per hour to a few inches per year.

Landslides generally occur by any one of three principal types: falls, slides, and flows or by their combination [Varnes, 1958]. Falls refer to rock or soil masses that "free fall" or tumble down the slope by leaps and bounds, largely under the direct force of gravity. Slides refer to earth material movements that result from shear failure along one or several surfaces which are either visible or may be reasonably inferred [Varnes, 1958]. Flows resemble viscous fluids in both velocity and displacement; however, they may be dry as well as wet in nature. Normally, flows are also characterized by little to no shear resistance along the surface of separation.

According to Terzaghi, slides are caused by both internal and external factors. Internal causes are those which lead to sliding without any change in surface conditions. They result primarily from an increase in pore-water pressure and a concurrent decrease in cohesion [Terzaghi, 1950]. When the shear stress within a given rock or soil exceeds the shear resistance, failure will ensue. It is this apparent disequilibrium within the rock and soil, together with gravitation forces, that permits this material to move down slope. Externally related causes may be: oversteepening of the slopes; additions of weight from materials placed along the upper portions of slopes; added weight from increased moisture content; and seismic- or man-induced vibrations. Causes related to the landslide phenomena can be quite complex, diverse and involve various interrelated natural processes. Although usually considered as a geologic process, landslides can also be dependent upon elements of the physical, chemical, and biological environment. However, often the inter-relationships between these various elements are not fully understood.

Chapter Two

Landslide Occurrence (Hazard Model)

Development of Intensity Probability

Numerous publications and studies have been prepared on the subject of landslides and/or slope failures. Assorted articles, papers, and discussions are scattered throughout the literary references, both in the United States and abroad. Unfortunately, most of these publications cite specific landslide events, referring only to a certain type of failure mechanism or discussing a particular type of remedial correction method. While these publications are both informative and functional, they fail to adequately consider the overall impact of the landslide hazard as it exists on a larger regional basis. Those studies that have attempted to define landslides on a regional or nationwide basis are few in number.

Two of the earlier studies completed in the 1950's involved a landslide severity map by Baker and Chieruzzi [1958] and a rather comprehensive compendium prepared by the Highway Research Board [Eckel, 1958]. Both studies relied heavily on questionnaires sent to various public and private agencies. Agencies responding to the questionnaire chiefly included state highway departments and railroad companies. Using these questionnaires, Baker and Chieruzzi [1958] prepared a map of the United States showing areas of major, medium, minor and nonexistent landslide intensity based upon physiographic provinces. The basic concept of the map is excellent; however, the diminutive size of the map and the limited breadth of the coverage by the questionnaires restrict its practical use.

The Highway Research Board study has become a "classic" publication relative to landslide description and classification. Although this publication does not present a landslide intensity map, it does list several landslide prone formations by regional distribution. This listing was extremely valuable to our own study efforts.

In more recent years, the U.S. Geological Survey (USGS) has been involved in a nationwide study of landslides and, in 1976 [i.e., Radbruch-Hall and others, 1976] published a preliminary landslide overview map (scale 1:7,500,000) of the conterminous United States. Although this map was not available during the initial phase of our study (i.e., November 1975 to February 1976), said map was used extensively during the recent updating of our earlier work. All three maps (original, USGS, and combined) are presented for analysis purposes.

At the state level, California by far has the most active landslide program. Several federal and state funded landslide studies have been prepared by both the U. S. Geological Survey [Nilsen and Turner, 1975; Campbell, 1975] and the California Division of Mines and Geology [Alfors and others, 1973; Cleveland, 1971]. Most states, however, do not have active landslide programs currently underway.

Additional studies prepared by private individuals or organizations are also available. These studies are, however, generally localized such as the Leighton report [1966] which shows landslide locations in a portion of southern California along the midland and coast from southern Ventura County to San Diego.

The landslide intensity probability scale and associated hazard map no. 1 developed for this report is based on the compilation of information obtained from numerous county, state, and national government agencies as well as selected individual data sources scattered throughout the country. This information is in the form of comments, personal opinions, published and unpublished documents. The chief source of information was provided by the State Geologist of each respective state. This material was supplemented by numerous literary references as well as data collected from selected highway departments, county agencies, and universities. All the information collected was subsequently reviewed, assimilated, and transformed into a landslide Probability Map of the United States, at a scale of 1:5,000,000.

After receipt of the 1976 USGS map and conversation with personnel who prepared the map, our initial landslide map was modified (updated) to encompass the USGS data. Basically, the addition of the USGS data [Map MF-77] to map no. 1 resulted in an overall increase in "high" and "moderate" landslide potential areas. Those areas of greatest modification included portions of the Plains, Mississippi Valley, and Appalachian states. The method used to develop the final map involved a direct comparison of the USGS map to the original map, both at the scale of 1:5,000,000. Areas of high occurrence and generally areas of high susceptibility on the USGS map were placed on map no. 1. In general, areas where the two maps differed, the highest rating was normally used (unless data or lack of data supported another rating).

It is our opinion, based on our own investigations as well as comments from various state geologists and USGS personnel (e.g., D. Radbruch-Hall, D. Varnes, and I. Lucchitta), that far more work is still required regarding landslide potential. Although both our original map and the USGS map are based on available data, these available data in many areas leaves much to be desired or does not exist. However, in those areas where the maps may differ, it is our opinion, that it would be very difficult to determine which map is correct (if either) based on available data, or perhaps more appropriately, the lack of available data.

Several factors may contribute to or influence landsliding. However, many of these factors do not have overall definite patterns to make them usuable as mappable entities. Therefore, for purposes of this study, only three principal conditions have been considered to define potential landslide areas. These factors include: topography, bedrock, and precipitation. Working maps for each of the three factors were simultaneously developed and following completion, were integrated to form the resulting Landslide Potential Maps.

Topography

Topography is a general term used to describe the actual physical shape and configuration of the earth's surface. Topographic relief refers to the vertical distance in elevation (relative to sea level) between hill tops or mountain summits and lowlands or valleys. Areas containing large elevation variations have high relief; likewise, minor elevation differences suggest areas of low relief [AGI, 1972]. Topographic relief is important because it regulates stream erosion and other energy sources which, in turn, influence slope angle or gradient.

Basically, the steeper a slope the more gravity can play a role in a landslide. The steeper, often cliff-like, slopes are susceptible to over-steepening and undercutting by stream erosion and, therefore, frequently are subject to landsliding.

A topographic relief working map (scale 1:5,000,000) was developed and used to define areas of steep, moderate, and low relief on a nationwide basis. Topographic relief designations presented herein were chiefly based on a surface landform map prepared by Raisz [1957] and to a minor extent on a map prepared by Hammond [1964]. The Raisz map was used to locate areas of hilly or mountainous terrain. The Hammond map was used to locate areas where the percentage of gentle sloping terrain (slope areas of 8% or flatter), were at a minimum (usually gently sloping areas consisting of less than 50% of the total area) and where relief was in excess of 500± feet. Together, both maps were used to establish arbitrary topographic relief designations (i.e., steep, moderate, and low), that were used to develop our regional relief working map. This method or approach required a great deal of interpretation and, therefore, is subjective. Although this method may not necessarily represent the best method for determining the effects of topography (relative to landslide potential), it does, however, represent perhaps the most reasonable approach based on available data and base maps.

Perhaps another method in which to use topography as it relates to landslide potential, would be to develop a nationwide slope map. No such map is currently available at the desired map scale. If such a map were to be developed, it could include the following criteria (Table 2-1).

TOPOGRAPHIC RELIEF RATINGS	DESCRIPTION
STEEP	MODERATELY STEEP TO STEEP HILLS AND MOUNTAINS (ESTIMATED RELIEF GREATER THAN 2000'± PER 1 MILE)
MODERATE	LOW TO MODERATELY STEEP HILLS (ESTIMATED RELIEF 500'± TO 2000'± PER 1 MILE)
LOW	LOW HILLS AND FLAT PLAINS (ESTIMATED RELIEF LESS THAN 500'± PER 1 MILE)

Table 2-1. Topographic Descriptions

Bedrock (or Soil) Type

The nature of the bedrock material represents a primary factor controlling the distribution of landslides. Landslide susceptibility as it may relate to rock type is a function of: (1) inherent bedrock properties and (2) bedrock structure and geometry. Some of the more common, inherent rock properties include: mineralogic composition, degree of cementation/induration and grain size. It is the various inherent properties that dictate rock strength. As the rock strength decreases or is influenced by natural or man-made changes in energy conditions, landsliding becomes more prominent [Panel on Methodology for Delineating Mudslide Hazard Areas, 1974]. As stated by Cleveland [1971], the strength of rocks, measured in terms of their resistance to weathering, is a basic geologic factor in the landslide process. Rock strength in this sense can be defined in a general way as the sum of the properties of a rock that governs its resistance to erosion by landsliding [Cleveland, 1971].

Bedrock structural and geometric features that may contribute to landsliding include the relationships between: bedding, foliation, cleavage orientations and slope direction. The amount, spacing, and type of faulting and jointing can also have a direct bearing on the overall stability of a given slope.

Landslides can occur in any type of rock material. However, certain bedrock formations or rock types appear to be more susceptible than others to landslide activity. It is these known landslide-prone rock units that have been so designated herein as being "adverse". Rock materials generally considered to be "adverse" are listed in Table 2-2.

The location and distribution of each known "adverse" rock unit was placed on a bedrock working map (scale 1:5,000,000). Whenever possible, the location and lateral extent of each known "adverse" rock unit was determined using the geologic maps of North America [USGS, 1965, 1974]. However, in most instances, the USGS map (scale 1:5,000,000) proved inadequate because many of the smaller bedrock formations are lineated on the maps. State geologic maps were, therefore required to supplement the national map. A listing of the state maps used in the compilation of the bedrock map are provided in the references (See also Appendix A).

1. Many of the younger (Mesozoic and Cenozoic) igneous (granitic) and metamorphic rocks found in the western United States have undergone intense fracturing and subsequent weathering. Therefore, these younger rocks generally have a greater propensity toward landsliding then many of the older, less fractured igneous rocks commonly found in the eastern portion of the country (i.e. New England States).
2. Mesozoic and Cenozoic sedimentary rocks generally tend to contain large amounts of clay, especially montmorillonite. The presence of the clay material has a definite deleterious influence on slope stability.
3. Many of the Cenozoic volcanic rocks in the western portion of the country appear to be landslide-prone in that they contain zones of montmorillonite (altered volcanic ash), in addition to being highly fractured and in some cases weathered.
4. Serpentines consist essentially of secondary minerals normally derived by alteration of magnesium rich silicate minerals. These materials, owing to inherently weak properties, are frequently susceptible to landsliding.
5. Landslides also occur in rock types other than those listed above. Therefore, all other known landslide-prone rock units either referred to in the literature or discussed by previously mentioned data sources were also considered as being "adverse", for purposes of this study.

Table 2-2. Adverse Characteristics of Rock Materials

Precipitation

Precipitation largely controls the distribution and occurrence of landslide. Precipitation has a pronounced effect on the morphology of the landscape. Slope development is influenced by precipitation in two ways: (1) water which runs off the slope via established drainage courses and (2) water that is absorbed by the slope soil and bedrock materials. Runoff waters, if in sufficient velocity and volume, may have the capacity to erode or undermine slope surfaces thereby removing slope support and causing landslide activity to occur.

Precipitation that infiltrates below the slope surface into the underlying materials may alter or change their strength by: (1) generating an increase in pore water pressure, (2) increasing the bulk density, (3) facilitating the partial removal of cementing agents and/or (4) lubricating potential zones of inherent weakness within either the soil or rock material.

The fact that high intensity rainfall leads to increasing landslide activity is amply documented in California [Nilsen and Turner, 1975]; Tennessee [Miller and Wiethe, 1975]; and Pennsylvania [Briggs and others, 1975] to name a few. The

USGS [Nilsen and Turner, 1975] indicates that in Contra Costa County, California, landslides occur during and immediately after storm periods in which more than seven (7) inches of rain have fallen, especially if the ground is already wet from previous storms. According to the Allegheny County, Pennsylvania Planning Department [W. R. Adams, Jr., personal communication, see Appendix B], heavy rains, chiefly from hurricanes, frequently cause increased landslide activity. This may, therefore suggest that intense storms and in some cases storms of even short duration can produce extensive landslide damage anywhere in the country.

It can be noted from Appendix B for example, that the intense rains of Agnes occurring in June of 1972 caused 52 slides averaging $27,477 in cost. Subsequent monthly averages were 15 in number for an average cost of $4,751 each. Storms increase both frequency and average damage per slide.

Rainfall, as defined on the landslide intensity map, is treated in terms of mean annual rainfall averages. Yearly rainfall rates have been divided into three basic categories: high, moderate, and low. An attempt was made to assign storm frequencies to each designated category. The following estimated rainfall categories as well as storm frequencies represent interpretative values (Table 2-3).

RAINFALL RATING (INCHES PER YEAR)	ESTIMATED NUMBER OF STORMS PER 10 YEARS
HIGH (GREATER THAN 32")	10
MODERATE (8"-32")	1-4 (or 2.5)
LOW (LESS THAN 8")	1

Table 2-3. Storm Frequency Estimates Related to Average Annual Rainfall

Generally, the regions with higher rainfall averages will also have a higher number of storms over a given interval of time. As previously mentioned, landslides are commonly associated with storm-years. Therefore, based on this premise, those areas receiving larger amounts of rain and consequently more storms will generally have more landslides than those areas receiving less rainfall and storms, providing all other factors (bedrock and topography) remain constant.

Derivation of Landslide Intensity Maps

Several assumptions were made during the compilation of the landslide intensity map. The following premises guided the map categorzation:

1. It has been assumed that adverse formations that have been associated with landslide activity in times past will continue to have a high potential for landslide activity in the future, providing all factors (topographic relief and precipitation) remain constant.
2. A given adverse formation may change lithologically, both vertically as well as laterally. Therefore, in one area the formation may be characteristically a weak shale, whereas a few miles away it may be a resistant sandstone. These differences in rock material could consequently influence slope stability. However, owing to the map size and scale, it was not possible to differentiate lithologic variations within a given adverse formation. Therefore, if a formation was considered to be adverse in one area, all other locations containing the same formation were also considered to be adverse.
3. Although a given landslide potential rating was assigned to an area, local portions of that area may have ratings both higher and/or lower than the rating shown. Some of the more common local geographical areas that could have erroneous rating include the following:
    a. As mentioned earlier, the landslide intensity map is based chiefly on known landslide-prone bedrock <u>formations</u>. The location and extent of these "adverse" formations were determined using published geologic maps. Unfortunately, not all adverse formations appear on geologic maps, even though these formations may be exposed and cause landslides along steep river canyons and gorges. Often overlain or hidden by more resistant rock units, the adverse formations may not be delineated on geologic maps and therefore may not appear on the landslide intensity map.
    b. Many of the states (i.e., North Dakota, Iowa, Illinois, Kansas, etc.) are of relatively low relief and thus have been assigned a low landslide severity rating. However, this is not to suggest that landslides do not occur in those states. Landslides are frequently associated with many of the steeper river banks and bluffs commonly found along the larger river systems (i.e., Mississippi, Missouri, Snake, Columbia, Salmon and Ohio Rivers)

> and their major tributaries. These bluffs incised valleys often tens of meters high tend to break up the comparative monotony of the plains above. "Because of the common desire for a home with a view these steeper slopes have proved to be desirable as building sites" [Cooke and Doornkamp, 1974]. An attempt has been made to delineate landslide potential along many of the larger river systems on the landslide intensity map. However, owing to constraints of map size and scale, many of the potentially moderate and high landslide areas along many of these drainage courses may not appear on the accompanying map.

Recognizing the above limitations and constraints the following maps have been developed which, if overlain one by the other, would provide the landslide intensity map referred to above. Figures 2-1 (map no. 1) and 2-2 (map no. 2 illustrate those areas underlain by varying amounts of adverse formations and topographic relief. The ratings are judgmental and interpretive from the author's viewpoint. Figure 2-3 is the USGS map MF-771 from which map no. 2 gathered additional data.

In order to bring the two parameters, formation type and topographic relief, together with rainfall average, the latter parameter was mapped (Figure 2-4). One of the main reasons for including average annual rainfall as a parameter affecting landslide intensity was that the USGS used this parameter for preparation of Figure 2-3. They also included the divisions: greater than 32 inches; 8 - 32 inches; and less than 8 inches. For consistency sake, we used the same parameter and rainfall divisions. However, one could be somewhat more scientific or physically correct by using the average maximum rainfall occurring within a 24 hour period (Figure 2-5), which indicates a measure of storm severity, in combination with frequency of occurrence by geographic region. These <u>two</u> parameters of precipitation could be used together with Figures 2-1 and 2-3 to provide a storm potential of greater accuracy than that assumed in Table 2-3.

One could produce even more accuracy by using Figure 3-1 as the rainfall forcing function for landslides as well as that for the expansive soil hazard. Since considerable research would need to be done on developing a proper forcing function, the USGS procedure outlined above was applied to this first approximation of hazard delineation.

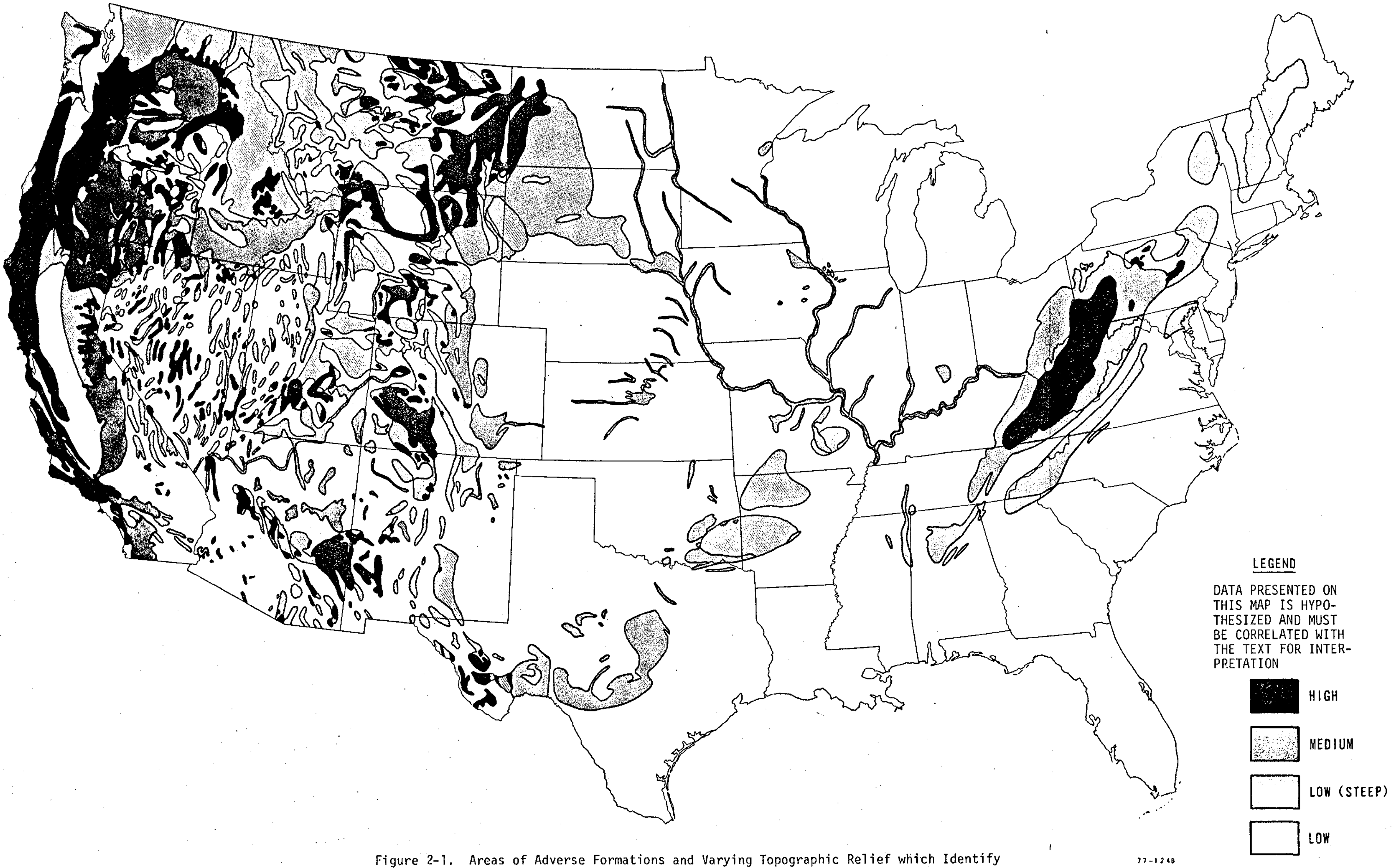


Figure 2-1. Areas of Adverse Formations and Varying Topographic Relief which Identify Intensity Categories for Landslide Potential

77-1240

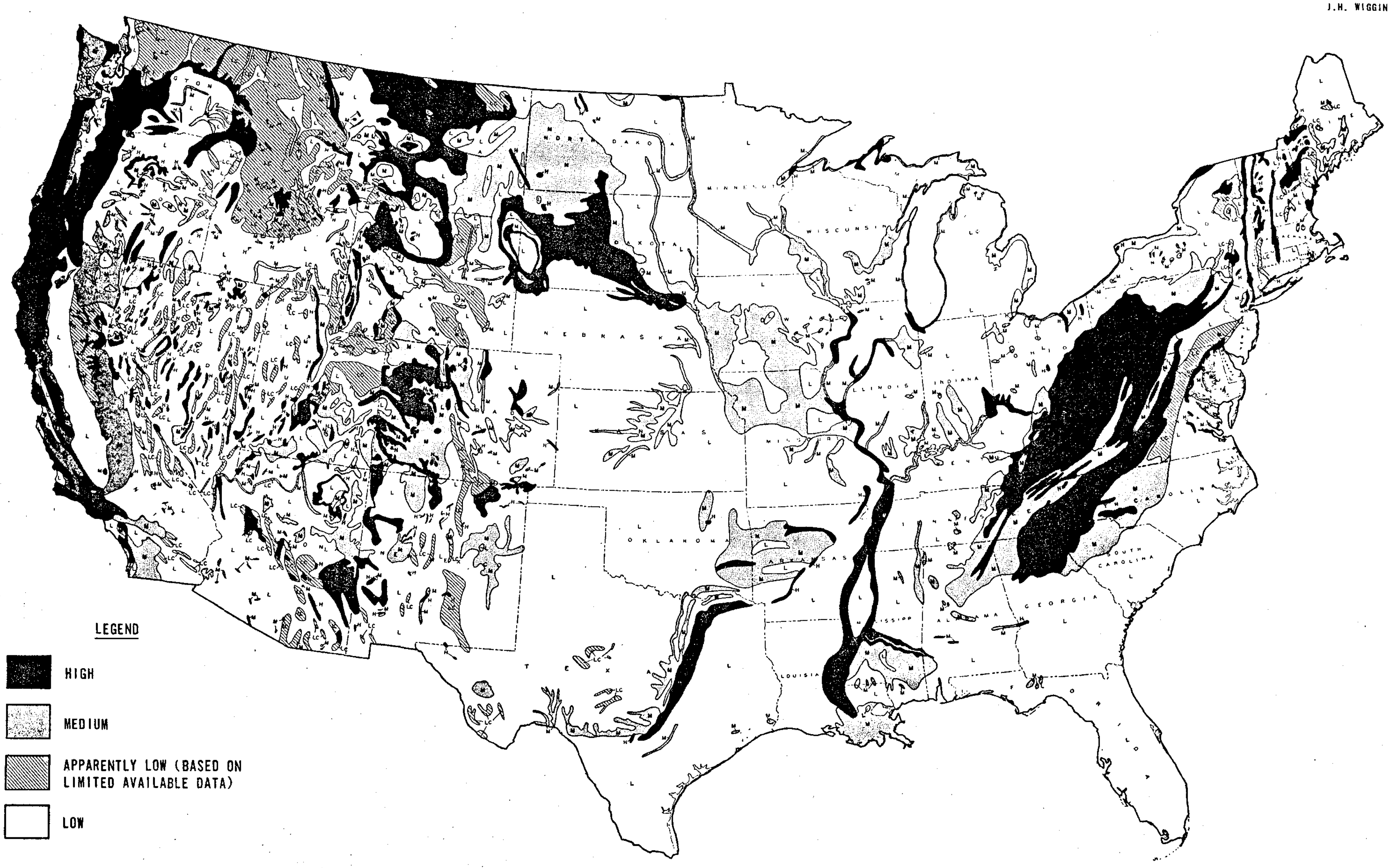


Figure 2-2. Map No. 1 Modified by Incorporating USGS Mapped Information (MF-771). This is Called Out as Map 770.2

78-1246

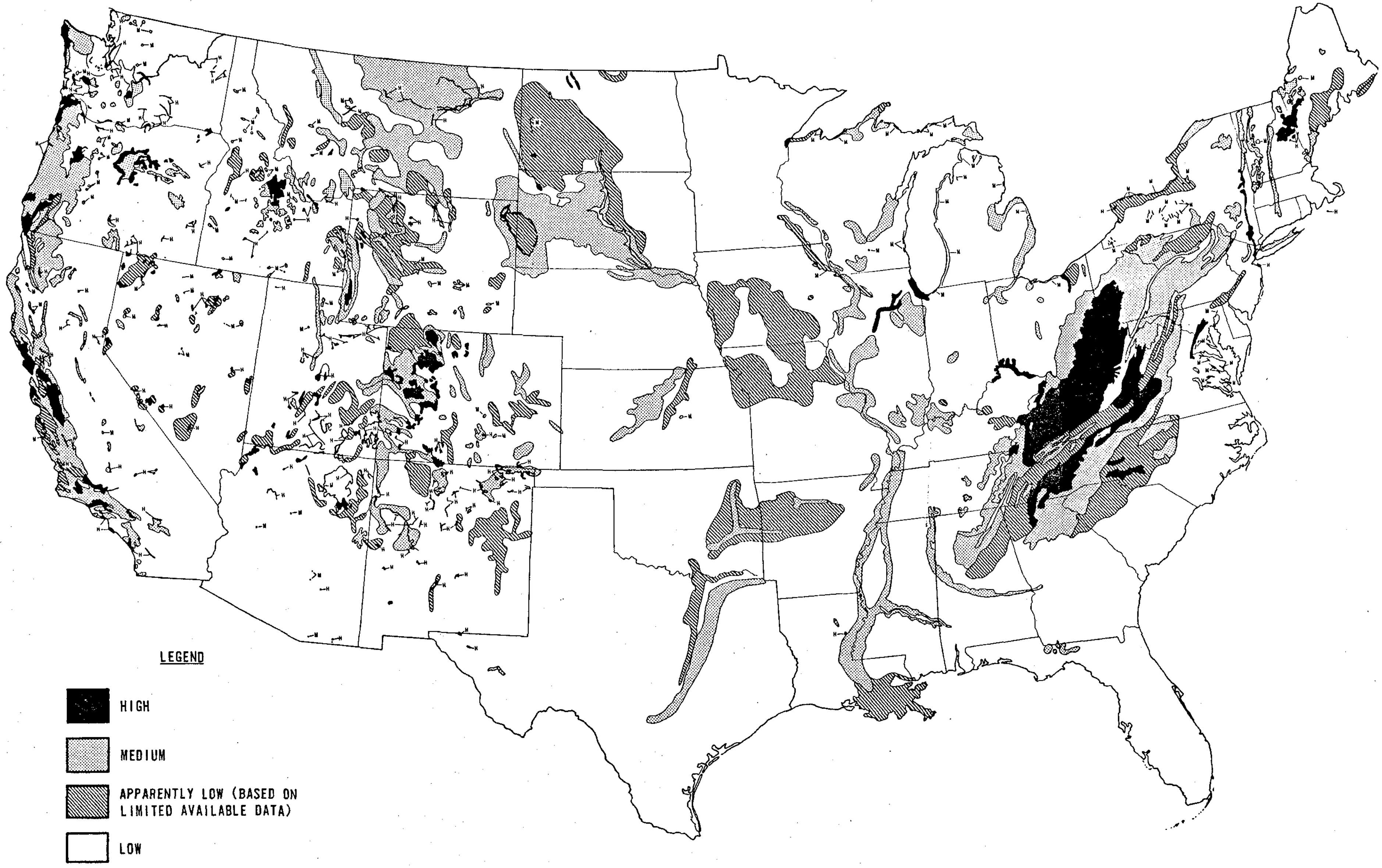


Figure 2-3. Rodbruch-Hall and Others - Miscellaneous Field Studies Map MF-771
"Landslide Overview, Conterminous United States"

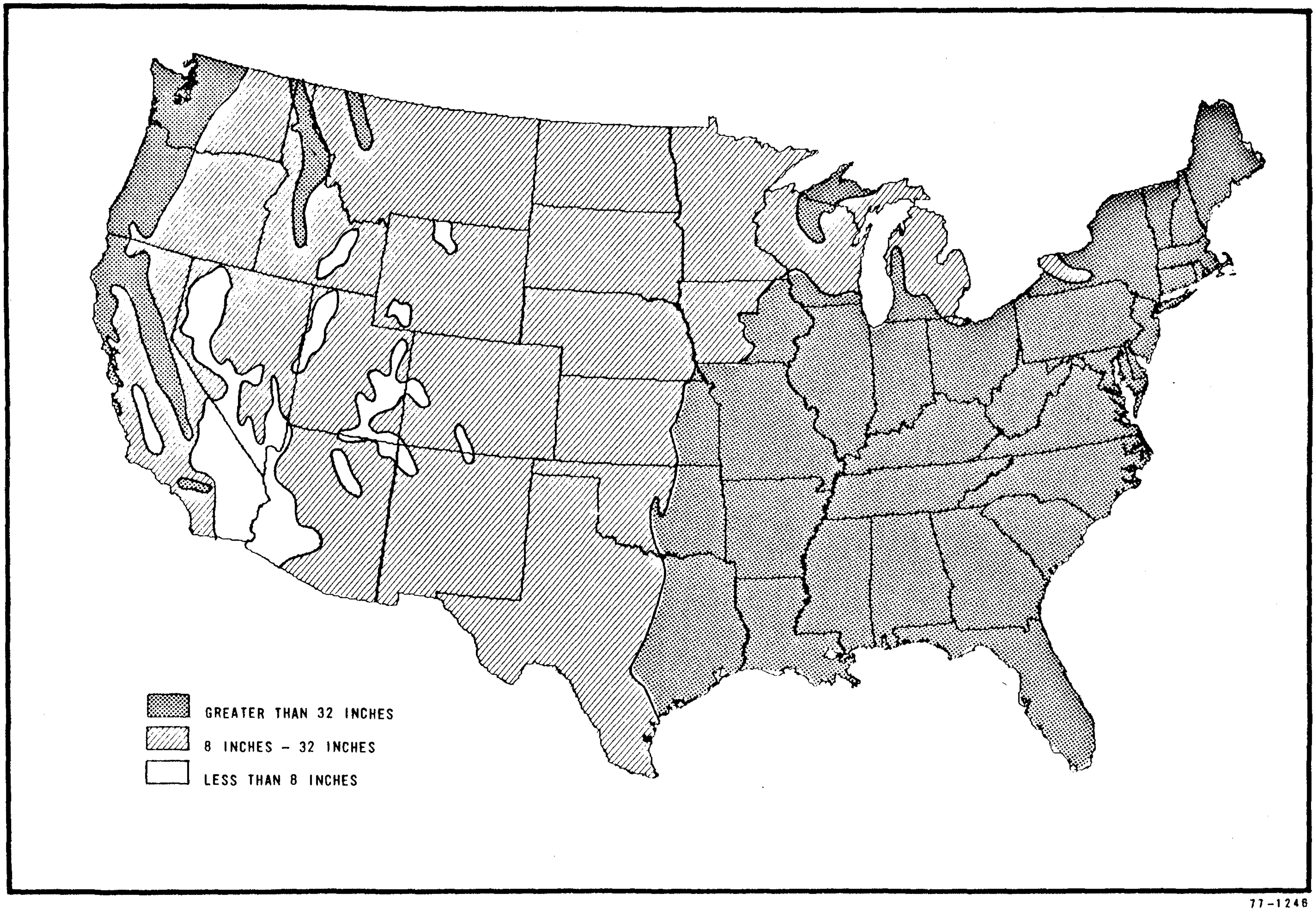


Figure 2-4. Average Annual Rainfall for the United States

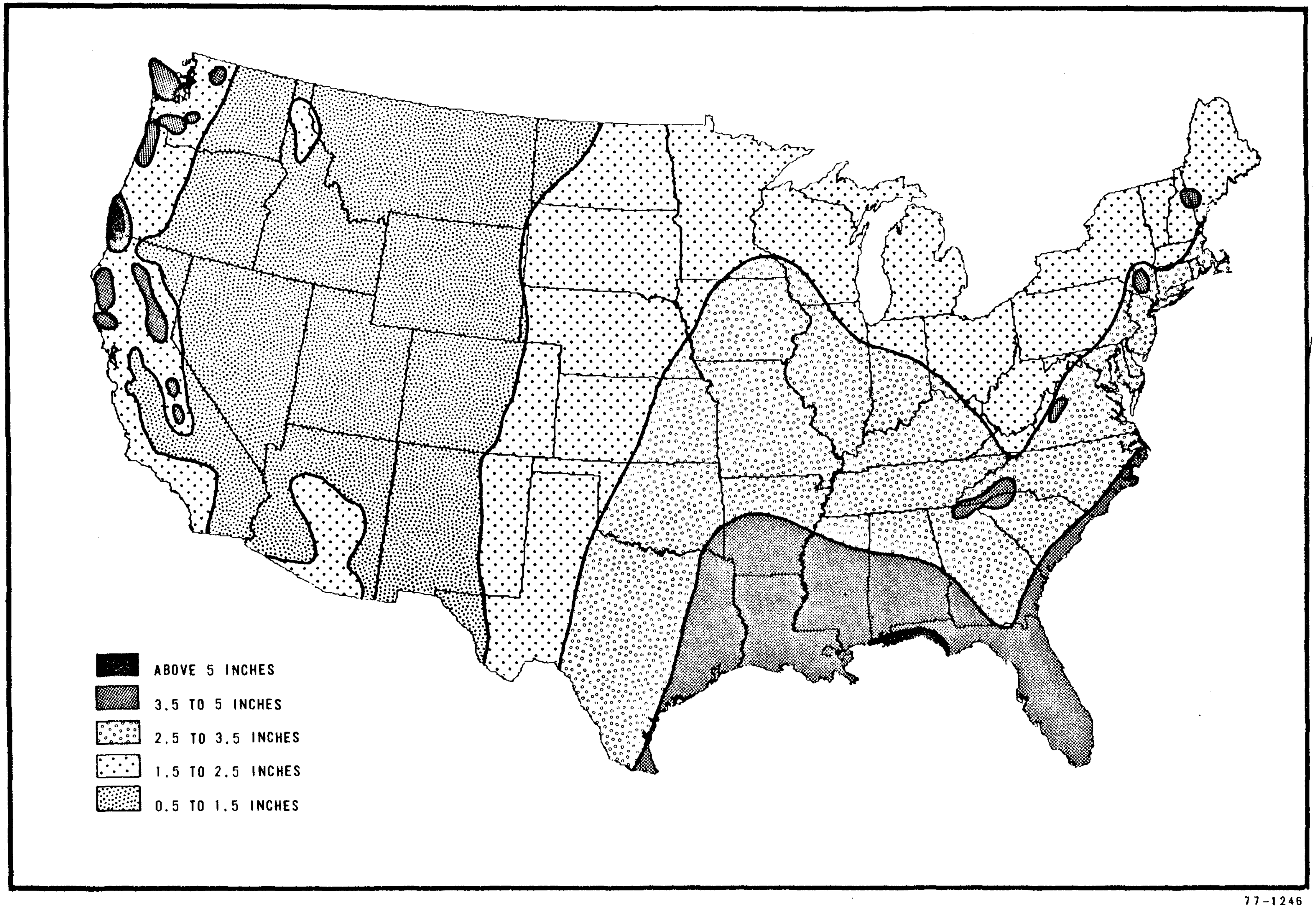


Figure 2-5. Average Maximum Rainfall Occurring in a 24 Hour Period

The landslide intensity map attempts to define landslide-prone areas within the continental United States. As mentioned before, this map is based on three principal factors: topography, bedrock, and precipitation. Topography and rock type were used to establish the high, moderate, and low landslide potential ratings defined in Figures 2-1 and 2-2. Mean annual rainfall must also be consulted in order to complete the map. Criteria used to establish the landslide potential rating are as follows:

High (H): An area of steep topographic relief with a known landslide-prone bedrock formation (rock type).

High = Adverse Formation + Steep relief

Moderate (M): An area of moderate topographic relief with a known landslide-prone bedrock formation (rock type).

Moderate = Adverse Formation + Moderate relief

Low (Lc): Apparently low potential for landslide (based on limited available data). Requires additional considerations, based on possibly steep terrain and/or adverse formation in low areas. Of the two low designations, (Lc) has a higher landslide potential.

Low (steep) = No Adverse Formation + Steep relief

= Adverse Formation + Low relief

Low (L): An area of low topographic relief and may or may not contain a known landslide-prone bedrock formation (rock type); or moderate relief with no known landslide-prone bedrock formation.

= No Adverse Formation + Moderate relief

Low = No Adverse Formation + Low relief

The contribution of the mean annual rainfall produces the following intensity rankings as developed judgmentally (Table 2-4).

LANDSLIDE POTENTIAL MAP RATING (FIGURE 2-1)	RAINFALL IN INCHES (FIGURE 2-2)	RELATIVE INTENSITY (HIGHEST RANKING IS THE MOST SEVERE)
HIGH	32"	XII
	8-32"	X
	8"	IX
MODERATE	32"	XI
	8-32"	IX
	8"	III
LOW (STEEP)	32"	VIII
	8-32"	VI
	8"	II
LOW	32"	VII
	8-32"	V
	8"	I

Table 2-4. Landslide Intensity Ranking Based on Rock Type, Topography and Precipitation

The above figures are not to be confused with the Modified Mercalli Intensity figures used for defining earthquake intensity. They simply give a rank order for landslide potential.

Chapter Three

Exposure Model (Value at Risk)

The exposure model developed for landslide is constrained to the sophistication of the damage algorithm. The exposure model reduces to the following:

$$E(c) = V(c)/V(N) \times V(C) \qquad (1)$$

where:

$E(c)$ = structure value by county (c) normalized to the seven California and one Pennsylvania counties used for loss estimating purposes

$V(c)$ = average structure value per person by county

$V(N)$ = average structure value per person in the eight California and one Pennsylvania counties used for loss estimating purposes

$V(C)$ = structure value by county (c)

No attempt to break out industrial-commercial properties from dwellings was made. Thus, since dwellings usually suffer from landslides greater than industrial-commercial properties, our estimates may trend toward the high side.

Chapter Four

Vulnerability Model and Damage Algorithm

Landslides within the United States are responsible for annual losses of life as well as damage. Factual data relating actual dollar values to landslide damage are generally limited to localized studies. From the limited local studies damage calculation will be projected to develop a nationwide assessment. The following localized studies are currently available.

1. Alfors, J.T., and others, 1971, Urban Geology Master Plan Project-Phase 1: California Division of Mines and Geology Open File Report 72-2

This report presents several examples of landslide damage and attempts to assign high, moderate, and low severity ratings for each damaged area. The following paragraphs are excerpts from that report:

> "The San Clemente area was selected as representative of a "high" severity area. This is an area of widespread and numerous landslides [Blanc and Cleveland, 1968], since approximately 25 percent of the area is shown to be covered by landslides.
>
> "Thus, if the urban unit were unknowingly situated, without geological or engineering guidance, within such an area, one fourth of the units would be expected to suffer building and land damage. This affected area would be 2.63 million square feet of the urban units' total of 10.53 million square feet. Value of the urban unit-improvements and land, less personal property--is $7.31 per square foot.
>
> "If we assume that the slides will move on the average of once every 50 years, then the loss is $19.3 million for the Urban Units' 3000 people, or $128.00 per person per year.
>
> "An area of 4.5 square miles, including the communities of Glorietta and Rheem in the Oakland East Quadrangle, has been selected as representative of the "moderate" landslide condition. This area is underlain by the Orinda formation which is shown on maps by Radbruch [1969, 1971] to contain numerous landslides.

Preceding page blank

"For example, 84 landslides are present in the 4.5 square mile area, or 18.7 landslides per square mile. Using this ratio, 7 landslides would be present in the Urban Unit's 0.377 square miles. However, it is very likely that detailed surface mapping and exploration would detect additional landslides, perhaps twice as many. Therefore, a more appropriate figure appears to be 14 landslides in the Urban Unit.

"Each landslide is assumed on the average to involve 3 homes. The loss per slide is then $230,994, using $76,988 as the single family dwelling value, which includes improvements and land, but less personal property.

"The loss to the Urban Unit is then $64,700 per year when 14 landslides occur every 50 years or a loss of $21.50 per person per year for the 3000 population of the unit.

"Although severity and recurrence of landslides is low in "low" severity areas, they do occur occasionally. In the absence of cost data, generally unavailable for low areas, we have assumed that two homes will be destroyed in the Urban Unit within any given 50 year period. This results in a loss of about $1.00 per year per person using the above value of $76,998 for each home.

<u>Life Loss in Urban Unit</u> - Life loss is fairly rare in landslides; however, it does occur frequently enough to be considered.

"In "high" severity areas, we have assumed that 5 persons are killed each 50 years in the Urban Unit. This results in a loss of $2.50 per person per year, using a value of $75,000 per life.

"In "moderate" severity areas, we have assumed 1 person killed each 50 years. This results in a loss of $0.50 per person per year.

"In "low" severity areas, it is assumed that there will be no loss of life.

The following Table 2-5 represents a summary of the conclusion presented in the Alfors, [1971] report.

Map Severity	Damage Per Capita Per Year	Life Loss Per Capita Per Year	Total Loss Per Capita Per Year
High	$128.00	$2.50	$130.50
Moderate	21.50	.50	22.00
Low	1.00	----	1.00

Table 2-5

2. Alfors, J. T., Burnett, J. L., and Gay, T. E., Jr., 1973 Urban geology - master plan for California, p.26-29, 96-97

This report is based on the earlier open-file report [Alfors and others, 1971]. The dollar values for the severity ratings were reduced significantly. These values were then projected as total loss figures for a thirty year time span (1970-2000). Table 2-6 represents the data presented in said report:

Landslide Severity Zone	Number of urban quadrangles of each severity	Estimated % of total population	Person-years exposure (to year 2000)	Expectable total loss rate ($ per capita per year)	Projected total loss 1970-2000
High	200	7	53,956,000	53	$2,859,000,000
Moderate	700	25	192,700,000	35	6,745,000,000
Low	900	32	246,656,000	1	247,000,000
					$9,851,000,000

Table 2-6. Revised Estimates of Losses in California Counties

3. Briggs, R. P., Pomeroy, J. S., and Davies, W. E., 1975, Landsliding in Allegheny County, Pennsylvania: U. S. Geological Survey Circular 728, 18p.

The Allegheny County Department of Planning and Development has estimated cost of damages from landsliding in the county from 1970 to 1974 at nearly $2 million annually. Estimated population of Allegheny County [USGS, 1970] is approximately

1,620,000 people. Thus, the average landslide cost is approximately $1.20 per capita per year.

4. Taylor, F.A., Nilson, T.H., and Dean, R.M., 1975, Distribution and cost of landslides that have damaged manmade structures during the rainy season of 1972-1973 in the San Francisco Bay Region, California; USGS Misc. Field Studies Map MF 679

Landslide damage losses presented in this report/map reflect those losses that can probably be expected during normal rainfall years. Figures represented in the following chart are considered to be minimum loss values.

County	Total Landslide Loss	1970 Population	Damage Loss per Person
Alameda	$ 400,000	1,005,000	$ .40
Contra Costa	1,700,000	495,000	3.00
Marin	3,000,000	184,000	16.00
Napa	130,000	75,000	2.00
San Mateo	3,595,310	531,000	7.00
Santa Clara	150,000	866,000	.20
Sonoma	210,000	173,000	1.00
			Mean = $ 4.22
			Median = $ 2.00

5. Taylor, F.A. and Brabb, E.E., 1972, Map showing distribution and cost by counties of structurally damaging landslides in the San Francisco Bay Region, California-winter of 1968-1969; USGS Misc. Field Studies Map MF-327

This report defines the landslide losses that can be incurred during and following a heavy rainfall period (in this case, 1968-1969). The total dollar loss values presented in the following chart are considered to be minimum figures.

County	Total Landslide Loss	1970 Population	Damage Loss per Person
Alameda	$5,400,000	1,005,000	$ 5.00
Contra Costa	5,200,000	495,000	10.00
Marin	1,000,000	184,000	5.00
Napa	1,500,000	75,500	20.00
San Mateo	3,600,000	531,000	7.00
Santa Clara	1,900,000	866,000	2.00
Sonoma	6,400,000	173,000	37.00
			Mean = $12.28
			Median = $ 7.00

6. Slosson, J.E., 1969, The role of engineering geology in urban planning: The Governor's Conference on Environmental Geology, Colorado Geological Survey Special Publication, p. 8-15

Landslide damage in the City of Los Angeles, California amounted to $6 million following heavy rains during the winter months of 1968-1969. Slosson relates site damage to the progressive development of grading codes. He divides the site damage into three categories: (1) Pre-1952 (No grading code, no soils engineering, no engineering geology), (2) 1952-1962 (Semi-adequate grading code, soils engineering required, very limited geology but no status and no responsibility); and (3) 1963 to Present (New modern grading code, soils engineering and engineering geology required).

The status of grading codes over most areas of the country is best reflected by the Los Angeles pre-1952 conditions. That is to say that most areas throughout the country either have inadequate grading codes or none at all. Therefore, pre-1952 site damage statistics have been used by the authors to develop the national landslide damage assessment.

The pre-1952 statistics indicate that approximately 1040 sites (out of approximately 10,000 sites) were damaged and that the damage amounted to about $3 million, or $300 per site. These damages occurred during a heavy rainfall (storm) year. It is estimated that these storm years occur on a frequency of two (2) per ten (10) years. Landslide damage during nonstorm years is essentially negligible. Therefore, if a ten (10) year period is considered, the landslide damage would be approximately $60 per site per year. This would be $20 per capita per year assuming three people per dwelling or site.

Table 2-7 codifies all of these data by landslide intensity.

REFERENCE	REGION	INTENSITY	LOSS PER PERSON (1970 $)
1.	CALIFORNIA	XII	$140.00
		IX	23.00
		V	1.10
2.	CALIFORNIA	XII	53.00
		IX	35.00
		V	1.00
3.	ALLEGHENY CO.	XII	1.20
4.	MARIN CO.	X 1/2	14.00
	SAN MATEO CO.	X 1/2	6.10
	CONTRA COSTA CO.	IX	2.60
	NAPA CO.	IX	1.80
	SONOMA CO.	XII	.88
	ALAMEDA CO.	XII	.35
	SANTA CLARA CO.	V	.18
5.	MARIN CO.	X 1/2	5.30
	SAN MATEO CO.	X 1/2	7.40
	CONTRA COSTA CO.	IX	11.00
	NAPA CO.	IX	21.00
	SONOMA CO.	XII	39.00
	ALAMEDA CO.	XII	5.30
	SANTA CLARA CO.	V	2.10
6.	LOS ANGELES CO.	V	2.10

Table 2-7. Landslide Damage to Buildings Per Person Normalized to 1970 Dollars

The above data were used in the above manner to compute building loss from landslide. References 1 and 2 were eliminated from the data as being unrealistic. Reference 3 was used to represent building losses and given a weight of one (1). References 4 and 5 were given weights of one half (1/2) each (since they dealt with the same counties)and the results divided by one half (1/2) to account for the building loss portion. Reference 6 was given a weight of one (1) and divided by one half (1/2) to account for the building loss portion.

By averaging the data in the manner described above one computes the mean value of the following intensity zones to be:

Zone	Intensity Range	$ Loss/Person/Year ($1970)-Z
3	IX - XII	$4.25
2	V - VIII	.80
1	I - IV	.05 (Extrapolation)

Chapter Five

Computations of Expected Losses (Risk Model)

The damage algorithms for landslide are developed in terms of 1970 dollar damage per capita per year for each county unit irrespective of structure class (Figure 2-6). However, since the county base data used to compute the annual damage by county per person were derived from eight California and one Pennsylvania counties, the damage computation for the other counties was normalized as follows for losses by county, L(c):

$$L(c) = Z \times V(c)/V(N) \times P(c)$$

where:
Z = loss per person per year by zone (1970$)
V(c) = average structure value per person by county
V(N) = average structure value per person in the eight California and one Pennsylvania counties from which data are available
P(c) = population by county

Summing up all damages by county using Figures 2-1, 2-2, and 2-4 and the exposure for each county, Table 2-8 was constructed. It can be noted that the total losses computed are about $214 million dollars (1970) for map no. 1. Map no. 2 created losses in the neighborhood of $370 million or 73 percent in excess of map no. 1. This figure agrees with that of White and Haas [1975] that, "Currently, landslides cause damages estimated at hundreds of millions of dollars annually."

Losses by the year 2000 are $503 million and $871 million for maps 1 and 2 respectively. The figures point to gains of 135 percent over the 30-year period. These gains are primarily due to population increase, value of improvements increase, and population movement to more hazardous regions. No inflation is considered.

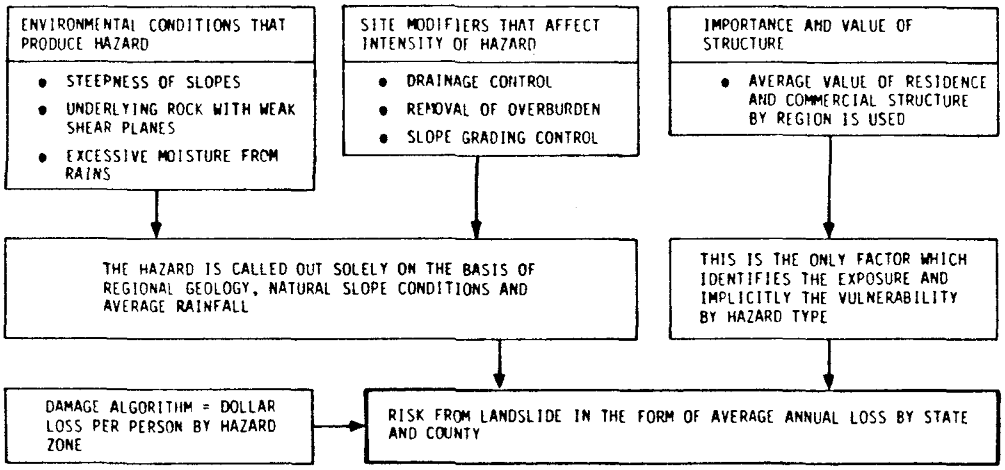


Figure 2-6. Landslide Risk Determination Procedure

1970					2000				
STATE	TOTAL STRUCTURE VALUE ($BILL.)	POPULATION (MILLIONS)	LANDSLIDE LOSSES ($ MILLIONS)		STATE	TOTAL STRUCTURE VALUE ($BILL.)	POPULATION (MILLIONS)	LANDSLIDE LOSSES ($ MILLIONS)	
			MAP NO.1	MAP NO.2				MAP NO.1	MAP NO.2
AL	26.7	3.44	3.9	4.6	AL	65.0	4.17	9.1	10.8
AK	3.9	0.27	-	-	AK	8.6	0.34	-	-
AZ	16.9	1.77	1.3	2.3	AZ	47.8	2.78	3.5	6.2
AR	13.6	1.92	1.7	3.0	AR	32.4	2.18	4.4	7.4
CA	228.0	19.96	33.3	36.8	CA	539.8	26.03	80.7	88.7
CO	22.7	2.21	3.4	6.3	CO	56.1	2.86	8.3	15.7
CT	35.0	3.03	2.3	10.3	CT	82.6	4.05	5.4	24.4
DE	5.7	0.55	0.4	1.6	DE	14.4	0.75	.9	4.0
DC	12.6	0.76	0.8	.8	DC	42.4	1.49	2.7	2.8
FL	61.1	6.79	3.8	3.9	FL	198.8	11.61	12.6	12.7
GA	41.5	4.59	2.8	5.1	GA	116.0	6.32	7.7	14.2
HI	10.0	0.77	-	-	HI	26.2	0.11	-	-
ID	6.3	0.71	1.1	1.0	ID	13.5	0.79	2.4	2.1
IL	126.8	11.12	10.4	33.2	IL	286.8	13.60	23.3	74.9
IN	48.8	5.20	3.2	6.8	IN	118.2	6.56	7.7	16.6
IA	25.8	2.83	3.1	5.2	IA	53.4	3.03	6.6	11.0
KS	21.5	2.25	1.5	3.4	KS	47.0	2.51	3.2	7.8
KY	25.6	3.22	3.3	6.0	KY	65.8	4.04	8.0	15.4
LA	30.3	3.64	2.0	6.0	LA	66.4	3.91	4.3	13.0
ME	8.3	0.99	.5	2.1	ME	17.0	1.05	1.1	4.5
MD	49.2	3.92	11.7	12.0	MD	133.3	5.71	30.2	31.0
MA	63.4	5.69	4.1	13.2	MA	151.3	7.48	9.8	31.3
MI	90.8	8.88	5.8	19.5	MI	206.6	10.89	13.3	43.3
MN	37.7	3.80	5.3	5.5	MN	91.8	4.80	14.6	13.1
MS	14.6	2.22	1.1	2.8	MS	33.0	2.36	2.5	6.4
MO	45.1	4.68	8.7	10.8	MO	101.2	5.40	18.7	24.5
MT	6.4	0.69	0.7	1.2	MT	12.3	0.68	1.2	2.3
NE	14.3	1.49	2.4	2.6	NE	31.2	1.67	5.5	6.0
NV	5.8	0.49	.2	.6	NV	17.7	0.84	.7	2.2
NH	7.4	0.74	0.5	1.5	NH	18.1	0.97	1.2	3.6
NJ	83.7	7.17	5.4	10.7	NJ	199.2	9.53	12.9	25.8
NM	9.1	1.02	0.7	.8	NM	20.2	1.15	1.5	1.8
NY	229.6	18.24	14.9	29.4	NY	511.3	22.55	33.1	66.2
NC	40.0	5.08	3.5	9.8	NC	103.0	6.53	8.9	25.6
ND	4.8	0.62	1.0	1.1	ND	8.9	0.57	1.8	2.1
OH	106.3	10.66	13.2	21.9	OH	242.5	12.82	29.2	48.4
OK	23.1	2.56	1.7	2.2	OK	55.8	3.08	4.0	5.2
OR	19.9	2.09	2.8	4.2	OR	45.1	2.49	6.2	9.6
PA	116.1	11.80	18.6	24.9	PA	252.0	13.49	38.9	53.2
RI	9.3	0.95	0.6	.6	RI	20.4	1.14	1.3	1.3
SC	19.6	2.59	1.3	3.2	SC	48.0	3.20	3.1	7.8
SD	5.3	0.67	0.7	1.3	SD	10.4	0.65	1.3	2.6
TN	30.8	3.92	2.7	2.0	TN	80.0	5.04	6.8	5.2
TX	103.7	11.20	7.3	11.4	TX	261.0	14.37	18.0	28.5
UT	10.6	1.06	2.8	3.1	UT	27.2	1.39	7.4	8.2
VT	3.8	0.44	.2	.5	VT	8.6	0.51	.6	1.2
VA	48.8	4.65	4.8	8.9	VA	133.0	6.46	12.6	25.3
WA	35.6	3.41	4.0	10.4	WA	78.5	3.99	8.5	23.1
WV	14.2	1.74	4.7	4.9	WV	29.5	1.73	9.8	10.1
WI	41.2	4.42	3.0	10.4	WI	89.5	5.10	6.5	22.8
WY	3.2	0.33	0.4	.7	WY	6.4	0.33	.7	1.4
U.S.	2064.5	203.24	213.6	370.5	U.S.	4925.2	255.10	502.7	871.2

Table 2-8. Annual Building Losses Due to Landslide in 1970 and 2000 (1970$)

Chapter Six

Effects of Mitigations on Landslide Losses

It is estimated that in two of the California counties studied and the one county in Pennsylvania that between 90-95 percent of the damage is man-related. In Contra Costa County, California alone, approximately eighty percent of the landslides are man-related [Nilsen and Turner, 1975]. Briggs and others [1975] have indicated that over 90 percent of the landslides in Allegheny County, Pennsylvania are man-induced.

The effectiveness of adequate grading codes is best dramatized by Slosson [1969] in his discussion of the landslide losses sustained by the City of Los Angeles, resulting from the 1968-1969 winter storm. He records that prior to 1952 (when no grading codes existed and soils engineering and engineering geology were not required, approximately 1040 sites were damaged out of 10,000 sites constructed (10.4 percent failure). During the period 1952 to 1962 (when semi-adequate grading codes and soils engineering with limited geology were required, but with no status and no responsibility), there were 350 sites damaged out of 27,000 sites constructed (1.3 percent failure). During the period 1963 to 1969 (when modern grading codes were used and soils engineering and engineering geology were required, as well as Design Engineers, Soils Engineers, and Engineering Geologists assuming responsibility), there were approximately 17 failures out of approximately 11,000 sites constructed (0.15 percent failure).

These figures indicate that landslide damage losses can be reduced significantly (from 10.4 percent to 0.15 percent) through the use of effective grading ordinances or codes. Statistical data and experience indicate that for a very minimal cost, the monetary losses resulting from landslides were reduced by approximately 97 percent.

A scan of limited data suggests that the loss of life from mudflows (a form of landslide) in California averages and may exceed 5 deaths per year. Expanding this to a national average, 25 deaths per year appears to be a reasonable assumption. In addition, Alfors et al [1973] have suggested that the loss of life from landslides in California, excluding mudflows, should average 5 per 50 years in high severity areas and 1 per 50 years in moderate severity areas. Thus the

Preceding page blank

total loss of life from all forms of landslide activity is about 25 lives per year.

The simple application of effective grading ordinances can go a long way in reducing the hazard of landslides. Assuming a 90 percent reduction in landslide losses, if proper grading ordinances were applied, an annualized reduction of 30 percent or $150 million can be expected by the year 2000 (Table 2-9).

EXPECTED NATIONAL ANNUAL LOSSES IN $ MILLIONS (1970)

MITIGATION	1970	1980	1990	2000
Baseline - No modifications to current grading ordinances are made	214	294	393	503
(1) Require grading ordinances that reduce hazard by 90% beginning after 1980	210 (0%)	294 (0%)	334 (-15%)	352 (-30%)

Table 2-9. Landslide Losses and Mitigation Effects

Other mitigations proposed in addition to grading ordinances are:

1. Improved runoff control.
2. Landuse control: hillsides are used for open spaces when appropriate.

It should be noted that a reduction of the damage to new construction of 90 percent causes a reduction in overall damage to all construction (both new and old) of 30 percent. This implies that $168 million (($503 - $352)/0.90 = $168 million) would have resulted on an annualized basis from new construction after 1980 and up to 2000 had not the mitigation been applied. Thus 33.3 percent of the construction in 2000 is equal to or less than 20 years old. Recalling that population is projected to be 220.53 million in 1980 and 255.1 million in 2000 and normalizing for this growth factor, it may be calculated that the average half life of buildings is 48.4 years. This helps to provide some insight to the slowness of loss reduction <u>if</u> only new structures have the additional protection.

Chapter Seven

Conclusions

The annualized building loss to the nation as the result of landslides is on the order of \$200 - \$400 million in 1970 (1970\$), \$290 - \$510 million in 1980 (1970\$), \$390 - \$700 million in 1990 (1970\$), and \$500 - \$900 in 2000 (1970\$) should the hazard go unchecked. Through the proper introduction of grading ordinances, land-use controls, and drainage of runoff controls, these loss figures could be dramatically reversed (90 percent reduction to new construction) at judged low costs.

The loss of life due to landslide is judged to be minimal when compared with other natural hazards such as tornado, flood and earthquake. However, approximately 25 persons per year can be expected to die from this hazard.

Major, sudden loss landslide scenarios were not treated in this report. Yet they are known to occur with loss estimates considerably in excess of those generated in the simple manner described. The recent landslide in Laguna Beach, California caused an estimated \$5 - \$10 million loss in 1978 dollars. Translated to 1970 values, these would represent a loss of about \$2.5 million to \$5 million. This value is much smaller than the sudden losses that are possible as the result of earthquake, hurricane wind or storm surge, tornado, flood, and tsunami. All of the latter devastate large areas at once. Further, land value loss and lawsuits in addition to real and improved property losses result in these instances. Although none of these costs were treated, they should be recognized for future research.

REFERENCES

Alden, W.C. "Landslide and Flood at Gros Ventre, Wyoming." American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc. Engineering Transactions, 1928.

Alfors, J.T., J.L. Burnett, and T.E. Gay, Jr. Urban Geology - Master Plan for California. Bulletin 198, California Division of Mines and Geology, 1971.

American Geological Institute (AGI). Glossary of Geology. Washington, D.C.: American Geological Institute, 1972.

Arora, H.S. and J.B. Scott. "Chemical Stabilization of Landslides by Ion Exchange." California Geology, Vol. 27, No. 5., 1974.

Baker,E.J. and J.G. McPhee. Land Use Management and Regulation in Hazardous Areas: A Research Assessment. National Science Foundation Report No. NSF-RA-75-008, 1975.

Baker, R.F. and R. Chieruzzi. "Regional Concept of Landslide Occurrence." An unpublished report. 37th Annual Meeting of the Highway Research Board, 1958.

Beaty, C.B. "Landslides and Slope Exposure." Journal of Geology, Vol. 64, 1956.

Beene, R.R.W. "Waco Dam Slide." Journal of the Soil Mechanics and Foundation Div. ASCE. Vol. 93, No. SM4, Proc. Paper 5306. 1967.

Bennett, W. "Landslides on Brazos Pass." Silver Anniversary Guidebook: Ghost Ranch, Central-Northern New Mexico. Economic Geology. New Mexico Geological Society Annual Field Conference Guidebook, No. 25, 1974.

Blackwelder, E. "The Gros Ventre Slide: An Active Flow." American Geological Society Bulletin, Vol. 23, 1911.

Blanc, R. and G.B. Cleveland. Natural Slope Stability as Related to Geology, San Clemente Area, Orange and San Diego Counties, California. California Division of Mines and Geology. Special Report 98, 1968.

Blank, H.R. "A Landslide Near Georgetown, Texas and Its Relation to Valley Development." American Journal of Science, Series 5, Vol. 245, 1947.

Bonilla, M. "A Sample of California Coast Range Landslides, Geological Survey Research, 1960." U.S. Geological Survey. Professional Paper 400B, 1960.

Bonilla, M. "Landslides in the San Francisco South Quadrangle, California." U.S. Geological Survey Open File Report, 1960.

Booey, E. and P.F. Kerr. "Landslide Affecting Highway Near Jackson Hole, Wyoming," (Abstract), American Geological Society, Vol 5, No. 7, 1973.

Brabb, E.E., E.H. Pampeyan, and M.G. Bonilla. Landslide Susceptibility in San Mateo County, California. U.S. Geological Survey Miscellaneous Field Studies Map MF-360, (BDC 43), 1972.

Preceding page blank

Brabb, E.E. and E.H. Pampeyan. Preliminary map of landslides deposits in San Mateo County, California. U.S. Geological Survey Miscellaneous Field Studies Map. MF-344 (BDC 42), 1972.

Brabb, E.E. and F.A. Taylor. Map showing distribution and cost by counties of structurally damaging landslides in the San Francisco Bay Region, California - Winter of 1968-1969. U.S. Geological Survey Field Studies Map MF-327 (BDC 37), 1972

Briggs, R.P., J.S. Pameroy and W.E. Davis. "Landsliding in Allegheny County, Pennsylvania." U.S. Geological Survey Circular 728, 1975.

Briggs, R.P. Map of overdip slopes that can affect landsliding in Allegheny County, Pennsylvania. U.S. Geological Survey Miscellaneous Field Studies Map 543, 1974.

Bruce, R.L. "Landslides in the Piere Shale." Proceedings of the 17th Annual Highway Geology Symposium. Iowa State University, Ames, Iowa, 1968.

Burchfiel, B.C. "Tin Mountain Landslide, Southeastern California, and the Origin of Megabreccia." Geological Society of America Bulletin, Vol. 77, 1966.

Byrne, J.V. and W.B. North. "Landslides of Oregon North Coast." Dept. of Oceanography, Oregon State University.

Campbell, R.H. "Soil Slips, Debris Flows, and Rainstorms in the Santa Monica Mountains and Vicinity, Southern California." U.S. Geological Survey Professional Paper 851, 1975.

Chandler, P.B. "Remote Detection of Transient Thermal Anomalies Associated with the Portuguese Bend Landslide." *Engineering Geologist Bulletin*. Vol. 12, No. 3, 1975.

Cleaves, A.B. "Flagg's Restaurant Area Landslide, Pacific Palisades, California." *Engineering Geologist*: Case Histories No. 7, GSA, 1969.

Cleaves, A.B. *Landslide Investimations: A Field Handbook for Use in High Location and Design*. U.S. Dept. of Commerce, Bureau of Public Roads, 1961.

Cleveland, G.B. "Regional Landslide Prediction." California Division of Mines and Geology Open File Release 72-73, Part 2. 1971.

Cleveland, G.B. "Fire + Rain = Mudflow, Big Sur." *California Geology*, Vol. 26, No. 6, 1973.

Cook, R.U. and J.C. Doornkamp. *Geomorphology in Environmental Management: An Introduction*. Clarendon Press, Oxford, 1974.

Crandell, D.R. "Postglacial Lahars from Mount Ranier Volcano, Washington." U.S. Geological Survey Professional Paper 677, 1971.

Crandell, D.R. and R.K. Fahnestock. "RocKfalls and Avalanches from Little Takoma Peak on Mount Ranier, Washington." Geological Survey Bulletin 1221-A, 1965.

Crawford, A.L. and F.E. Thackwell. "Some Aspects of the Mudflows North of Salt Lake City, Utah." Utah Academy. Scientific Paper, Vol. 8.

Curry, Robert R. "Observations of Mudflows in the Ten Mile Range, Central Colorado." Geological Society of America Bulletin, Vol. 77, No. 7, 1966.

Davies, W.E. "The Landslide at Cumberland, Harlan County, Kentucky." U.S. Geological Survey Open File Report, 1973.

DuMontelle, P.B., N.C. Hester and R.E. Cole. "Landslides Along the Illinois River Valley, South and West of LaSalle and Peru, Illinois." Illinois State Geological Survey, Environmental Geology Notes No. 48, 1971.

Eckel, E.B. (ed). "Landslides and Engineering Practice." Highway Research Board Special Report No. 29 NAS/NRC, Publication No. 544. National Academy of Science, Washington, D.C., 1978.

Evans, J.R. and C.H. Gray. "Analysis of Mudslide Risk in Southern Ventura County." California Division of Mines and Geology. Open File Release 72-73, Part I, 1971.

Flawn, P.T. and J.M. Burket. "Urban Geology of Greater Waco-Part I: Geology." Baylor Geological Studies Bulletin No. 8.

Focht, J.A. and R.A. Sullivan. "Two Slides in Over-consolidated Pleistocene Clays." Proceedings: Seventh International Conference on Soil Mechanics and Foundation Engineering, Mexico. 1969.

Font, R.G. "Influence of Fundamental Geologic Factors on Landslide Genesis and Morphology in Over-Consolidated Cretaceous Shales: A Study of Urban Engineering Geology"(abstract). In Engineering Geology and the National Resources Energy Spectrum, Association of Engineering Geologists Annual Meeting, Program abstract, No. 17, 1974.

Font, R.G. and E.G. Williams. "Urban Geology of Greater Waco-Part IV: Engineering." Baylor Geological Studies Bulletin No. 12, 1970.

Fox, F.M. and Associates. "Roaring Fork and Crystal Valleys and Environmental and Engineering Geology Study - Eagle, Garfield, Gunnison and Pitkin Counties, Colorado." Colorado Geological Survey. Environmental Geologist, No. 8, 1974.

Frizzell, V.A., Jr. Reconnaissance photo interpretation map of landslides in parts of the Hopland, Kelseyville and Lower Lake 15-minute Quadrangle, Sonoma County, California. U.S. Geological Survey Miscellaneous Field Studies Map MF-594, (BDC 66), 1974.

Frizzell, V.A., Jr., J.D. Simms, T.H. Nilson, and J.A. Bartow. Preliminary photo-interpretation map of landslides and other surficial deposits of the Mare Island and Carquinez Strait 15-minute Quadrangle Contra Cost, Marin, Napa, Solano, and Sonoma Counties, California. U.S. Geological Survey Miscellaneous Studies Map, MF-595, (BDC 67), 1974.

Geologic Hazard Conference. "Landslides and Subsidence: State of California." The Resources Agency Conference, Los Angeles, California, 1965.

Gray, H.H. "Glacial Lake Deposits in Southern Indiana - Engineering Problems and Land Use: State of Indiana." Dept. of Natural Resources: Geological Survey Report of Progress 30, 1971.

Hame, J.V., R. Adams, Jr., M.H. DeFreitas, et.al. "Some Field Examples of Toppling Failure." Geotechnique, Vol. 24, No. 4.

Hammond, E.H. "Classes of Land Surface Form in the Forty-eight States, USA." Annuals of the Association of America Geographers, Vol. 54, No. 1, Map Supplement No. 4, 1:5,000,000, 1964.

Hansen, W.R. Effects of the May 5-6 (1973) Storm in the Greater Denver Area, Colorado. U.S. Geological Survey Circular 689, 1973.

Howe, E. "Landslides in the San Juan Mountains, Colorado." U.S. Geological Survey Professional Paper 67, 1909.

Hunt, S.R. "Regional Geologic Control in a Landslide Area Along the Illinois River Valley" (abstract). North Central Section 8th Annual Meeting of Geological Society of America, Abstract, Vol. 6, No. 6, 1974.

Jacobs, A.M. Geology for Planning in St. Clair County, Illinois. Illinois State Geological Survey Circular, 1971.

Jennings, C.W. "Landslide in the Ventura Avenue Oil Field." Mineral Information Service, Vol. 7, No. 5, 1954.

Kent, P.E. "The Transport Mechanism in Catastrophic Rock Fall." Journal of Geology, Vol 74, 1966

Kerr, P.F. and I.M. Drew. Clay Mobility, Portuguese Bend, California. California Division of Mines and Geology Special Report 100, 1967.

Kerr, P.F. and I.M. Drew. "Quick-Clay Slides in the USA." Engineering Geology, Vol. 2, No. 4, 1968.

Kerr, P.F., and I.M, Drew. Clay Mobility in Ridge Route Landslides, Gorman, California. Air Force Cambridge Research Labs. AFCRL-70-0447, 1970.

Kerr, P.F., R.A. Stroud, and I.M. Drew. "Clay Mobility in Landslides, Ventura, California." American Association of Petroleum Geology Bulletin, Vol. 55, 1971.

Kerr, P.F. and J. Wilcox. A Landslide Complex Near Grants, New Mexico. Air Force Cambridge Research Laboratories, 1971.

Kiersch, G.A. "Pfeiffer Versus General Insurance Corporation." (Landslide Damage to insured dwelling - Orinda, California and relevant cases.) Engineering Geologist: Case Histories No. 7 GSA, 1969.

Kohl, W.R. and R.P. Briggs. Map of rock types in bedrock of Allegheny County, Pennsylvania. U.S. Geological Survey Miscellaneous Field Studies Map MF-685A.

Koons, E.D. Geology of the Uinkaret Plateau, Northern Arizona. Geological Society of America Bulletin, Vol 56. No. 2, 1945.

Krinitzsky, E.L. and C.R. Kolb. "Geological Influences on the Stability of Clay Shale Slopes." Proceedings of the 7th Annual Engineering Geology and Soil Engineering Symposium, Idaho, 1969.

Krynine, D.P. and W.R. Judd. Principle of Engineering Geology and Geotechnics. New York:McGraw-Hill, 1957.

Ladd, G.E. "Landslides and Their Relation to Highways." Public Roads, Vol. 8, 1927.

Larsen, J.I. "Geology for Planning in Lake County, Illinois." Illinois State Geological Survey Circular 481, 1973.

Legget, R.F. Geology and Engineering. New York:McGraw-Hill, 1962.

Leighton, F.B. "Landslide and Hillside Development in Engineering Geology in Southern California." Association of Engineering Geologists, Los Angeles Section, Special Publication, 1966.

Liebling, R. and P.F. Kerr. "Observations on Quick Clay." Geological Society of America Bulletin 76, 1965.

McGill, J.T. Preliminary map of landslides in the Pacific Palisades area, City of Los Angeles, California. U.S. Geological Survey Miscellaneous Geol. inv. Map 1-284.

Merriam, R. "Portuguese Bend Landslide, Palos Verdes Hills, California." Journal of Geology, Vol 68, 1960.

Miller, R.A. and J.D. Wiethe. "Landslides in the Nashville, Tennessee area-winter, 1975." Department of Conservation, Division of Geology, Environmental Geology Series No. 3, 1975.

Minard, J.P. Slump Blocks in the Atlantic Highlands of New Jersey. USGS Prof. Paper No. 898, 1974.

Minnesota Environmental Quality Council. Supplemental Considerations: Geologic Hazards in Power Plant Siting Program, 1975.

Morton, D.M. and R. Streitz. Landslides. Mineral Information Service, Vol. 20, No. 10, 1967.

Morton, P.K. "The Ortega Highway Landslide." In Geologic Guidebook to the Northern Peninsular Ranges, Orange and Riverside Counties, California. National Association of Geology Teachers - South Coast Geological Society. Orange, California, 1972.

Mullineaux, D.R. Geology of the Renton, Auburn, and Black Diamond Quadrangles, King County, Washington. U.S. Geological Survey Professional Paper 672, 1970.

McComas, M.R., J.P. Kempton and K.C. Hinkley. "Geology Soils, and hydrogeology of Vols Bog and vicinity, Lake County, Illinois." Illinois State Geological Survey. Environmental Geology Notes, No. 57, 1972.

National Research Council. Panel on Methodology for Delineating Mudslide Hazard Areas. Building Research Advisory Council, 1974.

Nilsen, T.H. Preliminary photointerpretation map of landslides and other surficial deposits of parts of the Los Gatos, Morgan Hill, Gilroy Hot Springs, Pacheco Pass, Quien Sabe, and Hollister 15-minute quadrangle, Santa Clara, California. U.G. Geological Survey Miscellaneous Field Studies Map MF-416 (BDC 46), 1972.

Nilsen, T.H. Preliminary photointerpretation map of landslides and other surficial deposits of the Mount Hamilton Quadrangle and parts of the Mount Boardman and San Jose Quadrangles, Alameda and Santa Clara Counties, California. U.S. Geological Survey Field Studies Map MF-339 (BDC 38), 1972.

Nilsen, T.H. Preliminary photointerpretation map of landslide and other surficial deposits of the Byron area, Costra Costa and Alameda Counties, California. U.S. Geological Survey Field Studies Map MF-338 (BDC 38), 1972.

Nilsen, T.H. Preliminary photointerpretation map of landslide and other surficial deposits of the Concord 15-minute quadrangle and the Oakland West, Richmond and parts of the San Quentin 7 1/2 minute Quadrangle, Contra Costa and Alameda Counties, California. U.S. Geological Survey Miscellaneous Field Studies Map MF-493 (BDC 57), 1973.

Nilsen, T.H. Preliminary photointerpretation map of landslide and other surficial deposits of the Livermore and parts of the Hayward 15-minute quadrangles, Alameda and Contra Costa Counties, California. U.S. Geological Survey Miscellaneous Field Studies Map MF-519 (BDC 59), 1973.

Nilsen, T.H. Preliminary photointerpretation map of landslide and other surficial deposits of part of the Altamont and Carbona 15-minute quadrangles, Alameda Counties, California. U.S. Geological Survey Field Studies Map MF-321 (BDC 34). 1972.

Nilsen, T.H and E.E. Brabb. Preliminary photointerpretation and damage maps of landslides and other surficial deposits in northeastern San Jose, Santa Clara County, California. U.S.G.S. Field Studies Map MF-3161 (BDC 45), 1972.

Nilsen, T.H. and B.L. Turner. Influence of Rainfall and Ancient Landslide Deposits on Recent Landslides (1950-1971) in Urban Areas of Contra Costa County, California. U.S.G.S. Bulletin 1388, 1975.

Pomeroy, J.S. and W. Davies. "Landslides in the Pittsburgh Area - Allegheny County, Pennsylvania" (Abstract). In Northeastern Section: 10th Annual Meeting, Geological Society of America Abstracts, Vol. 17, No. 1, 1915.

Radbruch, D.H. and K.C. Crowther. Map showing relative amounts of landslides in California. U.S.G.S. Geol. Inv., Map 1-747, 1973.

Raisz, E. Landforms of the United States in Atwood's Physiographic Provinces of North America. Map approximate scale 1:4, 561, 920, 1974.

Rogers, W.P. et. al. Guidelines and Criteria for Identification and Land Use Controls of Geologic Hazard and Mineral Resource Areas. Colorado Geological Survey Special Publication, No. 6, 1974.

Royster, D.L. An Overview of Recent Landslide Problems in Tennessee. Tennessee Department of Transportation, 1974.

Royster, D.L. Highway Landslide Problems Along the Cumberland Plateau in Tennessee. Association of Geological Engineers Bulletin, Vol. 10, No. 4, 1973.

Royster, D.L. "Highway Landslide and Stability Problems in Tennessee." 46th Annual Tennessee Highway Conference, 1964.

Russell, I.C. A preliminary paper on the geology of the Cascade Mountains in northern Washington. U.S.G.S. 20th Annual Department, Part 2, 1898-1899.

Russell, R.J. "Landslide Lakes of the Northwestern Great Basin." University of California Publication in Geology, Vol. 2, 1927.

Scheffel, E.R. "Slides in the Conemaugh Formation near Morgantow, West Virginia." Journal of Geology, Vol 28, 1920.

Sharpe, C.F.S. and E.G. Dosch. "Relation of Soil Creep to Earthflow in the Appalachian Plateau." Journal of Geomorphology, Vol. 5, 1942.

Sharpe, C.F.S. Landslides and Related Phenomena. New York: Columbia University Press, 1960.

Shroder, J.G., Jr. Landslides of Utah. Utah Geological and Mineralological Survey Bulletin 90, 1971.

Sims, J.D. and T.H. Nilsen. Preliminary photointerpretation map of landslides and other surficial deposits in parts of the Pittsburg and Rio Vista 15-minute quadrangles, Contra Costa and Solano Counties, California. U.S.G.S. Field Studies Map, MF-322 (BDC 35), 1972.

Slosson, J.E. The Role of Engineering Geology in Urban Planning. The Governor's Conference on Environmental Geology. Colorado Geological Survey. Special Publication No. 1, 1969.

Sorensen, J.H., N.J. Ericksen, and D.S. Mileti. Land Hazard in the United States: A Research Assessment. NSF-RA-E-75-016, 1975.

Sowers, G.F. and B.R. Carter. Slides in Residual Soils from Shale and Limestone. Proceedings of the Fourth Panamerican Conference on Soil Mechanics and Foundation Engineering. San Juan, Puerto Rico, 1971.

Spoljaric, N. "Geology of the Fall Zone in Delaware." Delaware Geological Survey Report, No. 19, 1972.

Strahler, A.J. "Landslides of the Vermillion and Echo Cliffs, Northern Arizona." Journal of Geomorphology, Vol. 3, 1940.

Sullivan, R. "Progression of Some Landslides Along Coast Highway 1 Between Thorton Beach and Mussel Rock." California Geology, Vol. 28, No. 2, 1975.

Taylor, F.A., T.H. Nilsen, and R.M. Dean. Distribution and cost of landslides that have damaged manmade structures during the rainy season of 1972-1973, in the San Francisco Bay Region, California. U.S.G.S. Field Studies Map MF-679, 1975.

Terzaghi, K. "Mechanism of Landslides". In Paige, S.M., Chairman, Application of Geology to Engineering Practice (Berkey Volume). New York: Geological Society of America, 1950.

Tompkin, J.M. and S.H. Britt. "Landslides, a Selected Annotated Bibliography." Bibliography, No. 10. Highway Research Board, 1951.

Trace, R.D. "Landslide Blocks Along the Margin of the Diablo Plateau, Texas." Field and Laboratory, Vol. 10, No. 2, 1942.

Uhrin, D.C. "Photointerpretation of landslide-prone areas in eastern Washington County, Pennsylvania and survey of residents of the Pittsburgh region, for landslide planning." (Abstract) In North-Central Section, 8th Annual Meeting. Geological Society of America, Abstracts, Vol. 6, No. 6, 1974.

U.S.G.S. The National Atlas of the United States, 1970.

U.S.G.S. Geologic map of North America, map scale 1:5,000,000. 1965.

U.S.G.S. Geologic Map of North America, map scale 1:2,500,000, 1974.

U.S.G.S. Landslide overview, conterminous United States Miscellaneous Field Studies Map MF-771 (Radbruch-Hall and others), 1976.

Utah Geological and Mineral Survey. "Manti Canyon Landslide." Utah Quarterly Review. Vol. 9, No. 4, 1975.

Utah Geological and Mineral Survey. "Landslide Triggers Acute Water Shortage in Manti." Utah Quarterly Review, Vol. 8, No. 3, 1974.

Vanderwilt, J.W. "A Recent Rockslide Near Durange, in La Plata County, Colorado." Journal of Geology, Vol. 42, 1934.

Van Horn , R. Landslide and associated deposits in the Sugar House quadrangle, Salt Lake County, Utah. U.S.G.S. Miscellaneous Geol. Inv. Map I-766-D, 1972.

Van Horn, R. Relative Slope Stability Map of the Sugar House quadrangle, Salt Lake County, Utah. U.S.G.S. Miscellaneous Geol. Inv. Map I-766-E, 1972.

Varnes, D.J. Relation of Landslides to Sedimentary Features, Chapter 13. Edited by P.D. Trask. Applied Sedimentation. New York: John Wiley and Sons, Inc., 1950.

Varnes, D.J. Landslide Types and Processes, Chapter 3. Edited by E.B. Eckel. Landslides and Engineering Practice. National Resources Council, Highway Research Board Special Report #29, 1958.

Varnes, H.D. "Landslide Problems in Southwestern Colorado." U.S.G.S. Circular 31, 1949.

Williams, H.B. "Geology Along the Illinois Waterway - A Basis for Environmental Planning." Illinois State Geological Survey Circular #478, 1973.

White, Gilbert F. and J. Eugene Haas. Assessment of Research on Natural Hazards. Cambridge, Massachusetts: MIT Press, 1975.

Whitney, A.T., G.F. Soers, and B.R. Carter. "Slides in Residual Soils from Shale and Limestone." Proceedings of the 4th Panamerican Conference on Soil Mechanics and Foundation Engineering. San Juan, Puerto Rico, 1971.

Wright, R.H. and T.H. Nilsen. Isopleth map of landslide deposits, Southern San Francisco Bay Region, California. U.S.G.S. Field Studies Map MF 550 (BDC 63), 1974.

Woods, H.D. "Causes of the Sears Point Landslide, Sonoma County, California." Engineering Geology Case No. 2, Geological Society of America, 1958.

Zaruba, Q and V. Mencl. Landslides and Their Control. Amsterdam:Elsevier Press, 1969.

Zook, R.L. and R.E. Bednar. "Landslide Problems of Eastern Kentucky Coal Fields." Association of Engineering Geologists Bulletin, Vol. 12, No. 4, 1975.

APPENDIX A

RESULTS OF INQUIRIES MADE TO LANDSLIDE INVESTIGATORS

STATE GEOLOGISTS LANDSLIDE QUESTIONNAIRE

RESULTS

States Contacted	Responses		Date of Response	Publications/Maps Received	State Geological Maps Reviewed
	Written	Phone			
Alabama	X		11-24-75		
Arizona	X		11-24-75		X
Arkansas	X		12-3-75		X
California	X		11-7-75	X*	X
Colorado	X		11-12-75	X	X
Connecticut		X	1-15-76		X
Delaware	X		1-6-76	X*	X
Florida	X		12-3-75	X*	X
Georgia		X	1-7-76		X
Idaho	X		1-30-76	X*	X
Illinois	X		11-20-75	X*	X
Indiana	X		12-3-75	X*	X
Iowa					X
Kansas	X		12-11-75	X*	X
Kentucky	X	X	1-26-76	X*	X
Louisiana	X		11-17-75	X*	X
Maine	X		12-3-75		X
Maryland	X	X	1-28-76	X*	X
Massachusetts	X		12-1-75	X*	X
Michigan	X	X	1-13-76	X*	X
Minnesota	X		11-9-75	X*	X
Mississippi	X		11-14-75	X*	X
Missouri	X		11-13-75		X
Montana	X		11-18-75	X*	X
Nebraska	X		11-20-75	X*	X
Nevada	X		11-17-75		X
New Hamshire		X	1-15-76		X
New Jersey	X	X	1-28-76		X
New Mexico	X		11-21-75	X*	X
New York		X	1-8-76		
North Carolina	X	X	1-15-76	X*	X
North Dakota	X		1-15-76	X*	X
Ohio	X	X	1-21-76		X
Oklahoma	X		12-12-75	X*	X
Oregon	X		11-19-75		X
Pennsylvania	X		11-20-75	X*	X
Rhode Island					X
South Carolina	X	X	1-27-76	X*	X
South Dakota	X		12-24-75		X
Tennessee	X	X	1-15-76	X*	X
Texas	X	X	1-21-76		X
Utah	X		11-20-75	X	X
Vermont					
Virginia	X		11-17-75		X
Washington	X	X	1-13-76	X*	X
West Virginia	X	X	1-14-76	X*	X
Wisconsin	X		11-18-76		X
Wyoming	X	X	1-15-76	X*	X

*Indicates map

PERSONNEL CONTACTED

Name	Title/Organization	State
K. T. Ackerson	Head, Soil Geography Unit (USDA, SCS, Hyattesville)	Maryland
W. R. Adams	Engineering Geologist Allegheny County	Pennsylvania
J. M. Allen	State Soil Scientist	Oregon
P. Allen	Geologist (Southern Methodist University)	Texas
H. G. Anderson	Geographer (Los Angeles Valley College)	California
M. Arndt	Geologist (North Dakota Geological Survey)	North Dakota
D. L. Bannister	State Soil Scientist	South Dakota
W. Bejnar	Geologist (New Mexico Highlands University)	New Mexico
H. D. Blaser	Western Regional Civil Engineer, Sacramento (HUD)	California
J. G. Bond	State Geologist	Idaho
C. Bowers	Soil Scientist	Tennessee
E. E. Brabb	Geologist (USGS, Menlo Park)	California
R. M. Breckenridge	Staff Geologist (State Geological Survey)	Wyoming
R. P. Briggs	Project Director (Greater Pittsburgh Regional Studies)	Pennsylvania
W. Brugger	Assistant Superintendent (Department of Building and Safety, City of Los Angeles)	California
W. J. Brune	State Conservationist	Iowa

Name	Title/Organization	State
W. V. Bush	Geologist (Arkansas Geological Commission)	Arkansas
J. L. Calver	State Geologist	Virginia
R. H. Campbell	Geologist (USGS, Menlo Park)	California
R. C. Carter	State Soil Sicentist	Mississippi
R. Chieruzzi	Civil Engineer (LeRoy Crandall and Associates)	California
J. Christenson	Resource Conservationist (USDA, SCS, Tustin)	California
G. B. Cleveland	Geologist (CDMG)	California
R. Clover	Assistant State Soil Scientist	California
J. W. Cobarrubias	Staff Geologist (Los Angeles Department of Building and Safety)	California
H. R. Collins	State Geologist	Ohio
R. B. Colton	Geologist (Branch of Central Environmental Geology, USGS, Denver)	Colorado
S. G. Conrad	State Geologist	North Carolina
R. E. Corcoran	State Geologist	Oregon
A. Court	Climatologist (California State University at Northridge)	California
J. R. Culver	State Soil Scientist	Nebraska
R. E. Daniell	State Soil Scientist	Kentucky
W. E. Davies	Geologist (Branch of Eastern Environmental Geology, USGS, Reston)	Virginia
C. F. Dodge	Chairman (Department of Geology, University of Texas, Arlington)	Texas

Name	Title/Organization	State
V. H. Dreeszen	State Geologist	Nebraska
S. C. Ekart	State Soil Scientist	North Dakota
L. T. Evans, Jr.	Civil Engineer (L. T. Evans, Inc., Los Angeles)	California
J. A. Ferwerda	State Soil Scientist	Maine
R. W. Flemming	Geologist (USGS, Denver)	Colorado
W. W. Fuchs	State Soil Scientist	Oklahoma
D. L. Gallup	State Soil Scientist	Idaho
T. E. Gay, Jr.	Acting State Geologist	California
T. R. Gerald	Acting State Soil Scientist	South Carolina
F. L. Gilbert	State Soil Scientist	New York
R. L. Googins	State Soil Scientist	Virginia
C. H. Gray, Jr.	District Gologist (CDMG, Los Angeles)	California
H. H. Gray	Head Stratigrapher (Indiana Geological Survey)	Indiana
D. G. Grice	State Soil Scientist	Massachusetts
O. B. Griess	Senior Geologist (Department of Roads)	Nebraska
C. S. Groat	Acting State Geologist	Texas
S. L. Groff	State Geologist	Montana
G. J. Gromko	Civil Engineer (City and County of Denver)	Colorado
T. C. Gustavson	Acting Coordinator (Bureau of Economic Geology)	Texas
R. L. Guthrie	State Soil Scientist	Alabama
C. W. Guernsey	State Soil Scientist	Arizona

Name	Title/Organization	State
W. W. Hagan	State Geologist	Kentucky
R. F. Harner	State Soil Scientist	Michigan
W. F. Hatfield	Assistant State Soil Scientist	North Carolina
O. T. Hayward	Professor, Baylor University	Texas
C. W. Hendry, Jr.	State Geologist	Florida
R. E. Hershey	State Geologist	Tennessee
T. J. Holder	State Soil Scientist	Colorado
L. W. Hough	State Geologist	Louisiana
W. B. Howe	State Geologist	Missouri
T. B. Hutchins	State Soil Scientist	Utah
R. W. Johnson	State Soil Scientist	Florida
D. E. Jones	Chief Engineer (HUD)	Washington, D. C.
R. R. Jordan	State Geologist	Delaware
P. B. King	Geologist (USGS, Menlo Park)	California
A. J. Klingelhoets	State Soil Scientist	Wisconsin
F. E. Kottlowski	State Geologist	New Mexico
R. C. Kronenberger	State Soil Scientist	Wyoming
P. E. LaMoreaux	State Geologist	Alabama
E. M. Lanctot	Bureau of Geology	Maine
G. J. Latshaw	State Soil Scientist	Pennsylvania
W. K. Lee, III	Highway Distrcit Engineer	Maryland
P. Lessing	Geologist (State Geological Survey)	West Virginia
G. Lloyd	Information Division (USDA, SCS)	Washington, D. C.

Name	Title/Organization	State
K. V. Luza	Engineering Geologist (Oklahoma Geological Survey)	Oklahoma
R. L. Lytton	Department of Civil Engineering (Texas A & M University)	Texas
M. L. Markley	State Soil Scientist	New Jersey
J. V. Martin	State Conservationist	Missouri
C. W. McBee	State Soil Scientist	Kansas
D. J. McGregor	State Geologist	South Dakota
C. A. McGrew	State Soil Scientist	Arkansas
R. G. McKeen	University of New Mexico	New Mexico
D. T. McMillan	State Geologist	Utah
B. Miller	Geologist (State Geological Survey)	Tennessee
D. N. Miller, Jr.	State Geologist	Wyoming
R. F. Mitchel	State Soil Scientist	Washington
E. B. Moore, Jr.	Director, Power Plant Siting	Minnesota
H. M. Moore	State Geologist	Mississippi
R. T. Moore	Principal Geologist (Arizona Bureau of Mines)	Arizona
D. Moran	Engineering Geologist-Civil Engineer (Private Consultant, Irvine)	California
E. A. Naphan	State Soil Scientist	Nevada
M. C. Noger	Geologist (Kentucky Geological Survey)	Kentucky
W. W. Olive	Chief - Environmental Geology Branch (USGS)	Kentucky

Name	Title/Organization	State
N. K. Olson	State Geologist	South Carolina
S. M. Pickering	State Geologist	Georgia
S. A. L. Pilgrim	State Soil Scientist	New Hampshire
A. R. Poor	Associate Professor of Civil Engineering (University of Texas-Arlington)	Texas
G. J. Post	State Soil Scientist	Ohio
D. Radbruch-Hall	Geologist (USGS, Menlo Park)	California
J. W. Rogers	State Soil Scientist	Montana
J. W. Rold	State Geologist	Colorado
M. A. Roshardt	Geologist (State Geological Survey)	Wisconsin
D. L. Royster	Chief of Soil and Geologic Engineering (Dept. of Transportation)	Tennessee
E. H. Sautter	State Soil Scientist	Connecticut
R. L. Schuster	Chief, Branch of Engineering Geology (USGS, Denver)	Colorado
K. O. Schmude	State Soil Scientist	West Virginia
F. M. Scilley	State Soil Scientist	Minnesota
B. D. Seay	State Soil Scientist	New Mexico
M. E. Shaffer	State Soil Scientist	Georgia
R. P. Sheldon	Chief Geologist (USGS, Reston)	Virginia
W. Sherman	Chief Geologist (Highway Department)	Wyoming
R. L. Shields	State Soil Scientist	Maryland

Name	Title/Organization	State
J. A. Simon	State Geologist	Illinois
R. P. Sims	State Soil Scientist	Tennessee
H. R. Sinclair, Jr.	State Soil Scientist	Indiana
J. A. Sinnott	State Geologist	Massachussetts
A. E. Slaughter	State Geologist	Michigan
D. R. Smethen	Civil Engineer (U. S. Army Engineer, Waterways Experiment Station)	Mississippi
A. A. Socolow	State Geologist	Pennsylvania
G. F. Sowers	Regents Professor of Civil Engineering (Georgia Institute of Technology)	Georgia
C. E. Stearns	Geologist (USDA, SCS, Davis)	California
R. D. Stieglitz	Head, Regional Geology Section (State Geological Survey)	Ohio
H. C. S. Thom	Chief Climatologist (Retired) (U. S. Weather Bureau)	Washington, D. C.
C. M. Thompson	State Soil Scientist	Texas
G. W. Thorsen	Geologist (Division of Geology and Earth Resources)	Washington
D. T. Trexler	Research Associate (Nevada Bureau of Mines and Geology)	Nevada
E. E. Voss	State Soil Scientist	Illinois
D. Waco	Climatologist (Edwards Air Force Base)	California
R. E. Wallace	Geologist (USGS, Menlo Park)	California

Name	Title/Organization	State
B. G. Watson	State Soil Scientist	Vermont
M. Walton	State Geologist	Minnesota
K. N. Weaver	State Geologist	Maryland
B. Webster	Climatologist (National Weather Bureau, Los Angeles)	California
R. D. Wells	State Soil Scientist	South Carolina
C. M. Wentworth, Jr.	Geologist (USGS, Menlo Park)	California
K. Widmer	State Geologist	New Jersey
F. W. Wilson	State Geologist	Kansas
R. J. Wilson	CALTRANS-Sacramento (Maintenance Planning)	California
C. A. Yelverton	Risk Analysis Insurance (Whittier)	California

APPENDIX B

LISTING OF SLIDES AND COSTS
FOR ALLEGHENY COUNTY, PENNSYLVANIA
FOR SIX MONTHS (JUNE - NOVEMBER, 1972)

RECEIVED JAN 14 1976

COUNTY COMMISSIONERS
James J. Flaherty
CHAIRMAN
THOMAS J. FOERSTER
Robert N. Pierce, Jr.

DEPARTMENT OF PLANNING AND DEVELOPMENT
William R. Dodge, Jr.
DIRECTOR

County of Allegheny
ALLEGHENY BUILDING, 429 FORBES AVENUE, (412) 355-5960
PITTSBURGH, PA. 15219

January 9, 1976

Mr. Jim Krohn
Engineering Geology Consultants
14054 Victory Boulevard
Van Nuys, California 91401

Dear Mr. Krohn:

Enclosed is a list of landslides that were reported to have occurred in Allegheny County between June and December of 1972. As we discussed during our telephone conversation on January 6, 1976, most of these slides occurred during and shortly after a period of high precipitation related to Hurricane Agnes.

The first column of the list refers to a numbering system which I have used in identifying the various landslides. The second column identifies the date associated with a given expenditure or estimate.

If you have any further questions please feel free to contact me.

Yours,

William R Adams Jr.

William R. Adams, Jr.
Engineering Geologist

WRA:jms

Enclosure

NO. OF SLIDE	DATE	COST
	JUNE	
0040		21,966
0070		82,000
0078		100,000
0239		250,000
0055		16,000
0072		8,000
0173		500
0198		250
0049		62,000
0081		47,123
0049		62,000
0081		47,123
0081		10,000
0155		200
0156		200
0157		250
0181		50,000
0101		357
0093		354
0096		13,105
0053		25,000
0056		160,776
0066		7,500
0100		770
0100		4,306
0107		1,868
0164		1,278
0165		275
0166		280
0168		650
0169		20,000
0170		5,000
0171		2,000
0172		2,000
0011		2,400
0015		2,700
0021		2,100
0108		803
0054		11,000
0080		15,000
0105		14,090
0106		19,305
0106		60,000
0162		2,188
0152		228
0152		25,000
0084		76,736
0094		315
0123		1,848
0079		159,000
0133		3,000
0137		30,000
		$1,428,851

No. = 52

AVERAGE = $27,477

NO. OF SLIDE	DATE	COST	
	JULY		
0029		6,633	
0140		3,176	
0141		15,825	
0031		3,650	
0206		2,135	
0233		2,834	
0045		19,405	
0047		1,502	
0047		10,410	
0147		10,410	
0237		250	
0046		41,177	
0165		4,200	
0166		75	
0041		11,440	
0039		3,499	
0190		3,650	
0190		2,220	
0036		5,140	
0038		5,595	
0033		5,000	
0148		1,638	
0149		2,332	No. = 23
		$ 162,198	AVERAGE = $ 7,052
	AUGUST		
0139		5,478	
0528		3,840	
0013		1,410	
0013		5,526	
0229		3,175	
0215		2,150	
0019		20,295	
0654		8,929	
0184		4,774	
0035		2,161	
0044		1,653	
0208		7,116	
0209		7,500	
0205		2,074	No. = 14
		$ 76,081	AVERAGE = $ 5,434
	SEPTEMBER		
0234		4,543	
0528		3,660	
0199		2,160	
0206		1,280	
0231		2,725	
0232		750	
0230		500	
0252		454	

NO. OF SLIDE	DATE	COST	
0215		4,936	
0215		2,347	
0215		1,973	
0216		4,443	
0186		2,677	
0188		5,040	
0092		16,508	No. = 15
		$ 53,996	AVERAGE = $ 3,600
	OCTOBER		
0235		1,415	
0528		2,585	
0013		1,580	
0013		7,572	
0195		650	
0196		550	
0250		2,855	
0223		6,090	
0224		2,335	
0225		900	
0254		3,659	
0187		936	
0028		4,020	No. = 13
		$ 35,147	AVERAGE = $ 2,704
	NOVEMBER		
0253		200	
0013		3,705	
0202		12,504	
0203		1,010	
0225		870	
0226		1,085	
0027		2,745	
0228		6,240	
0046		2,289	
0185		2,225	
0251		800	No. = 11
		$ 33,673	AVERAGE = $ 3,061

SECTION III

EXPANSIVE SOIL

Chapter One

Description of the Hazard

Expansive soil applies to those earth materials (soil, and in some, cases bedrock formations) which have the capacity to undergo volumetric changes when subjected to variances in the water content. When the water content is increased, the soil will swell; likewise, a decrease in moisture content will facilitate soil shrinkage. The degree of shrink/swell capacity is related to clay mineralogy; more specifically, to active clay minerals such as montmorillonite; mixed layer combinations of montmorillonite together with other assorted clay minerals; and under certain conditions vermiculites and chlorites [Snethen, et al, 1975]. Swelling of pure montmorillonite clay (bentonite) can affect volume changes as much as 2000 percent [Tourtelot, 1974] and generate swelling pressures in excess of 30,000 pounds per square foot [Dawson, 1953]. Although illites and kaolinites are generally not considered active, they may also contribute to expansive properties if sufficient amounts are present within a given soil or rock [Snethen, et al, 1975]. Other minerals that may cause expansion problems include anhydrite, certain micas that react with phosphates, and the clay material allapulgite [Sowers, 1975].

Expansion is chiefly caused by the hydration or attraction and absorption of water molecules into the expansible crystal lattice of the clay minerals [Alfors et al, 1973]. Soil shrinkage occurs when the process is reversed and the water is removed or extricated from the clay crystal lattice. The amount of water available to the clay lattice is chiefly dependent on various environmental factors. Of these, climatic conditions can be considered as the single most dominant factor affecting expansive clays. In this respect, the most important aspect of climate is the relationship between rainfall and the rate of evapotranspiration [Lambe, 1960]. In areas where the seasonal climatic changes are greatest (i.e., long droughts alternating with excessive rainfall), expansive clays are very active with pronounced shrinking and swelling quite common. Similarly, in areas where the seasonal changes are less dramatic and the expansive clays are kept wet throughout the year, little or no volume change may occur within expansive clay lattice.

It is known that extensive structural damage occurs in many areas where expansive soils are known to exist. In Texas, it is estimated that expansive soil-related problems cost Texas taxpayers six to ten million dollars annually for highway maintenance [Wise and Hudson, 1971] and that homeowners in Dallas, alone, spend as much as 15 million dollars per year for foundation repairs [Tucker and Poor, 1973].

Jones and Holtz [1973] have estimated that the total annual expansive soil-related damage throughout the United States is a little under 2.5 billion dollars. Their total damage figure is divided into the following:

Single family homes	$ 300,000,000*
Commercial buildings	360,000,000*
Multi-story buildings	80,000,000*
Walks, drives, parking areas	110,000,000
Highways and streets	1,140,000,000
Buried utilities and services	100,000,000
Airport installations	40,000,000
Involved in urban landslides	25,000,000
Other	100,000,000
Total annual damage in U.S.	$ 2,255,000,000

*Note that the amount of damage resulting to buildings, the subject of this study, is 740 million, 1973 dollars.

The Jones and Holtz [1973] study represents at best a conservative estimate of the total damage attributed to expansive soil. Many problems related to expansive soil exist; however, they (i.e., cracked pavement, walls, et cetera) are either: (1) repaired but not recognized as being expansive soil-related or (2) recognized as being expansive soil-related but ingored as a nuisance and not repaired. Also, the Jones and Holtz [1973] figures probably do not reflect the amount of monetary loss attributed to the over-design of structures in either highly or moderately expansive soil areas.

Factual data relating to actual values are either non-existent or limited to localized areas. Further, available studies generally involve residential foundation problems. For convenience, all expansive earth materials subject to shrink-swell volume changes commonly are termed "expansive soils," [Jones, 1976]. For the purposes of this discussion, expansive soils are considered to be soil or rock materials in which clays, white alkali or pyrites constitute a significant fraction of the material's mineral content, and which have a potential for sufficient shrinking or swelling volume change to displace or distort buildings placed on them.

Expansive soils often can be tentatively identified by visual observation, and they generally can be positively identified by appropriate laboratory testing, as laboratory tests for expansive soil identification and for quantification of potential volume changes are commonly described in the technical literature. However, some clues can help identify naturally occurring potentially expansive soils [Jones, 1976]:

Expansive clay soils:

Under dry soil conditions:

- Soil hard and rock-like; difficult to impossible to crush by hand.
- Glazed, almost shiny surface where previously cut by scrapers, ditcher teeth or shovels.
- Very difficult to penetrate with hand held pick or shovel.
- Ground surface displays cracks occurring in a more or less regular pattern. (Crack width and spacing provide some indication of the relative expansion potential in the horizontal plane.)
- Surface irregularities, such as tire tracks, cannot be obliterated by foot pressure.

Under wet soil:

- Soil very sticky and clingy. Exposed soil will build up on shoe soles to a thickness of from two to four inches, or more, when walked upon for a short distance.
- Can be easily molded into a ball by hand. Hand molding will leave a nearly invisible powdery residue on hands after they dry.
- A shovel will penetrate soil quite easily and the cut surface will be very smooth and will tend to be shiny.
- Freshly machine-scraped or cut areas will tend to be very smooth and shiny.

- Heavy construction equipment, such as metal wheels and compacting rollers, will develop a very thick soil coating that may impair their function.
- In semi-arid areas having distinct wet and dry seasons, expansive soils that have been undisturbed for ten to fifteen years or more may display a pattern of closed ridges spaced regularly on ten to fifty foot centers. These ridges are termed "gilgai," an Australian aboriginal term imported by Dr. Robert Lytton. Gilgai spacing provides a coarse indication of the degree of potential volume change.

Under any conditions:

- Creep ridges (visible evidence of solifluction) on slopes. Generally an indication of incipient slope instability as well as of potentially expansive soils.
- Tops of fence posts tilted downhill. This may give obvious indication of downhill creep movements in situations where solifluction patterns are indistinct.
- Extensive visible cracking in walks, streets, driveways, patios, and often in buildings. This does not always mean that expansive soils are present, but they often are when such symptoms are visible.

Alkali in soils:

- Upper few inches to one foot of soil very powdery and loose when the the soil is dry.
- Land having the appearance of being heavily frosted (or lightly covered with snow) shortly before sunrise on cool mornings.
- A narrow white outline around shaded damp soil areas, especially noticeable when air temperature is below about 60°F.
- "Salt Grass" growing in a loose or flaky soil.
- Old fence or other wooden posts having the wood fibers swelled or disrupted immediately above ground level. At times, crystalline deposits may be visible in cracks in the wood.
- Where there are significant concentrations of white alkali in the soil, the soil will have a salty taste.

- Where lightly loaded building floor slabs are cracked and heaved, but relatively heavy exterior building walls show no distress, <u>and</u> the location is in a semi-arid to arid climate, alkali should be suspect although refined testing would be necessary to confirm alkali action.
- Where concrete has extensively spalled or flaked exposed surfaces. This is a particular characteristic of exposure in alkali areas, but also is a common result of repetitive exposure to sodium and calcium chlorides. The basic cause of such flaking is physical swell.

Pyrites in soils:

- Freshly cut or graded areas smell of sulphur dioxide or hydrogen sulphide (rotten eggs).
- On cold days, freshly cut surfaces may give the appearance of smoking.
- Recently exposed materials of a shaly nature may appear split, like the leaves of a partially fanned book. This will be most evident at the ground surface.
- Pyrites may be suspect when there is any indication of acid runoff waters, such as orange to orange-brown stains on concrete culverts or on stones in drainageways.

In general, the following laboratory procedures may be relied upon to be definitive to the extent indicated:

- Atterberg Limit tests (Plastic Limit, Liquid Limit and Plasticity Index) often will identify expansive soils, as most expansive soils will have a Plasticity Index greater than about 15. The expansive potential of soil generally increases with increasing Plasticity Index.
- Shrinkage Limit tests are simple and generally provide significant guidance regarding a soil's possible expansive behavior.
- Consolidometer tests in which compacted soils are loaded and then wetted, with measurements of displacements, generally provide assured and reliable quantifications of a soil's expansive potential. The consolidometer test is the most reliable test listed. (See Appendix A for further discussion.)

The geotechnical engineer generally works in the province that the geologist terms "surficial geology." Maps delineating surficial geology often identify known expansive materials, such as the Denver Shale, Pierre Shale or the Yazoo Clay Shale. Surficial geologic maps often can be advantageously supplemented by modern United States Department of Agriculture Soil Conservation Service soils maps, usually covering entire counties. Interpretative information accompanying the published soils maps generally identifies specific pedologic soil series having expansive potentials, and often identifies a range of swell potential values that may be anticipated for each listed soil series. Everyone should be cautioned, however, that individual site exploration and soils testing is always appropriate for individual properties and is the only fully reliable approach to identifying and quantifying an expansive potential. This is stated because mapping scales and information are coarse and can be grossly misleading if relied upon alone [Jones, 1976].

Damages range from minor cracking of interior finishes in dwellings, which is very common, to irreparable displacements of major dwelling structural elements. The movements also damage utilities. It has been rumored that the gas leak in the New London School disaster, one of the world's worst modern disasters which killed 296 Texas school children, may have been caused by expansive soil deformation of a gas pipe [Jones, 1976].

Virtually none of the cited damages are covered by insurance, as expansive soil damage is generally uninsurable. Note that over one-half of the loss is a public loss, and that a significant portion of the private loss can be a tax expenditure.

Chapter Two

Expansive Soil Occurrences (Hazard Model)

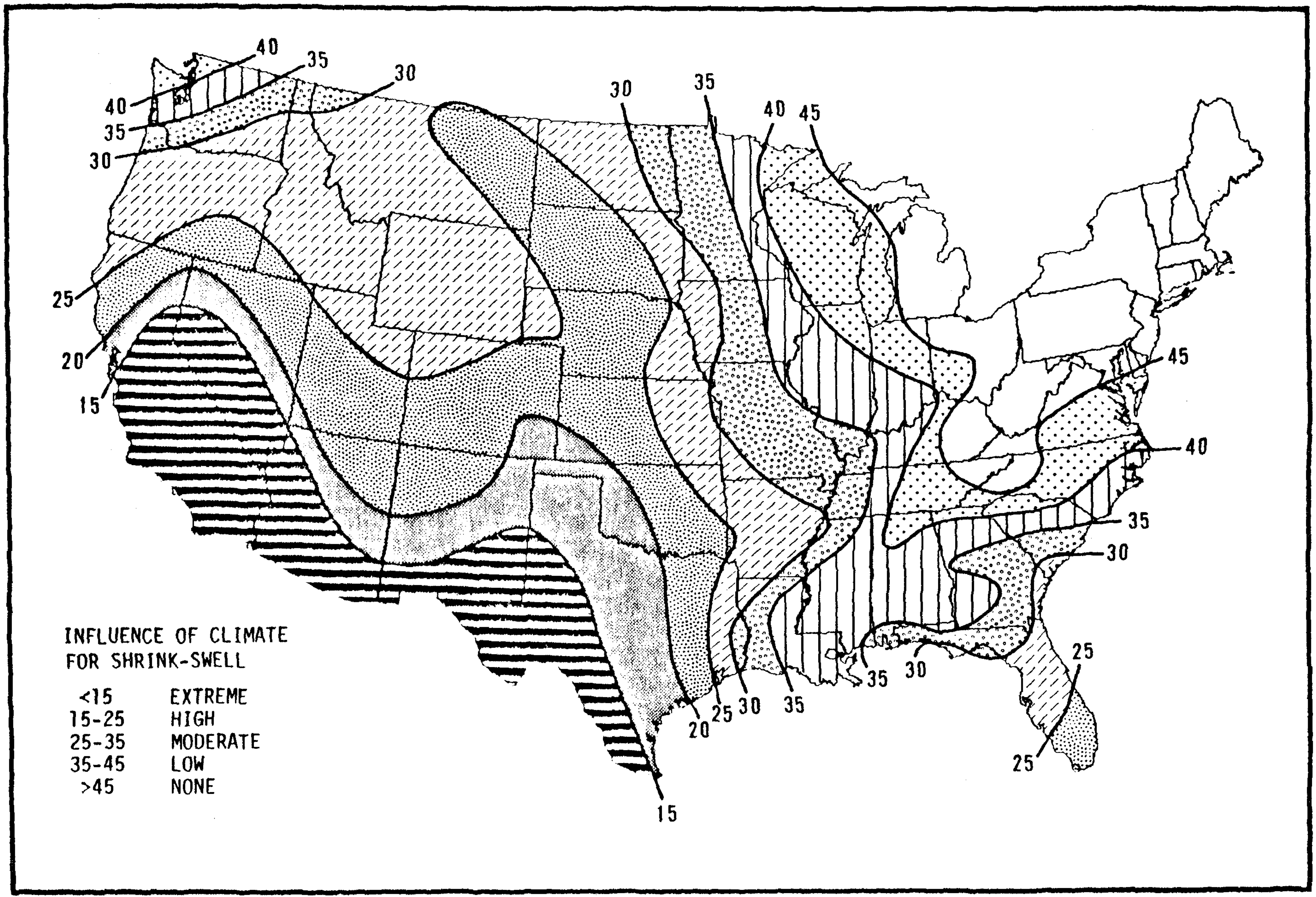
Development of Intensity Probability

Several workers have attempted to devise climatic rating systems based on rainfall distribution, evapotranspiration, and/or drainage characteristics [Thornwaite, 1948; Prescott, 1949; and Thom and Vestal, 1968]. Based on work performed by Thom and Vestal [1968], the Building Research Advisory Board (BRAB) for the Federal Housing Administration (FHA) produced a climatic rating system for the United States in 1971. These ratings, along with a unified soil classification designation, constitute the FHA approved way of selecting the required foundations where a lower expansive soil index rating suggests a potentially worse condition [Mathewson and others, 1975].

Figure 3-1 represents the climatic rating chart as present in the BRAB 1968 publication, the contour intervals 15-45 represent the summation of monthly gamma distribution values for 122 first order weather stations scattered throughout the country. For further discussion of the gamma distribution, the reader is referred to Thom [1958] and Thom and Vestal [1968]. Basically, the contour intervals relate to a frequency distribution for precipitation. The lower numbers reflect areas where climatic change is likely to be most severe (i.e., periods of rainfall mixed with periods of drought) which aggravates expansive soil. Likewise, the higher numbers correspond to generally wetter and climatically more invariant regions where the expansive soil conditions are less aggravated.

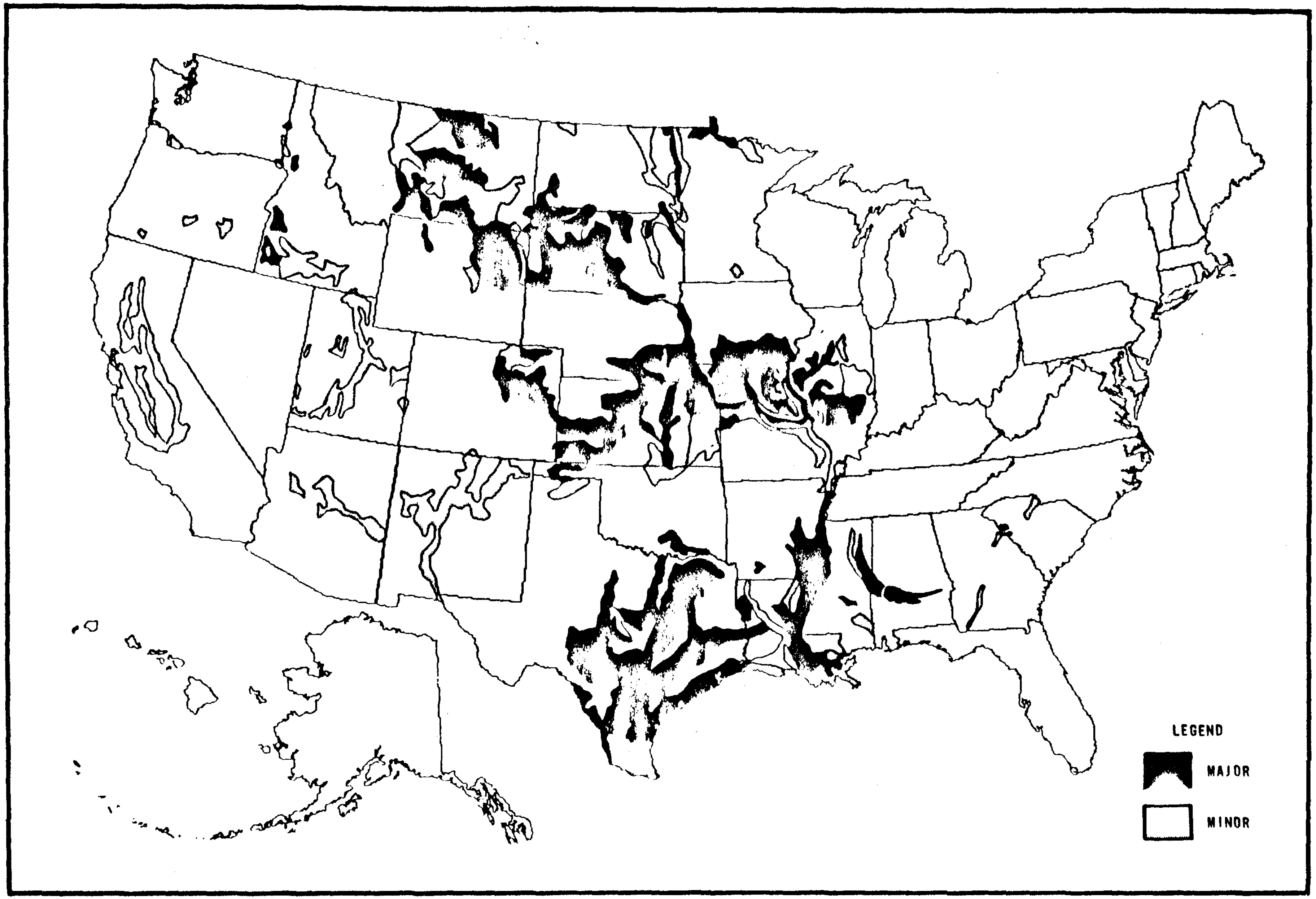
Figure 3-1 could be combined with the distribution of major areas of soils classified in montmorillonitic families in order to produce an intensity index for expansive soil. Such a distribution was constructed by the Soil Geography Unit, Soil Conservation Service, U.S. Department of Agriculture in January of 1976 (unpublished) at our request. Their map has been highlighted in Figure 3-2.

The map shows the areas in which soil series of montmorillonitic and montmorillonitic (calcareous) families are distributed. In general, these soils have subsoils with high or very high shrink-swell potentials (COLE of 0.06 or more).



77-1246

Figure 3-1. Climatic Ratings for the Continental United States (after Building Research Advisory Board, 1968; based on Thom and Vestal, 1968)



77-1246

Figure 3-2. Distribution of Major Areas of Soils Classified in Montmorillonitic Families (Prepared by Soil Geography Unit, SCS, USDA)

Areas of these soils other than those delineated on the map also exist but either could not be shown at the scale of this map or were not sufficiently extensive to be identified and located on the reference maps used in this compilation.

Other soils with moderate to very high shrink-swell potentials that occupy a significant proportion of the landscape are not shown on the map. These soils are fine-textured ones with either illitic or mixed mineralogy, e.g., those developed in the glacial lake sediments in the northwestern part of Ohio.

Delineations on the map are based on those map units on general soil maps of the respective states which include soil series having montmorillonitic mineralogy. However, those shown in the states of Arizona, California, New Mexico, Oregon, and Utah are based on soil series identified as "examples", "representative series", or "characteristic series". The areas shown in Colorado are based on an older general soil map of the state, inasmuch as the recently published one does not identify soil series in the map legend and there is no accompanying descriptive text.

Relative extent was estimated from the number of montmorillonitic series in the name of the map units and the sequence of soil series names in the names of the map units on the reference maps [Distribution of Principal Kinds of Soils: Orders, Suborders, and Great Groups, National Cooperative Soil Survey Classification of 1967, Compiled by the Soil Conservation Services, 1967].

Other environmental sources of moisture supply or depletion are basically related to the development of an area by man and can be controlled [Vijay-Vergiya and Sullivan, 1974]:

1. Vegetation, particularly trees with high water demand can dry out a clay, causing shrinkage [Hammer, 1966].
2. Poor drainage, a function of topography, can cause surface water to pond thereby resulting in localized swelling [Mathewson, et al, 1975].
3. Faulty or leading subsurface utility systems (i.e., water and sewage).
4. Local watering of lawns and gardens can adversely affect ambient moisture conditions [Snethen, et al, 1975].
5. The presence of a building or structure may reduce the rate of water evaporation from the foundation soil, thereby affecting moisture content.

If the water is not removed from the foundation soil it will be imbibed by the soil rather than evaporated, resulting in swelling [Lambe, 1960].

The above examples represent just a few of the many factors, besides climate, which can influence the intensity probability of expansive soils.

Expansive soil occurs throughout the United States in some states more than others. The appearance of the highly expansive material is generally quite distinctive following desiccation. Ground surfaces characterized by polygonal shrinkage areas (desiccation cracks) reflect the presence of clay and possible expansive clay minerals. Generally, smaller polygons are indicative of higher clay content. Desiccation surfaces which appear to be the size and texture of "popcorn" probably reflect the presence of bentonite or other soil/rock rich in montmorillonite [Snethen, et al, 1975]. The depth to which desiccation may occur varies from few feet to as much as 60 feet below the ground surface [Lambe, 1960].

There is an "apparent" lack of information involving the extent and distribution of expansive soil intensity on a nationwide basis. Several authors have addressed the problem; however, in most instances their work is in the form of "case histories" and limited to localized areas.

Many federal (i.e., U.S. Department of Agriculture, U.S. Geological Survey, etc.) and state (Geological Surveys, Soil Scientists, etc.) agencies recognize the problem; unfortunately, many of these agencies have done little or no work in the expansive soil intensity field. At the federal level, work that has been done to date is generally localized and of limited value. Most of the work in the form of countywide soil surveys has been done by the U.S. Department of Agriculture, Soil Conservation Service. At the state level, California is the only state that has an expansive soil map, per se.

Only a few workers have attempted to delineate areas of expansive soil intensity on a nationwide basis [Witczak, 1972; Tourtelot, 1974; and Snethen, et al, 1975], these previous studies are of only limited value owing to restriction in map size (approximate map size smaller than 1:17,000,000) and/or to the highly generalized nature of the data.

Derivation of Expansive Soil Intensity Map

The expansive soil map developed for this report is based on a compilation of information obtained from numerous county, state, and national governmental agencies as well as selected individual data sources scattered throughout the country. These "data" were in the form of comments, personal opinions, published and/or unpublished documents. The chief source of information was provided by the Soil Geography Unit of the Soil Conservation Service, U.S. Department of Agriculture [Ackerson]. At our request, the Soil Geography Unit prepared a soil map of the continental United States Figure 3-2, (approximate scale 1:7,500,000). Their map defines the approximate extent and distribution of montmorillonite soil. Additional comments and documents were collected from the State Geologists and State Soil Scientists from each state. This material was further supplemented by literary references as well as data collected from selected highway departments, county agencies, and universities [see Appendix B]. All of the data collected were then reviewed, assimilated, and transformed into an Expansive Soils Map of the continental United States at a scale of 1:5,000,000 [Figure 3-3]. This map may be compared with that recently published in Civil Engineering Magazine [1978] [see Figure 3-4].

The map attempts to delineate those broad geographic areas which contain montmorillonite soils. There are over 12,000 soil series throughout the entire country, of which approximately 10% contain montmorillonite mineralogy. Of these, about 250 soil series are extensive enough to be shown as mappable units on intermediate scale generalized state soil maps. Therefore, for purposes of this study only these larger mappable units have been considered. Most state soil maps, however, do not list engineering properties, or indicate shrink-swell potential. Consequently, heavy reliance was placed on comments supplied by the Soil Conservation Service, namely the Soil Geography Unit, and the various State Soil Scientists, in order to distinguish montmorillonitic soils from other soils.

Soils other than those having montmorillonitic mineralogy are known to have high shrink-swell potentials. These soils contain many of the clay minerals mentioned earlier in the text (i.e., illites, mixed-layered clay, etc.). However, owing to constraints imposed by time and difficulty in retrieving estimates of shrink-swell potentials from existing data, these soils have not been included in this compilation. Therefore, areas containing moderate or high shrink-swell may exist in regions other than those delineated on the accompanying Expansive Soils Map.

J.H.WIGGINS CO.

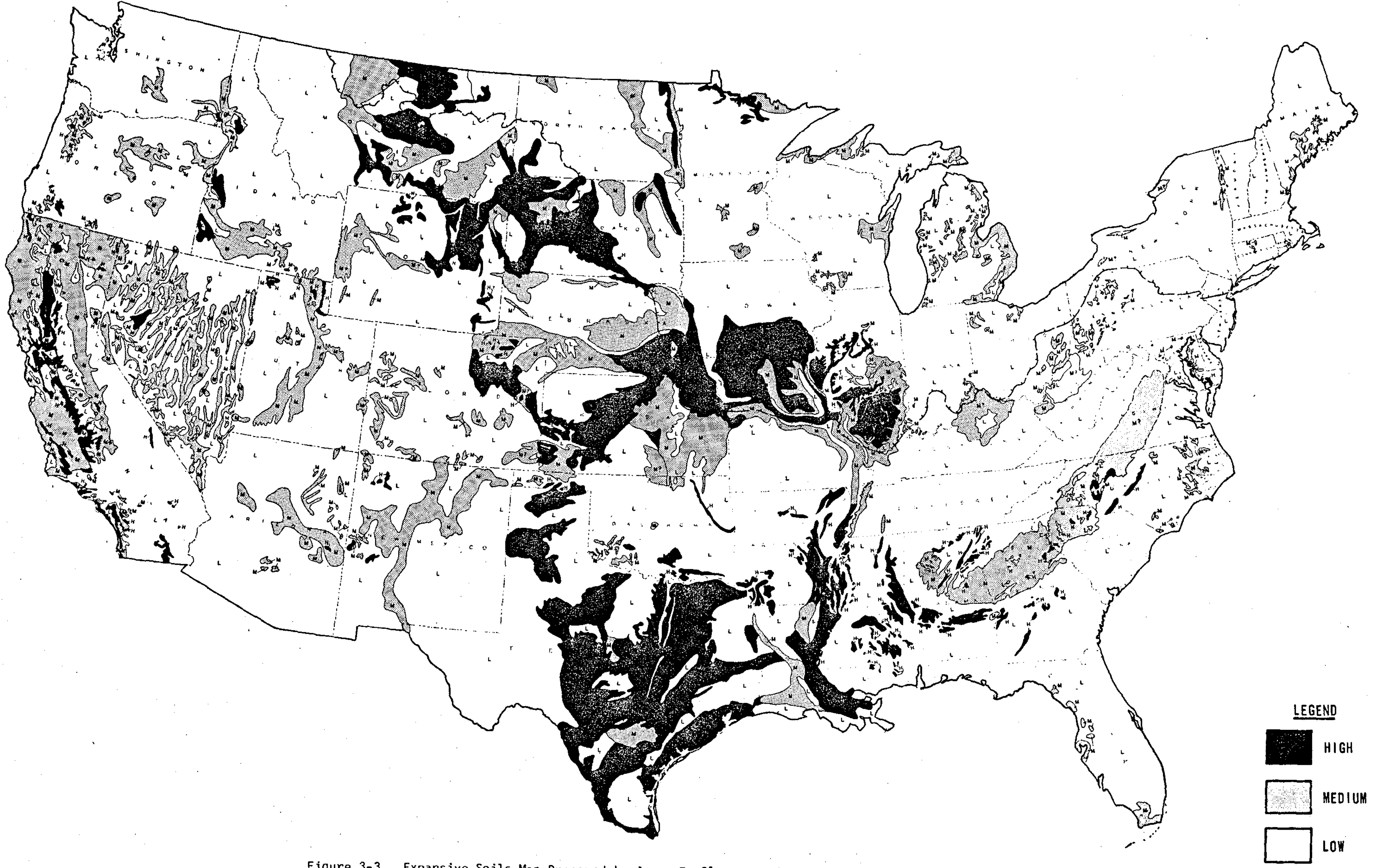
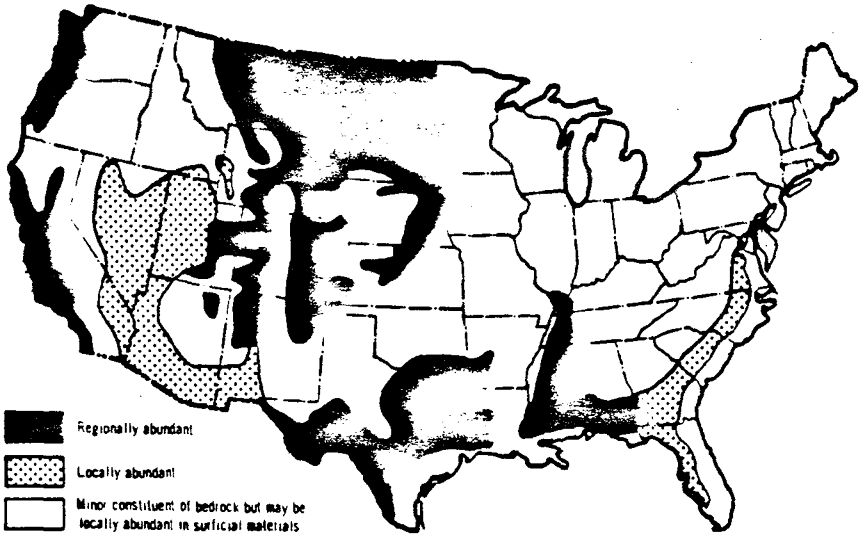


Figure 3-3. Expansive Soils Map Prepared by James E. Slosson and Associates Engineering Geologists February, 1976

77-1248



Source: <u>Civil Engineering</u>, ASCE, October 1978

Figure 3-4. Map of U.S. shows that expansive soils are present in many of the states. Such soils are the mose widespread problems in areas labeled "Regionally Abundant." However, many locations of these areas will have no expansive soils; and in white portions of the map, in some places, expansive soils will be found.

It should be emphasized also that the quality of the map is only as good as the reference material used to compile the map. In this respect, some states have obviously done more work than others in the expansive soil field. This fact is very evident, especially where highly or moderately expansive soil from one state stops abruptly at the state line, instead of proceeding into the adjoining state. Therefore, the ultimate accuracy of the accompanying Expansive Soils Map is dependent upon the work done to date in each respective state.

Intensity

The Expansive Soils Map is divided into three general categories of intensity. They range from high (H) the most severe rating through moderate (M) to low (L), the least severe rating. These ratings generally correspond to shrink-swell potentials as defined by the Soil Conservation Service. The quantitative method used by the Soil Conservation Service [1971] for determining shrink-swell behavior of soil is referred to as the Coefficient of Linear Extensibility (COLE). COLE basically represents an estimate of the vertical component of swelling in a natural soil clod. In preparation of the Expansive Soils Map the following somewhat modified Soil Conservation Service definitions were used to define the map severity ratings.

High: Generally includes soils high in clay, that are made up of a large percentage of montmorillonitic minerals. These soils have a COLE value usually greater than 6%.

Moderate: Generally includes soils containing moderate amounts of clay that also contain some montmorillonitic minerals. COLE values for these soils vary between 3% and 6%.

Low: Generally includes soil containing some clay; however, the clay consists mainly of kaolinite and/or other low shrink-swell clay minerals. These soils have COLE values generally lower than 3%.

Several assumptions were made during the compilation of the Expansive Soils Map. The following premises guided our judgement in developing the map categorizations.

1. Areas underlain by soils containing montmorillonitic rocks, sediments or soils will control the degree of expansiveness.
2. The degree of expansion is a function of the amount of expandable clay minerals present.
3. The categorization does not consider climate or environmental aspects, owing to a lack of pertinent data.
4. Many of the areas north of the glacial boundary (i.e., Montana, North Dakota, et cetera) may contain potential expansive material (i.e., Pierre Shale). However, several of these areas have been categorized as non-expansive, owing to the cover of glacial deposits. Whether the glacial material is expansive is a function of the texture and mineralogy of the source material. Glaciated areas remain wet the year around, owing to high precipitation, poor drainage and high water tables. This detection of expansive soil is also limited by these environmental conditions. Insufficient data were available during this study to determine the expansive properties of much of this glacial material.
5. Although a given severity rating has been assigned to an area, smaller portions of that area may have ratings both higher and/or lower than the rating shown.

6. Soils as they appear on most state maps, appear as soil "associations." These associations generally consist of one, two, or three soil "series." A hypothetical soil association may contain three soil series (A-B-C), with (A) always representing the dominant soil series followed by B, then C. Therefore, for purposes of this study, if soils in positions A, AB, AC, and BC were montmorillonitic, the soil association was assigned a high shrink-swell rating. However, if only those soils in positions B and C were montmorillonitic, then the entire soil association was given a moderate shrink-swell rating. In the case of a soil association consisting of only one (A) or two (A-B) soil series, a high rating was assigned to the entire association, providing the lone soil series (A) or one of the two soil series (A or B) contained montmorillonitic material.
7. The vast majority of the area depicted on the Expansive Soils Map has been designated as having a low severity rating. It is recognized that many areas throughout the country are void of expansive soil material; however, owing to constraints imposed by time and the lack of sufficient data, there has been no distinction between areas containing "low" quantities of expansive soil versus areas containing "no" expansive material. Most Soil Conservation Service Soil Surveys consider "low" or "very low" as the minimal rating when discussing shrink-swell potential. Therefore, for purposes of this study a low severity rating includes both low and non-expansive soil areas.

Chapter Three

Exposure Model (Value at Risk)

Because of the simplicity of the damage algorithm developed in the following chapter, it was necessary to restrain the development of our exposure model to an equally simple level. The damage algorithms are developed in terms of average foundation repair cost being $1650, irrespective of the foundation type. Further, this value was computed only for dwellings (houses) and does not relate to commercial-industrial-public type buildings which are heavier per square foot and are usually engineered.

However, since expansive soil pressures can be extreme even for engineered structures, since repair costs for a damaged engineered structure can be proportionately higher than that for a dwelling, and since the values at risk in the commercial-industrial-public sector of the building stock is high, damages to this sector must be treated. Treatment of the exposure loss model was developed by the equation,

$$E(c) = V(c)/V(r) \times P(c) \tag{1}$$

where $E(c)$ = Equivalent building value at risk sensitive to expansive soil (persons)

$V(c)$ = the total building value per person in county, c(1970$)

$V(r)$ = average residential building value between California and Dallas County, Texas per person (1970$)

$P(c)$ = population in the county in question

The above equation, although coarse, allows one to modify the Dallas County and California data for the rest of the country's residential and other buildings.

Chapter Four

Vulnerability Model and Damage Algorithms

Homeowners in Dallas County, Texas report approximately 8470 residential foundation failures annually [Smith and Allen, 1974]. The failures all involve expansive soil related problems (i.e., cracked walls, foundations, et cetera). It appears that approximately 67 percent of the foundation failures occur within "high" expansive soil areas, 32 percent relate to "moderate" expansive soil areas, and less than one percent occur in "low" expansive soil areas. In 1970, based on census data, there were 292,637 residential foundations in Dallas County [Smith and Allen, 1974]. Of the total number of foundations, approximately 46 percent exist on "high" expansive soil, 51 percent occur on "moderate" expansive material and 3 percent were constructed in "low" expansive soil areas. Assuming that the average foundation repair cost is $1,650 [Smith and Allen, 1974], the following generalizations can be inferred:

1. The average annual damage cost for residential foundations in Dallas County, Texas for high expansive soil areas appears to be $70.00 per foundation per year. Foundation costs in moderate and low expansive soil regions are estimated to be $30.00± and $8.00 per foundation per year.

Map Severity Rating Zone Z	Total No. Foundation	Annual Foundation Failures		Cost per Foundation		Total Cost of Annual Foundation Failures
High	134,434	5700	x	$1,650.00	=	$9,405,000.00
Moderate	150,000	2730	x	$1,650.00	=	$4,504,500.00
Low	8,203	40	x	$1,650.00	=	$ 66,000.00
TOTAL	292,637	8470		-		-

$$\text{Damage Loss per Foundation per year} = \frac{\text{Total Cost of Annual Foundation Failures}}{\text{Total Number of Foundations per Severity Rating}} =$$

Preceding page blank

Map Severity Rating Zone Z	Damage Loss per Foundation per year
High	$70.00±
Moderate	$30.00±
Low	$ 8.00±

2. The average population rate per dwelling in Dallas County is estimated, by 1970 census data, to be approximately 3 persons per housing unit. Therefore, residential foundation failure loss per capita are:

Map Severity Rating Zone Z	Damage Loss per Capita per year
High	$23.00
Moderate	$10.00
Low	$ 3.00

Expansive soil related losses have also been calculated for California and are discussed in the California Division of Mines and Geology, Open File Report 72-2. The method used to establish the map severity code used in the California study is somewhat similar to the method incorporated in this report. Results of the California report [Alfors, et al, 1971] are as follows:

Map Severity Rating Zone Z	Damage Loss per Capita per year
High	$22.30
Moderate	$ 6.92
Low	$ 1.14

Averaging the California statistics with those of Dallas County, the following figures would result:

Map Severity Rating Zone Z	Damage Loss per Capita per year
High	$23.00
Moderate	$ 8.00
Low	$ 2.00

These figures, in our opinion, probably represent the best estimated expansive soil damage related losses based on the limited data at our disposal. Using different estimates of the Dallas County data, damage loss per capita per year averaged with the California data, the losses are estimated to be: High, $26; Medium, $8; and Low, $1.50.

Climate ratings [Figure 3-1] were not considered in the above damage loss calculations. Unfortunately, both Dallas County and most of California are located in the more severe climate rating areas (below the 25 contour in Figure 3-1). Therefore, without sufficient data from less severe climatic regions, the total impact of the climatic rating system can not be developed. However, it may be noted that the values per capita for Dallas are virtually the same as those for California. Yet the climatic rating for Dallas is about 20 while that for California is about 15.

Chapter Five

Risk Model - Computations of Expected Losses

In order to develop an appreciation for the size of the national annualized loss to buildings due to expansive soil, the exposure model developed above was multiplied by the intensity factor, Z. Z is \$23/person for "high", \$8/person for "moderate", and \$2/person for "low" zones of expansive materials. It was assumed that all population was centered at the latitude/longitude location of each county seat. Therefore, the zone factor for each county seat was read from Figure 3-3, and the loss by county, L(c) calculated.

$$L(c) = Z \times P(c)^{*} \qquad (2)$$

Note that <u>no</u> estimate for commercial-industrial damages by expansive soil is made. Although there has been considerable experience about this type of damage, it is believed by the authors to be conservative for us not to include this exposure. The annualized losses estimated for 1970 conditions are about \$1,100 million (see Table 3-1 for a complete breakdown by state), for <u>all</u> single and multi-family structures.

Table 3-1 shows not only the losses computed for 1970 but also those expected in the year 2000. There is an expected growth of expansive soil losses by 142% during the interim period. Table 3-1 also illustrates the effects of reading the map by two different observers. The difference in total damage estimated is 2.83%. Finally, Table 3-1 shows the effect of using two different sets of damage intensity factors, Z. The difference in total damage estimated is virtually zero.

It may be argued that all of the population in each county does not live in single family dwellings from which the damage intensity factors were generated. As a further limiter, it may be argued that engineered condominium, apartment, or other multi-family dwelling structures, as well as commercial-industrial structures are not damaged by expansive soils. Table 3-2 gives a breakdown of population living in single and multi-family dwellings by expansive soil zone and state. Using the percentage computed, a new figure for 1970 losses for single family dwellings only is developed to be \$798 million as compared with \$1,132 million. The decrease of \$335 million represents about 30 percent of the original total.

---

*To include the commercial, industrial and government buildings, this term must be replaced by E(c).

Preceding page blank

					EXPANSIVE SOIL LOSSES ($MILL.)			
STATE	TOTAL STRUCTURE VALUE ($BILL.)		POPULATION (MILLIONS)		H=$23; M=$8; L=$2 MAP READING NO.1		H=$26; M=$8; L=$1.50 MAP READING NO. 2	H=$23; M=$8; L=$2 MAP READING NO.2
	1970	2000	1970	2000	1970	2000	1970	1970
AL	26.7	65.0	3.44	4.17	11.6	27.1	17.9	18.1
AK	3.9	8.6	0.27	0.34	-	-	-	-
AZ	16.9	47.8	1.77	2.78	3.9	11.0	3.1	4.0
AR	13.6	32.4	1.92	2.18	6.5	14.4	8.2	8.4
CA	228.0	539.8	19.96	26.03	226.8	541.3	268.1	245.2
CO	22.7	56.1	2.21	2.86	23.3	59.3	26.3	24.2
CT	35.0	82.6	3.03	4.05	12.9	30.6	12.0	12.9
DE	5.7	14.4	0.55	0.75	1.1	2.8	0.8	1.1
DC	12.6	42.4	0.76	1.49	2.5	8.3	2.2	2.5
FL	61.1	198.8	6.79	11.61	17.6	56.1	21.0	23.4
GA	41.5	116.0	4.59	6.32	23.8	69.9	24.2	24.9
HI	10.0	26.2	0.77	0.11	-	-	-	-
ID	6.3	13.5	0.71	0.79	3.5	7.6	2.9	3.1
IL	126.8	286.8	11.12	13.60	47.3	108.4	38.7	41.6
IN	48.8	118.2	5.20	6.56	10.7	26.2	8.1	10.7
IA	25.8	53.4	2.83	3.03	23.2	50.3	17.7	17.2
KS	21.5	47.0	2.25	2.51	28.4	65.1	31.9	29.3
KY	25.6	65.8	3.22	4.04	11.9	31.4	10.8	11.9
LA	30.3	66.4	3.64	3.91	44.1	98.4	34.9	32.7
ME	8.3	17.0	0.99	1.05	3.7	7.8	3.4	3.7
MD	49.2	133.3	3.92	5.71	10.8	28.8	9.6	11.2
MA	63.4	151.3	5.69	7.48	12.4	29.5	9.6	12.4
MI	90.8	206.6	8.88	10.89	56.9	129.0	55.7	56.9
MN	37.7	91.8	3.80	4.80	9.6	22.3	8.0	9.6
MS	14.6	33.0	2.22	2.36	14.3	34.1	15.4	14.8
MO	45.1	101.2	4.68	5.40	62.9	143.4	50.0	46.9
MT	6.4	12.3	0.69	0.68	5.2	10.0	5.3	5.2
NE	14.3	31.2	1.49	1.67	24.6	55.8	28.2	25.5
NV	5.8	17.7	0.49	0.84	4.2	12.9	1.9	2.0
NH	7.4	18.1	0.74	0.97	1.4	3.5	1.1	1.5
NJ	83.7	199.2	7.17	9.53	16.3	38.8	12.9	16.3
NM	9.1	20.2	1.02	1.15	4.8	10.9	4.7	4.9
NY	229.6	511.3	18.24	22.55	45.0	100.2	36.6	45.0
NC	40.0	103.0	5.08	6.53	24.0	62.7	23.4	24.3
ND	4.8	8.9	0.62	0.57	2.7	5.0	2.6	2.7
OH	106.3	242.5	10.66	12.82	25.3	57.9	20.3	25.3
OK	23.1	55.8	2.56	3.08	20.5	54.5	5.7	6.7
OR	19.9	45.1	2.09	2.49	16.8	38.0	6.4	7.1
PA	116.1	252.0	11.80	13.49	26.1	56.2	20.4	26.1
RI	9.3	20.4	0.95	1.14	1.8	4.0	1.4	1.9
SC	19.6	48.0	2.59	3.20	7.2	17.6	10.2	11.0
SD	5.3	10.4	0.67	0.65	3.9	7.5	4.5	4.3
TN	30.8	80.0	3.92	5.04	10.1	26.4	8.3	10.1
TX	103.7	261.0	11.20	14.37	173.8	454.9	181.1	163.3
UT	10.6	27.2	1.06	1.39	7.1	18.5	7.4	7.4
VT	3.8	8.6	0.44	0.51	0.9	1.9	0.7	0.9
VA	48.8	133.0	4.65	6.46	13.6	36.7	11.8	13.8
WA	35.6	78.5	3.41	3.99	7.9	17.0	6.2	7.9
WV	14.2	29.5	1.74	1.73	5.4	11.0	4.6	5.4
WI	41.2	89.5	4.42	5.10	10.9	23.8	8.9	10.9
WY	3.2	6.4	0.33	0.33	2.9	5.5	3.2	3.0
U.S.	2064.5	4925.2	203.24	255.10	$1132.1	$2734.3	$1098.3 Δ = 2.99%	$1100.0 Δ = 2.83%

Table 3-1. Expansive Soil Losses by State (1970$)

STATE	POPULATION TOTALS (1970)	TOTAL POPULATION RESIDING IN:			TOTAL POPULATION RESIDING IN SINGLE FAMILY UNITS					DOLLAR LOSSES IN 1970 (H-$26/p, M-$8/p, L-$1.50/p)				LOSSES IN 2000
		HIGH ZONES	MEDIUM ZONES	LOW ZONES	HIGH ZONES	MEDIUM ZONES	LOW ZONES	TOTAL	STATE AV. %	HIGH ZONES	MEDIUM ZONES	LOW ZONES	TOTAL	
ALABAMA	3,444,297	339,761	681,647	2,422,889	271,056	551,254	1,996,643	2,818,953	82.9	7,047,456	4,410,032	2,994,964	14,452,452	27.9
ARIZONA	1,772,658	3,230	60,801	1,708,627	2,771	44,385	1,247,298	1,294,454	73.0	72,046	355,080	1,870,947	2,298,073	4.4
ARKANSAS	1,923,239	217,840	--	1,705,399	185,818	--	1,454,705	1,640,523	85.3	4,831,268	--	2,182,058	7,013,326	13.6
CALIFORNIA	19,948,352	8,611,514	4,189,730	7,147,108	5,878,225	2,866,256	4,548,949	13,293,430	67.0	152,833,850	22,930,048	6,823,424	182,587,322	353.0
COLORADO	2,207,259	899,105	155,147	1,153,007	601,461	111,551	827,859	1,540,871	71.8	15,637,986	892,408	1,241,789	17,772,183	34.4
CONNECTICUT	3,032,217	--	1,143,961	1,888,256	--	676,081	1,115,959	1,792,040	59.1	--	5,408,648	1,673,939	7,082,587	13.7
DELAWARE	548,104	--	3,165	544,939	--	2,390	411,429	413,819	75.5	--	19,120	617,144	636,264	1.2
DIST.OF COLUMBIA	756,510	--	157,730	598,780	--	58,045	220,351	278,396	36.8	--	464,360	330,527	794,887	1.5
FLORIDA	6,790,360	--	1,669,730	5,120,630	--	1,158,793	3,553,717	4,712,510	69.4	--	9,270,344	5,330,576	14,600,920	28.2
GEORGIA	4,589,981	142,603	2,122,063	2,325,315	112,260	1,454,960	1,739,336	3,306,556	74.8	2,918,760	11,639,680	2,609,004	17,167,444	33.2
IDAHO	712,837	13,322	237,059	462,456	11,615	194,942	371,815	578,372	80.4	301,990	1,559,536	557,723	2,419,249	4.7
ILLINOIS	11,112,738	584,478	1,188,180	9,340,080	493,648	923,036	5,647,594	7,064,278	59.2	12,834,848	7,384,288	8,471,391	28,690,527	55.5
INDIANA	5,195,332	--	45,606	5,149,726	--	35,573	4,016,786	4,052,359	78.0	--	284,584	6,025,179	6,309,763	12.2
IOWA	2,825,379	548,760	--	2,276,619	457,751	--	1,859,998	2,317,749	81.7	11,901,526	--	2,789,997	14,691,523	28.4
KANSAS	2,249,071	939,990	849,743	459,338	760,305	693,390	374,820	1,828,515	81.6	19,767,930	5,547,122	562,230	25,877,282	50.0
KENTUCKY	3,219,345	--	911,568	2,307,777	--	727,431	1,841,606	2,569,037	79.8	--	5,819,448	2,762,409	8,581,857	16.6
LOUISIANA	3,643,173	1,128,999	278,338	2,235,836	837,173	253,985	1,661,975	2,753,133	78.0	21,766,498	2,031,880	2,492,962	26,291,340	50.8
MAINE	993,722	--	291,509	702,213	--	198,226	477,505	675,731	68.0	--	1,585,808	716,258	2,302,066	4.5
MARYLAND	3,924,804	18,924	493,840	3,412,040	16,161	339,762	2,347,484	2,703,407	68.8	420,186	2,718,095	3,521,225	6,659,506	12.9
MASSACHUSETTS	5,689,170	--	162,693	5,526,477	--	81,997	2,785,344	2,867,341	50.4	--	655,976	4,178,016	4,833,992	9.3
MICHIGAN	8,880,122	--	6,527,276	2,352,846	--	4,954,202	1,785,810	6,740,012	75.9	--	39,633,616	2,678,715	42,312,331	81.8
MINNESOTA	3,804,801	36,383	211,940	3,556,478	28,094	154,928	2,599,785	2,782,807	73.1	730,444	1,239,424	3,899,678	5,869,546	11.3
MISSISSIPPI	2,216,994	493,220	--	1,723,774	422,196	--	1,475,550	1,897,746	85.6	10,977,096	--	2,213,325	13,190,421	25.5
MISSOURI	4,677,618	1,307,175	1,685,827	1,684,616	1,059,933	972,954	1,248,805	3,281,692	73.7	27,558,258	7,783,632	1,873,208	37,215,098	71.9
MONTANA	694,345	55,259	445,088	193,998	44,935	329,810	143,753	581,498	74.1	1,168,310	2,638,480	215,630	4,022,420	7.8
NEBRASKA	1,485,321	904,788	580,533	--	678,503	460,943	--	1,139,446	79.4	17,641,078	3,687,544	--	21,328,622	41.2
NEVADA	488,738	2,628	162,037	324,073	2,000	97,384	194,768	294,152	60.1	52,000	779,072	292,152	1,123,224	2.2
NEW HAMPSHIRE	737,681	--	--	737,681	--	--	468,427	468,427	63.5	--	--	702,640	702,640	1.4
NEW JERSEY	7,172,164	--	329,279	6,842,885	--	190,653	3,962,030	4,152,683	57.9	--	1,525,224	5,943,045	7,468,269	14.4
NEW MEXICO	1,016,000	10,943	446,724	558,333	8,593	363,633	454,483	826,709	81.4	223,418	2,909,064	681,725	3,814,207	7.4
NEW YORK	18,241,266	--	1,424,345	16,816,921	--	574,011	6,777,219	7,351,230	40.3	--	4,592,088	10,165,828	14,757,916	28.5
NORTH CAROLINA	5,084,430	270,256	1,401,603	3,412,571	210,924	1,153,519	2,808,546	4,172,989	82.3	5,484,024	9,228,154	4,212,819	18,924,997	36.6
NORTH DAKOTA	617,792	37,870	111,886	468,036	26,808	82,684	345,879	455,371	73.9	697,008	661,472	518,818	1,877,298	3.6
OHIO	10,656,533	--	663,772	9,992,761	--	476,588	7,174,802	7,651,390	71.8	--	3,812,704	10,762,203	14,574,907	28.2
OKLAHOMA	2,559,451	70,241	19,239	2,469,971	61,947	15,931	2,081,861	2,159,739	84.9	1,610,622	127,448	3,122,792	4,860,862	9.4
OREGON	2,091,533	51,671	306,165	1,733,697	40,661	239,718	1,333,213	1,613,592	76.9	1,057,186	1,917,744	1,999,820	4,974,750	9.6
PENNSYLVANIA	11,797,342	--	422,319	11,375,023	--	306,604	8,258,266	8,564,870	72.6	--	2,452,832	12,387,399	14,840,231	28.7
RHODE ISLAND	949,723	--	--	949,723	--	--	490,057	490,057	51.6	--	--	735,086	735,086	1.4
SOUTH CAROLINA	2,590,210	43,138	811,630	1,735,442	36,807	693,370	1,436,946	2,167,123	82.8	956,982	5,546,960	2,155,419	8,659,361	16.7
SOUTH DAKOTA	666,257	143,623	--	522,634	110,117	--	418,107	528,224	80.0	2,863,042	--	627,161	3,490,203	6.7
TENNESSEE	3,924,927	--	377,958	3,546,969	--	301,988	2,834,028	3,136,016	79.9	--	2,415,904	4,251,042	6,666,946	12.9
TEXAS	11,196,852	6,662,280	168,119	4,366,453	5,282,406	136,351	3,506,262	8,925,019	80.3	137,342,556	1,090,808	5,259,393	143,692,757	277.8
UTAH	1,059,273	18,788	815,721	224,764	14,348	612,606	168,798	795,752	75.1	373,048	4,900,848	253,197	5,527,093	10.7
VERMONT	444,732	--	--	444,732	--	--	292,189	292,189	65.7	--	--	438,284	438,284	.8
VIRGINIA	4,652,328	8,958	714,883	3,928,487	7,525	534,018	2,934,804	3,476,347	74.7	195,650	4,272,144	4,402,206	8,870,000	17.1
WASHINGTON	3,410,519	--	172,110	3,238,409	--	130,115	2,448,237	2,578,352	75.6	--	1,040,920	3,672,356	4,713,276	9.1
WEST VIRGINIA	1,744,237	--	318,754	1,425,483	--	263,291	1,177,449	1,440,740	82.6	--	2,106,328	1,766,174	3,872,502	7.5
WISCONSIN	4,417,933	--	350,406	4,067,527	--	247,036	2,867,607	3,114,643	70.5	--	1,976,288	4,301,411	6,277,699	12.1
WYOMING	332,416	92,347	62,605	177,464	65,980	46,516	131,856	244,352	74.3	1,715,480	372,128	197,784	2,285,392	4.4
HAWAII	--	--	--	--	--	--	--	--	64.8	--	--	--	--	--
ALASKA	--	--	--	--	--	--	--	--	51.3	--	--	--	--	--
TOTAL	202,190,086	23,658,094	33,172,729	145,359,263	17,730,021	23,710,910	98,320,710	139,761,641		460,980,546	189,687,283	147,481,072	798,148,901	1542.7

Table 3-2. National Annual Losses Due to Expansive Soil Computed for the years 1970 and 2000 by State (In 1970$)

There is yet another factor that should be considered in determining the expansive soil losses that the nation bears. That is the shortened life of a building due to continual cracking which is not repaired or not repaired frequently enough. Moisture entry through cracks or alternating freeze-thaw conditions aggravates conditions to the point where the structure may be abandoned. The neighborhood thus deteriorates. Not only do the improvements decrease in value, but also the real property value decreases. An economic consequence of the former condition is that the normal half life of a building which may be 50 years, for example, may be lowered to 35 years in "high" zones, 45 years in "moderate" zones, and 50 years in "low" zones of expansive soil. The added cost to the nation caused by the deterioration and early retirement factors could be considerable.

As an example, the half life of all structures subjected to landslide damage was computed to be 48.4 years. A similar computation was made for structures suffering from expansive soil damages and found to be 44.4 years. This suggests an eight percent lower life time, if our calculations are correct. However, the cause for the differences may be caused simply by geographic preferences whereby expansive soil plays no role.

Chapter Six

Effects of Mitigations on Expansive Soil Losses

According to Engineering News Record [November 4, 1972],

> Contractors in some Texas cities that have been maligned for poor workmanship when foundations crack and walls split, could be the victims of accepted construction practices that haven't been thoroughly researched. The result of this combination of expanding soils and unsophisticated use of concrete slab foundation construction nationally is a staggering $700 million in damage each year. Wray, of Texas A&M, says that more than a quarter million new homes are built on expansive soils each year and some 60% will experience damage during their lifetime, and 10% will experience major damage even beyond economical repair.

By the mid-1950's, rigid materials such as slabs and brick veneers were failing at alarming rates in expansive soil areas. The Building Research Advisory Board of the National Research Council [1968] studied slab-on-ground problems in expansive soil areas and determined that if a slab were strengthened sufficiently it should perform well despite expansive soil movement.

> Use of the BRAB approach would have increased the cost of many foundations by from $500 to $1700 at a time when a typical home was selling for about $15,000. Builders were reluctant to pour such extra cost into foundation forms where prospective homebuyers could neither see nor appreciate it. The builder preferred to install kitchen conveniences or other features which would visually appeal to the desires of homebuyers in a very competitive market. The building industry resisted spending $1000 on every home to prevent damage [Jones, 1972].
>
> The housing industry and housing agencies are still searching for better, more rewarding approaches to avoidance of expansive soils problems. Lack of clear identification and definition of potential problems has aggravated seriously the ultimate losses. In both activities, foreseeable human motivations toward uninformed simplistic solutions impeded meaningful problem investigations and remedial actions [Jones, 1972].

A problem will not be solved if it is not recognized. Identification of potentially expansive soils and shales must be the first step toward expansive soil damage mitigation. Laboratory tests of soils are valuable for helping to identify potentially troublesome expansive soils, but they do not now provide the full range of information needed for sound design.

The most important environmental factor is probably the presence or absence of ground water beneath an expansive soil. If an expansive soil is perched over a water-bearing gravel, the upward migration of moisture vapor tends to replenish moisture losses in the expansive soil, which seems to limit its shrink-swell behavior. Where expansive soils with similar laboratory swell potential are underlain by rock, with no intervening ground water, dry weather dessication seems to proceed much more rapidly and to extend to greater depths, producing greater ground surface movements. Two major environmental conditions affect intensity and therefore the mitigation of expansive soil in housing developments:

- Control of natural and man-made moisture conditions, such as irrigation of urban landscaping, and
- Control of solutes that may trigger base exchange reactions introduced through the water supply, by fertilization, and/or by snow and ice control.

The biggest problem encountered in trying to build housing on expansive soils is the problem of maintaining moisture control. Earth work placed carefully to achieve moisture and density control too often dries out between the time the subcontractor completes grading and the time the builder pours his foundations. If expansive soils are used in fills, it is essential that moisture control be continuous throughout the fill placement operation and be maintained until foundations are poured. If construction will be on cut areas or on natural soils, it is desirable to defer foundation construction until moisture control meets preselected objectives:

- When a soil's moisture content is as desired, it is much simpler to maintain that moisture content than to reestablish it after drying. Covering of new fills with sheet plastic retards moisture losses, and occasional light sprinkling of the fill will maintain its desired moisture content even over a protracted dry period.
- When construction is to be on natural expansive soils, and construction sites are known, it may pay dividends to check soil moisture contents (at appropriate depths) as the wet season proceeds and cover the building site and a peripheral area when soil moisture meets desired objectives.

- Daily sprinkling of uncovered soils is an alternative to covering and occasional sprinkling, but the daily sprinkling requires copious amounts of water.
- The use of a foot or two of loose sand to cover expansive soils has been described as promising.
- Such small loads produce only negligible consolidation, so it has been practical to make the upper reaches of expansive soil fills (to support slab-on-grade houses) less dense than is generally customary in fill construction. This lowers the expansive soil intensity.

None of the above mitigations could be tested using the simple damage algorithm developed in the report. Rather, estimates by various ASCE members yield the following single-dwelling loss reductions [Jones, 1972]:

- pre-construction moisture control - 30% reduction (cost - two tanks of water plus plastic moisture barrier)
- soil stabilization, 80% to 90% reduction ($\$.60/\text{ft}^2$)
- use of structural measures - 85% reduction (from $\$1.50/\text{ft}^2$ to $4000 per dwelling.

It is grossly but conservatively estimated that, if these or combinations of these mitigations could be partially implemented into practice through grading and building code regulations, annualized loss reduction to new construction could amount to about 10%. A drought scenario loss decrease in the midwest similar to that experienced in the 1930's could amount to about 25%.

The annual losses to buildings have been estimated through our loss model to be about $1.1 billion for all construction and $800 million for single family dwellings only. These agree well with Jones and Holtz [1973] estimates of $1,480 million for all construction and the Engineering News Record estimate for single family dwellings [November 4, 1976] equalling $700 million.

Table 3-3 shows the effects of expansive soil intensity control on projected loss estimates if applied to new construction in 1981 and continued for 20 years through the year 2000.

Table 3-3. Expansive Soils Losses and Mitigation Effects

EXPECTED NATIONAL ANNUAL LOSSES IN $ MILLIONS (1970)				
MITIGATION	1970	1980	1990	2000
BASELINE - NO MITIGATIONS ADDED TO 1970 CONDITIONS	1132	1519	2039	2734
(1) CORRECTION MEASURES ARE INCLUDED IN DESIGN SO THAT DAMAGE TO NEW CONSTRUCTION IS REDUCED BY 10% AFTER 1980.	1132 (0%)	1519 (0%)	1996 (-2.1%)	2620 (-4%)
(2) PRECONSTRUCTION MOISTURE CONTROL IS REQUIRED IN ALL STATES FOR NEW CONSTRUCTION AFTER 1980.	1132 (0%)	1519 (0%)	1910 (-6.3%)	2392 (-12.5%)
(3) SOIL STABILIZATION AND/OR STRUCTURAL MEASURES ARE REQUIRED FOR ALL NEW CONSTRUCTION AFTER 1980 AS APPROPRIATE TO THE SOIL IN QUESTION (COST INCREASE ABOUT $\$0.50/ft^2$ to $\$2.50/ft^2$)	1132 (0%)	1519 (0%)	1674 (-17.9%)	1765 (-35.4%)

Chapter Seven

Conclusions

Expansive soil is basically made up of three types of materials: clays with substantial amounts of montmorillonite, alkali materials or materials with mica interspersed. The term "soil" is a little misleading in that "rocks" can also shrink and swell if these materials are present.

This type of hazard is slow working (as contrasted to earthquake or landslide) and is not usually hazardous to life (as are the other natural hazards). Because of this low visibility, it has received relatively little attention by the professions in proportion to its annual cost ($1.1 billions to buildings alone, not to mention other infrastructure values at risk such as roads, sewer lines, etc.).

It is concluded that this hazard contributes not only to considerable dollar losses to the nation, but also causes buildings to deteriorate faster than would ordinarily be the case on stable soils or expansive soils which had been controlled for differential movements by some means. Rehabilitation of existing structures is not necessarily recommended; however, some procedures for control of new construction should be instigated in grading and building regulations in order to reduce the problem for the future. Because of the difficulty, uncertainty and lack of control in chemically stabilizing soils, it is recommended that principally proper slab design and emplacement procedures be required.

REFERENCES

Adams, E.D. Soil Survey of Eastern Maricopa and Northern Pinal Counties Area, Arizona. U.S. Department of Agriculture, Soil Conservation Service, 1974.

Adams, J.K., D.H. Boggess and C.F. Davis. "Water-table, Surface-drainage and Engineering Soil Map of the Dover Quadrangle, Deleware." U.S.G.S. Hydrologic Investment, Atlas HA-139.

Ackerson, K.T. Distribution of Major Areas of Soils Classified in Montmorillonite Families." U.S. Department of Agriculture, Soil Conservation Service, unpublished map, 1976.

Agricultural Experiment Stations of the Western States Land-Grant University and Colleges. Soils of the Western United States. 1964.

Alfors, J.T., et.al. Urban Geology - Master Plan for California: Phase 1, A Method for Setting Priorities. California Division of Mines and Geology, Open File Report 72-2, 1971.

Alfors, J.T., J.L. Burnett and T.E. Gay, Jr. Urban Geology - Master Plan for California. Bulletin 198, California Divisions of Mines and Geology, 1973.

Allen, P. "Foundation Failures in Dallas County." Southern Methodist University, unpublished paper, 1974.

Allen, P.M. "Urban Geology of the Interstate Highway 35 Growth Corridor from Hillsboro to Dallas County, Texas." Baylor Geological Studies Bulletin No. 28, 1975.

Arneman, H.F. "Soils of Minnesota." Agriculture Extension Service, University of Minnesota Extension Bulletin 278, 1963.

Arora, H.S. and J.B. Scott. "Chemical Stabilization of Landslides by Ion Exchange." California Geology, Vol. 27, No. 5, p. 98-106, 1974.

Baldwin, E.E. "Urban Geology of the Interstate Highway 35 Growth Corridor Between Belton and Hillsboro, Texas." Baylor Geological Studies Bulletin, No. 27, 1974.

Basile, R.M. The Geography of Soils. Dubuque, Iowa:Brown Company Publishers, 1971.

Bidwell, O.W. and C.W. McBee. "Soils of Kansas." Kansas Agriculture Experimental Station, Department of Agriculture Experimental Station, Department of Agronomy Contribution No. 1349, map supplement 1:1,250,000. 1973.

Black, P.J. "Urban Geology of Dallas County, Texas," (thesis abst.). Department of Geology, University of Texas at Arlington, 1974.

Building Research Advisory Board. "Criteria for Selection and Design of Residential Slab-on-ground." National Academy of Sciences, National Council Publication 657, 1959.

Building Research Advisory Board. "Criteria for Selection and Design of Residential Slab-on-ground." FHA Report No. 33, NAS Publication 1571, 1968.

Preceding page blank

Butler, G.M. "Clays of Eastern Colorado." Colorado Geological Survey Bulletin No. 8, 1914.

Clark, G.N. "Kansas Procedure for Highway Construction in Swelling Clays and Shales." Association of Engineering Geologist Bulletin, Vol. 11, No. 4, p. 371-378, 1974.

Clark, I.P., Jr. "Interim Report Design Criteria for Residential Slab-on-ground." Building Research Advisory Board, Report No. 17, NAS-NRC Publication 657, 1959.

Colorado Land Use Commission. Soil shrink-swell potential map of Colorado; Denver, Colorado, Scale 1:500,000. 1974.

Corley, J.B. "An Investigation of Modeling Techniques for Expansive Clay Soil." University of Texas at Arlington, Texas, 1975.

Craddock, G.R. and C.M. Ellerbe. "Land Resource map of South Carolina." South Carolina Agricultural Experiment Station in cooperation with U.S. Department of Agriculture - Soil Conservation Service. Soil Map Leaflet 47, map supplement 1:1,000,000. 1966.

Davis, R.C. "Soil Moisture and Temperature Variations Beneath a Slab Barrier on Expansive Clay," (Dissertation abst.). University of Texas at Arlington, 1973.

Dawson, R.F. "The Design of Building Footing on Expansive Clay Soils in Housing and Building in Hot-humid and Hot-dry Climates." Building Research Adivsory Board, Research Conference Report No. 5, p. 83-90. 1953.

Dawson, R.F. "Modern Practices Used in the Design of Foundations for Structures in Expansive Soils." Colorado School of Mines Quarterly, Vol. 54, No. 4, 1969.

Elder, J.A. "Soils of Nebraska." University of Nebraska, Conservation and Survey Division, Resource Report No. 2, 1969.

Elder, W.R. "Urban Geology of Greater WACO - Part 2: Soils." Baylor Geological Publications Bulletin No. 9, 1965.

Fehrenbacher, J.B., G.O. Walker, and H.L. Wascher. "Soils of Illinois." University of Illinois College of Agriculture, Agricultural Experiment Station with U.S. Department of Agreculture. Soil Conservation Bulletin 725, 1967.

Fitzpatrick, E.A. Pedology. Oliver and Boyd Publishing Company, 1971.

Flesker, E.C., Jr., K.E. Stone, L.K. Young and D.R. Urban. "Soil Survey of Henry County, Ohio." U.S. Department of Agriculture, Soil Conservation Service, 1974.

Gnuse, R.S. "The Effect of Incremental Moisture Increased on the Swell Characteristics of an Expansive Clay," (thesis abstr.). University of Texas at Arlington, 1974.

Godfrey, C.L., G.S. McKee and H. Oakes. "General Soil Map of Texas." Department of Agricultural Communications, Texas A & M Univeristy, map supplement 1:500,000. 1973.

Gray, F. and H.M. Galloway. "Soils of Oklahoma." Oklahoma State University Experiment Station, Misc. Publication MP-56, 1959.

Green, G.L. "Soil Survey of Trout Greek-Shaniko Area, Oregon." U.S. Department of Agriculture, Soil Conservation Service, 1970.

Gromko, G.J. "Review of Expansive Soils." Journal of the Geotechnical Engineering Division, ASCE, Vol. 100, No. GT6, Proceedings Paper 10609, p. 667-687, 1974.

Gustavson, T.C. "Miro Relief (GILGAI) Structures on Expansive Clays of the Texas Coastal Plane - Their Recognition and Significance in Engineering Construction." Bureau of Economic Geology, University of Texas at Austin. Geological Circ. 75-7, 1975.

Hajek, B.F., F.L. Gilbert and C.A. Steers. "Soil Associations of Alabama." Agriculture Experimental Station, Auburn University Agronomy and Soils Department Series, No. 24, 1975.

Hamilton, J.J. and G.O. Handegord. "House Basements on Prairie Clays." National Research Council, Canada Housing Note, No. 20, 1964.

Hamilton, J.L. and W.G. Owens. "Geologic Aspects, Soils and Related Foundation Problems, Denver Metropolitan Area, Colorado." Colorado Geological Survey Environmental Geological Report, 1972.

Hammer, M.J. "Foundation Clay Shrinkage Caused by Large Trees." Journal of Soil Mechanics and Foundation Division, ASCE, Vol. 92, No. SM6, p. 1-17, 1966.

Harrington, C.E., Jr. "Soil Parameters and Clay Mineralogy of the Southwest Arlington Area, Tarrant County, Texas," (thesis abstr.). Department of Geology, University of Texas at Arlington, 1974.

Hart, S.S. "Potentially Swelling Soil and Rock in the Front Range Urban Corridor, Colorado." Colorado Geological Survey, Colorado Environmental Geology, No. 7, 1974.

Hayhurst, E.N., T.N. Rubel, G.E. Delley and P. Berning. "Soil Survey on Monroe County, Ohio." U.S. Department of Agriculture, Soil Conservation Service, 1974.

Holtz, W.G. "Expansive Clays - Properties and Problems." Colorado School of Mines Quart., Vol. 54, No. 4, p. 98-117, 1967.

Holtz, W.J. and H.J. Gibbs. "Engineering Properties of Expansive Clays." ASCE Trans., Vol. 121, Paper 2814, p. 641-677, 1956.

Howard, W.J. "A Survey of Subgrade Moisture Control Techniques for Residential Foundations." University of Texas at Arlington, 1973.

Jenkins, D.S., D.J. Belcher, L.E. Gregg and K.B. Woods. "The Origin, Distribution, and Air Photo Identification of United States soils." Civil Administration, Technical Development Report, No. 52, 1946.

Johnson, L.D. "Review of Literature on Expansive Clay Soils." U.S. Army Engineers, Waterways Experiment Station, Misc. Paper S-69-24, 1969.

Johnstone, J.G., Sethurama Ramarathnam, and D.B. Richards. "The Soils of Eastern Colorado--Their Origin, Distribution, and Engineering Characteristics." Colorado School of Mines Quart., Vol. 57, No. 3, 1962.

Jones, D.E., Jr. "Expansive Soils and Housing Development," in D.R. Lamb and S.V. Hanna, eds., Proceedings of Workshop on Expansive Clays and Shales in Highway Design and Construction. Federal Highway Administration, Office of Research Development, Vol. 1, p. 16-43, 1972.

Jones, D.E., Jr. and W.G. Holtz. "Expansive Soils--The Hidden Disaster." Civil Engineering, Vol. 43, No. 8, p. 49-51, August 1973.

Jones, D.E., Jr. "The Expansive Soil Problem." Prepared for Symposium on Expansive Soils, Geological Society of America, Denver, Colorado, 1976.

Karazynski, L.M. and L.J. Lee. "Identification and Test of Expansive Soils." In Seminar on the Importance of the Earth Sciences to the Public Works and Building Official. Association of Engineering Geologist Annual Meeting, p. 100-171, 1966.

Lamb, D.R. "Expansive Clays and Shales and the Highway." Proceedings of the 12th Annual Engineering Geologist and Soils Engineers Symposium, Idaho, p. 38-49, 1974.

Lambe, T.W. and R.V. Whitman. "The Role of Effective Stress in the Behavior of Expansive Soils." Colorado School of Mines Quart., Vol. 54, No. 4, p. 35-65, 1969.

Lambe, T.W. "The Character and Identification of Expansive Soil." A report completed for the Technical Studies program of the Federal Housing Administration, 1960.

Lytton, R.L. "Expansive Clay Roughness in the Highway Design System: In Active Clays in Engineering and Construction Practice." Association of Engineering Geologist Bulletin, Vol. 11, No. 4, p. 399-419, 1974.

Maker, H.J., C.W. Keetch and J.U. Anderson. "Soil Associations and Land Classification for Irrigation, San Juan County." Agricultural Experiment, New Mexico State University Research Report 257, 1973.

Maker, H.J., R.E. Neher and J.U. Anderson. "Soil Associations and Land Classification for Irrigation, Catron County." Agricultural Experiment Station, New Mexico State University Research Report 229, 1972.

Mathewson, C.C., J.P. Castelberry and R.L. Lytton. "Analysis and Modeling of Performance of Home Foundations on Expansive Soils in Central Texas." Assoc. of Engineering Geologist Bulletin, Vol. 12, No. 4, p. 275-302, 1975.

Means, R.E. "Building and Expansive Clay." Colorado School of Mines Quart., Vol. 54, No. 4, p. 1-31, 1969.

Meekan, R.L. and M.T. Dukes. "A Case History of Expansive Claystone Damage." ASCE Journal, Geotech Engineering Division, Vol. 101, p. 933-948, 1975.

Miller, F.P. "Maryland Soils." Cooperation Extensive Service, University of Maryland Extension Bulletin 212, 1967.

Miller, M.L. and K. Larsen. "Soil Survey of Apache County, Arizona - Central Part." U.S. Department of Agriculture, 1975.

Ohio Department of Natural Resources. "Know Ohio's Soil Regions." Division of Lands and Soil map supplement 1:500,000, 1973.

Ohio Soil and Water Conservation Needs Committee. "Soil and Water Conservation Needs Inventory." U.S. Department of Agriculture, 1971.

Oschwald, W.R., F.F. Riechken, R.I. Diederiksen, W.H. Scholtes and F.W. Shaller. Principle Soils of Iowa. Department of Agronomy, Iowa State University of Science and Technology Cooperative Extension Service, Special Report No. 42, 1965.

Parson, R.B., Moncharoan and E.G. Knox. "Geomorphic Occurrence of Pelloxererts, Willamette Valley, Oregon." Soil Science Society of America Proceedings, Vol. 37, p. 924-927, 1973.

Pennsylvania State University. Soil map of Juniata County, Pennsylvania. College of Agriculture, Agricultural Experiment Station map supplement 1:620,000, 1954.

Prescott, J.A. "A Climatic Index for the Teaching Factor in Soils." Journal of Soil Science, Vol. 1, p. 9-19, 1949.

Proceedings, 1st International Research and Engineering Conference on Expansive Clay Soils. Texas A & M University, College Station, Texas, 1965.

Robinson, G.C., F.G. Buie, H.S. Johnson, Jr. "Common Clays of the Coastal Plain of South Carolina and Their Use in Structural Clay Products." South Carolina Division of Geology, State Development Board Bulletin No. 25.

Rourke, R.V. and J.S. Hardesty. Soils of Maine. Agriculture Experiment Station in cooperation with U.S. Department of Agriculture, Soil Conservation Service, Misc. publication 676, 1966.

Schneider, G.L. "The Prediction of Soil Heave and Swell Pressures Developed by an Expansive Clay," (thesis abstr.). University of Texas at Arlington, 1974.

Shiflett, M. "The Effect of Recycled Rubber upon Lightly Loaded Structures Founded on Expansive Clay Soils," (thesis abstr.). University of Texas at Arlington.

Smith, D.M. and P.M. Allen. "A Cost-benefit Analysis of Housing Foundation Failures." Department of Economics, Southern Methodist University, Dallas, Texas, 1974.

Snethen, D.R., et.al. "A Review of Engineering Experience with Expansive Soils in Highway Subgrades." U.S. Army Engineers, Waterways Experiment Station, Interim Report. Prepared for Federal Highway Administration, Office of Research and Development, Washington, D.C., 1975.

Southard, A.R. "Soils of Montana." Agricultural Experiment Station Bulletin 621. Montana State University, 1973.

Sowers, G.F. "Review of Expansive Soils," (discussion of Gromko, ASCE paper 10609) Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 101, No. GT4, p. 405-406, 1974.

Sowers, G.F. and G.M. Kennedy. "High Volume Change of the Southern Coastal Plain." Proceeding of the Third Pan American Conference on Soil Mechanics and Foundation Engineering, Caracas, Vol. 2, p. 99-120, 1967.

Spencer, J.M. "Urban Geology of Greater WACO - Part 3: Water." Baylor Geological Studies Bulletin, No. 10, p. 47, 1966.

Teng, T.C.P., Mattox, R.M. and M.B. Clisby. "Mississippi Experimental Work on Active Clays." Association of Engineering Geology, Vol. II, No. 4, p. 331-351, 1974.

Thom, H.C.S. "A Note on the Gamma Distribution." Monthly Weather Review, Vol. 86, No. 4, p. 117-122, 1958.

Thom, H.C.S. and I.B. Vestal. Quantities of Monthly Precipitation for Selected Stations in the Contiguous United States. Environmental Science Services Administration Technical Report EDS 6, 1968.

Thronthwaite, C.S. "An Approach Toward a Rational Classification of Climate," Geographical Review, Vol. 38, p. 55-94, 1948.

Tourtelot, H.A. "Geologic Origin and Distribution of Swelling Clays." Association of Engineering Geology, Vol. 11, No. 4, p. 259, 1974.

Tucker, R.L. and A.R. Poor. "A Study of Behavior of Slabs Found on Active Clay Soils." Construction Research Center, University of Texas at Arlington, 1973.

U.S. Department of Agriculture, Soil Conservation Service. Soil Classification, A Comprehensive System, 7th Approximation. Washington, D.C., 1965.

U.S. Department of Agriculture, Soil Conservation. Soil Survey Laboratory Data and Descriptions for Some Soils in Kansas. In cooperation with Kansas Agriculture Experiment Station-Soil Survey Investigation Report, No. 4, 1966.

U.S. Department of Agriculture, Soil Conservation Service. General soil map of Addision County, Vermont, map supplement 1:126,720. 1970.

U.S. Department of Agriculture, Soil Conservation Service. Guide for Interpreting Engineering Uses of Soils. Washington, D.C.:1971.

U.S. Department of Agriculture, Soil Conservation Service. General soil map of Rutland County, Vermont, map supplement 1:150,263. 1972.

U.S. Department of Agriculture, Soil Conservation Service. General soil map of Franklin County, Vermont, map supplement 1:126,720. 1972.

U.S. Department of Agriculture, Soil Conservation Service. Engineering test data of Wisconsin soils: in cooperation with Wisconsin Department of Transportation, 1972.

U.S. Department of Agriculture, Soil Conservation Service. General soil map of Chitterden County, Vermont, map supplement 1:126,720. 1972.

U.S. Department of Agriculture, Soil Conservation Service. General soil map with soil interpretations for land use planning, Jackson County, Oregon. 1974.

U.S. Department of Agriculture, Soil Conservation Service. Soil Survey of Catawba County, North Carolina: in cooperation with North Carolina Agricultural Experiment Station, 1975.

U.S. Geological Survey. The National Atlas of the United States. 1970.

Vijayvergiya, V.N. and R.A. Sullivan. "Simple Technique for Identifying Heave Potential." Association of Engineering Geologists, Vol. II, No. 4, 1974.

Westin, F.C. and D.L. Bannister. Soil Association of South Dakota. Plant Science Department. South Dakota Agricultural Experiment Station, South Dakota State University, map scale 1:500,000. 1971.

White, W.A. and M.K. Kryiazis. "Effects of Waste Effluents of the Plasticity of Earth Materials." Illinois State Geological Survey Environmental Geology Notes, No. 23, 1968.

Whiteside, E.:., I.F. Schneider and R.L. Cook. "Soils of Michigan." In cooperation with the Extension Service Agricultural Experiment Station, Michigan State University Extension, Bulletin E-360, 1968.

Wilson, L., M.E. Olsen, T.B. Hitching, A.R. Sowthard and A.J. Erickson. "Soils of Utah." Agricultural Experiment Station, Utah State University Bulletin 492, 1975.

Williams, L.H. "Soil Survey of Marion County area, Oregon." U.S. Department of Agriculture, Soil Conservation Service, 1972.

Wise, J.R. and W.R. Hudson. An Examination of Expansive Clay Problems in Texas. Center for Highway Research, Report 118-5, 1971.

Witczak, M.W. Relationships Between Physiographic Units and Highway Design Factors. National Cooperative Highway Research Program Report 132, Highway Research Board. Washington, D.C. 1972.

Woodward-Clyde and Associates. A review paper on expansive clay soils prepared for Portland Cement Association, Vol. 1, p. 134, 1967.

Woodward-Clyde and Associates. "Recommended Practice for Residential Concrete Floors on Expansive Soil." Prepared for Portland Cement Association, Vol. 2, p. 39.

APPENDIX A

Factors to be Considered in Evaluating Expansive Soil Conditions

[Jones, 1976]

Location and Geologic Factors:

- The natural in-place density of the soil is an important factor when assessing how a soil may behave. Laboratory tests usually are of remolded samples compacted to 100% of Standard or Modified density, which may be significantly more or less than the natural in-place soil density. When the natural soil will be "undisturbed", it is well to perform consolidometer tests of the soil in an undisturbed, in-place condition, to avoid distorted findings.

- Remolded and compacted soil samples often have a shrink or swell potential two or more times greater than undisturbed soil samples. As such behavior is typical of quite expansive clays, it should be clear why a building or other structure supported by both cut and fill may be particularly unfavorably sited. Structures should be located to have consistent depth of either cut or fill beneath them, and never upon mixed cut and fill.

- An expansive soil located immediately above rock will become wet or will dry out particularly rapidly, much more rapidly than an expansive soil located above, say, a gravel deposit that contains a free ground water table. In the latter case, upward migration of water vapor will tend to replenish the moisture content in the expansive soil as moisture is lost due to evaporation or transpiration. Accordingly, the former situation is usually more sensitive to actual volume changes over short periods, and is more sensitive to short periods of drought.

- As expansive soils dry out and shrink, surface cracks are formed which permit even faster drying because of the increased soil area exposed to evaporation. As cracking proceeds, horizontal cracks occur, leading from vertical cracks, further accelerating the drying and shrinking process. If soil moisture cannot be replenished from below by upward migration of water vapor, the site will be particularly subject to rapid shrinking movements. When a soil has dried and is deeply cracked, the cracks provide a direct route for entry of surface waters, usually is suprisingly large volume, and subsequent swelling can be rapid, also.

- The depth to which an expansive soil has been weathered or dessicated often is an index to the depth to which expansive movements usually will occur. It should be noted that the depth of penetration of roots usually will be somewhat less than the dessicated depth that should be defined. That depth of dessication defines the soil column height subject to volume change.

- Underlying expansive soils are to some degree insulated against moisture changes by either pervious or impervious soil overburdens. In most areas, two feet of sand, for example, will effectively provide a barrier to evaporation, but NOT to infiltration.

- Inasmuch as changes in surface drainage patterns affect the opportunity for moisture penetration of expansive clays, it is well to anticipate the moisture balance that may be expected after construction on an expansive soil is completed. Construction usually shields some soil areas and often results in the net application of more than natural amounts of water to other areas, setting the stage for damaging differential soil movements.

- The moisture content of an expansive soil is not constant; if it were, there usually would be no movement problem. Expansive soils are usually moist in the spring and dry in the late summer. Expansive soils capped by concrete slab foundations will usually, therefore, be subject to peripheral shrinkage around the slab perimeter during dry weather if the slabs were poured in the spring, and to peripheral heave if the slabs were poured in the late summer or early fall. Where such heave occurs under the latter condition, it ultimately will progress across the slab, heaving the slab's center.

Environmental Factors:

- Trees, shrubs and other vegetation have varying moisture requirements which usually are met by extraction of water from the soil. That extracted water usually is wasted to the atmosphere by a process known as transpiration. A large tree can remove surprisingly large amounts of water from the soil, more each year of its life. This suggests two cautions that should be observed with regard to trees and other vegetation:

- Trees and shrubs should not be planted closer than their ultimate drip line to any structure that could be adversely affected by soil shrinkage.

- When trees or large shrubs are removed during summer grading (or during dry winter grading), stump removal will rarely remove all soil that has been dried through transpiration action. When the stump removal void has been refilled and the area returned to grade, a long-term moisture gain of a soil bulb may be expected, resulting in considerably more localized swell than in surrounding areas. This can result in excessive differential movements. It is particularly common where trees along old fence lines are removed, as in new highway and street construction. Such a phenomenon is often known as a "dry bulb."

- Land development, at least for housing, usually results in application of more than natural amounts of water to the land, primarily because of lawn and garden irrigation. Over time, this can result in appreciable changes in the soil moisture content, with resulting volume changes, and should be anticipated and provided for.

- Waters applied to a soil following development often have a pH and solutes appreciably different from those of rainfall. Such waters can be the source of free ions that simulate a base exchange in the soil, amplifying its expansive characteristics, often as much as 3X amplification.

- When man's works such as pavements, patios and walks are directly exposed to sunlight and atmospheric temperature changes, the soil beneath them may tend to become quite wet, due to a process known as "hydrogenesis." In hydrogenesis, cool, moisture laden air is drawn into the voids in base courses during the late night and early morning.

During sunlit hours, the pavement warms, as does the air trapped in voids, and the air expands and flows from the voids but the moisture concentrates in the soil. The process is repeated day after day, with a net long-term gain in soil moisture. This is foreseeable and suggests that particular thought should be directed towards ways in which adverse effects of such action can be minimized.

- Shading from direct sunlight can be a factor in differential expansive soil behavior. The shaded north side of a dwelling, for instance, will usually have higher summer soil moisture contents than the south side of the dwelling, which is subject to both direct sunlight and sunlight reflected from the south dwelling wall.

- The seasonality of probable rainfall has been previously mentioned. In some areas, rainfall is relatively uniform throughout the year, but in other areas, there may be distinct wet and dry seasons. The expansive soil problem usually is greatest in the latter kind of area, as there is greater opportunity for extremes of soil moisture variation and hence of shrinkage and swelling.

- Some expansive soils are underlain by structures containing a shallow ground water table. Where a shallow ground water table is assured, potential shrink-swell movements may be minor, even if the soil has a significant expansive potential otherwise. An example would be the fringes of San Francisco Bay, where many of the Bay Muds have a Plasticity Index as high as 80 or more but where the soils continuously stay damp and very few differential movement problems attributable to expansive soil volume changes are experienced. A similar condition has been observed in Denver on very expansive soils located adjacent to irrigation canals that flow most of the year. In the latter case, cessation of canal use could result in extensive areal shrinkage and structural damage.

Site Occupancy Factors

- Some of the foregoing cites factors that should be considered when planning specific site occupancy.

- The Proceedings of Workshop on Expansive Clays and Shales in Highway Design and Construction, prepared for the Federal Highway Administration Office of Research and Development, May 1, 1973, pages 34-42, outline a method for selecting optimal soil moisture content and soil moisture content tolerances prior to construction, to assure maximum soil strength and, hopefully, minimum probable residual moisture content variation. That procedure will help lead to minimum probable shrink-swell action following some types of construction.

- Soil moisture content in fill materials may be rather carefully and precisely controlled during fill placement, in accordance with site-specific objectives selected in accordance with the immediately preceding foregoing item. In cut materials and natural soils, the opportunity to establish soil moisture control is very limited. Application of water to a site by sprinkling or flooding has not proved controllable and practical for expansive clays as a general procedure and is not represented as reliable in general, although it has proved effective in some instances. Where fill is involved, establishment of soil moisture control is usually practical.

- Construction grading and associated soil moisture content control often is excellently performed, but then the construction site is left exposed to the weather for an appreciable period before actual construction commences, with the result that the soil moisture so carefully established varies from the objective and the construction may be seriously affected by subsequent differential movements. It is essential that soil moisture control be maintained after grading until the construction is finally in place. Surface sprinkling and shielding of completed grading by moisture barriers have been tried for such purposes and are reportedly very helpful.

- Flexible structures, such as frame residences without rigid components have generally proved less susceptible to shrink-swell damages than rigid masonry and concrete buildings. A variation of the "flexible" approach, used in South Africa, is to construct the building of several rigid cells, each free to move independently of the surrounding cells.

- A number of refined structural design and construction procedures are available to produce small buildings having sufficient strength to resist potential stresses associated with maximum foreseeable shrink-swell movements. There is no doubt that such approaches are effective, but they typically add significantly to construction costs, possibly adding more initial cost than the present value of expected losses.

- An alternative to provision of excess structural strength has been to stabilize potentially expansive soils. Lime (CaO) has been found effective in many instances when mixed with montmorillonitic clays. It seems important that the lime be intimately mixed with the clay. It is wise to evaluate the corrective action that can be induced using lime, by laboratory analyses, and to estimate the cost of lime stabilization before final action decisions are reached.

- A Denver firm, Soil Technology, has experimented extensively and offers site stabilization services using proprietary chemical stabilization. Their efforts have proved effective in a number of instances involving very expansive materials, based upon their reported lack of subsequent site movements. Inasmuch as they guarantee their services, they would be worthy of investigation.

- As mentioned above during discussion of hydrogenesis, soil moisture tends to flow away from heat. This has proved particularly troublesome at times when boilers or other heating equipment were installed on floor slabs supported by expansive soils. The long-term drying effects of heating equipment operation have been known to dry the soil beneath the slab, destroying its support by shrinkage. In the worst such case observed, more than two feet of movement resulted. Avoidance of such situations seems wise.

- Where alkali is involved, it has proved useful to leach the soluble alkali to the subgrade surface and then provide space (as in the voids in a base course) in which the alkali crystals can grow, rather than in the soil voids. That approach has proved effective, and has been pioneered by the Nevada Testing Laboratories in Las Vegas, Nevada (Mr. Oscar J. Sherer) and by Mr. Harold D. Blaser of the HUD staff in Sacramento, California.