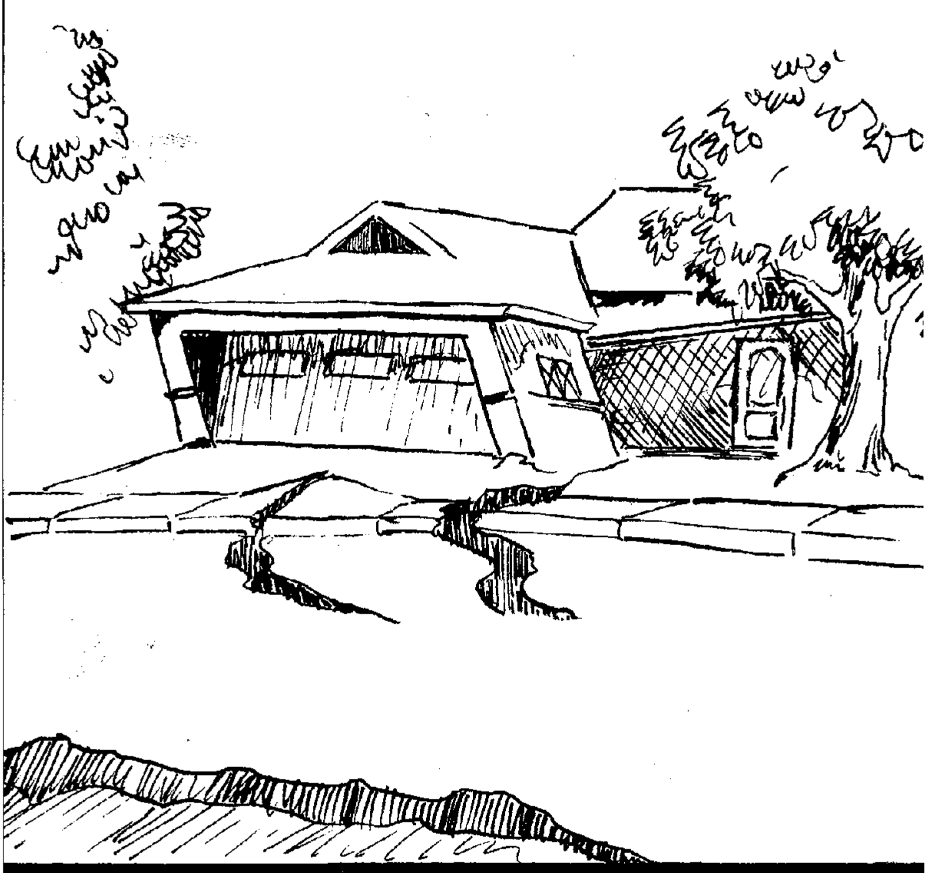
# EARTHQUAKE AND TSUNAMI HAZARDS IN THE UNITED STATES: A Research Assessment

**Robert S. Ayre**



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ASSESSMENT OF RESEARCH ON NATURAL HAZARDS

*Institute of Behavioral Science*

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A Research Assessment


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Program on Technology, Environment and Man

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Many of the ideas and procedures grew out of discussion with the following participants in the Workshop on January 22 - 24, 1973.

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ASSESSMENT OF RESEARCH ON NATURAL HAZARDS
AIMS AND METHODS

The Assessment of Research on Natural Hazards is intended to serve two purposes: (1) it provides a more nearly balanced and comprehensive basis for judging the probable social utility of allocation of funds and personnel of various types of research on natural hazards; (2) it stimulates, in the process, a more systematic appraisal of researc needs by scientific investigators in cooperation with the users of their findings.

The basic mode of analysis is to examine the complex set of interactions between social systems and natural systems which create hazards from the extreme geophysical events. The chief hazards investigated relate to: coastal erosion, drought, earthquake, flood, frost, hail, hurricane, landslide, lightning, snow avalanche, tornado, tsunami, urban snow, volcano, and windstorms. For each of those hazards the physical characteristics of the extreme events in the natural system are examined. The present use of hazardous areas and the variety of adjustments which people have made to extreme events are reviewed. The range of adjustments includes measures to modify the event, as by seeding a hurricane; modifying the hazard, as by adjusting building or land use to take account of the impact of the extreme event; and distributing the losses, as by insurance or relief. Taking all of the adjustments into account, the impact of the hazard upon society is estimated in terms of property losses, fatalities and injuries, and systemic disruption. An effort is made to identify the directions of change in the mix of adjustments and in their social impact. As a part of this review, those forces in the national society which shape the decisions about adjustments are appraised.

Authorities in the field are consulted through the medium of literature review, workshops on specific hazards, a national conference which was held in October, 1973, and individual reviews. Where appropriate and practicable, simulations of the extreme events and of their social impacts were carried out. In selected areas scenarios of past anc possible future events and their consequences are constructed.

In the light of this analysis the possible contributions of research to amelioration of the national condition with respect to each hazard are assessed. Each set of adjustments is reviewed in terms of its potential effects upon national economic efficiency, enhancement of human health, the avoidance of crisis surprise, the equitable distribution of costs, and the preservation of environmental options. Evaluation of particular research activities includes (1) the average sum of social costs and social benefits from application of a given adjustment in changing property use, and (2) reduction in average fatalities and casualties. In addition to the direct impacts of extreme events upon society, account is taken of the costs and benefits which society reaps in seeking to cope with the hazards, as in the case of costs of insurance or of control works.

In addition to calculating the average effects of hazard adjustments, an effort is made to estimate the degree to which the occurrence of a very rare event which has dramatic destructive potentialities, such as an 8.0 earthquake or a 200-year flood, would disrupt society.

Estimates also are made of the extent to which the adoption of an adjustment reduces the options of maintenance of environmental values, and the degree to which the pattern of distribution of income among various groups in society may be changed.

Research proposals are appraised in the light of the likelihood that the research undertaken could yield significant findings, and the likelihood that once the research is completed satisfactorily, the findings may be adopted and practiced by the individuals or public agencies in a position to benefit.

The United States as a whole is doing a competent job of dealing with some aspects of its natural hazards and a very ragged job of handling other aspects. The overall picture is one of rising annual property damage, decreasing loss of life and casualties, coupled with a marked growth in the potentiality for catastrophic events. On the whole, the public costs of adjustments are increasing.

The assessment reveals that very little is known about the dynamic relationships among many of the adjustments. It is difficult to predict with any confidence what the consequence of new Federal investments of initiatives will be in particular adjustments.

For each hazard a set of research opportunities deserving special consideration for early adoption is presented. In addition, thr types of research which cut across the various hazards are assessed: warning systems, land management, and relief and rehabilitation.

Among the research basic to other aspects of natural hazards activity are: carefully planned post-audits of certain disasters by interdisciplinary teams; community observations over time of critical points (recovery policies and administration, health, mental health, and preventive measures) of change and of the effects of Federal-state-community interaction; and a clearinghouse service.

In most research fields it is noted that certain types of research which have claimed substantial amounts of public support offer little prospect of effecting a basic change in the character of the national hazard situation. In those instances there are new lines of emphasis which promise larger returns. Many of these involve more explicit collaboration of social scientists and natural scientists than has been customary in past. Wherever appropriate, the research recommendations include explicit provision for the translation of research findings into action by individuals or public groups.

To initiate effectively the desirable new lines of research will in some instances require a readjustment in legislative authority. In other cases it will require an increase in or reallocation of public funds for research. Much of it will involve changes in administrative procedures and policies of the responsible funding agencies. In many instances the effectiveness of the research will be linked strongly with the resolution of issues of public policy. These issues evolve around national land use management, financial assistance to sufferers from disasters, and the sharing of responsibility among local, state, and Federal agencies in designing and maintaining community preparedness.

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# SUMMARY

The popular conception of the earthquake hazard in the United States often limits it to the Pacific Coast, especially California, and to such well-known disasters as San Francisco (1906), Long Beach (1933), the Alaskan coast (1964), and San Fernando (1971). But major earthquakes have occurred in the interior of the country and on the eastern seaboard: in the St. Lawrence River region on several occasions; in the vicinity of Boston (1755); at New Madrid, Missouri, in the central Mississippi Valley (1811 and 1812); at Charleston, South Carolina (1886); and at Hebgen Lake, Montana (1959). Most of the nation displays some risk of seismic disturbance.

Tsunamis are sea waves generated by submarine disturbances. Often associated with earthquakes, they are sometimes referred to as seismic sea waves. They also may be caused by volcanic eruptions. They are scarcely noticeable to a ship at sea, but as they approach the shore their crests may build up to great heights, depending on the amount of energy stored in the waves and on the shape of the coastline.

Tsunamis are limited in destructive effect to areas immediately adjacent to the coastline; they destroy by the impact of water and by inundation. The destructive energy of earthquakes, except for surface faulting, is transmitted through the vibration of the ground. The effects of tsunamis and earthquakes on a community may closely coincide in time and place, as in Alaska in 1964; or they may be widely separated as in the tsunami at Hilo, Hawaii, in 1960, which was generated by an earthquake off the coast of Chile and took many hours to reach Hilo. The Pacific coastlines are regarded as most vulnerable, but the Atlantic coast is not entirely free from a rare sea wave.

Earthquakes sometimes result in compound disasters, in which the major event triggers a secondary associated event. The secondary event may be natural, may result from the failure of some man-made system, or may be a combination of both. In some cases, the secondary event may overshadow the major triggering event in casualties and damage.

Fire is the greatest secondary hazard. More than 80% of the

total damage in San Francisco during the disaster of 1906 has been attributed to fire, and the Managua disaster in 1972 also involved devastating fires.

The compound disaster of an earthquake and a resulting tsunami has been rare on this continent, but the event in Alaska in 1964 indicates that it can occur in the United States.

A flash flood may result from an earthquake-caused dam failure. Flooding was narrowly averted in the partial failure of earth dams at the Van Norman Lakes during the San Fernando earthquake of 1971. The potential for disaster resulted in the evacuation of an estimated 80,000 people.

Other associated hazards which are often triggered by earthquakes are landslides and avalanches, as was the case at Hebgen Lake, and in Alaska in 1964. It is conceivable that disasters combining earthquakes and landslides could occur in localized areas of overdevelopment on the coast of California.

More than 70 million inhabitants of the United States live in the two highest (of four) seismic risk zones. Earthquake damage has been on the increase in the United States. Dollar loss per capita shows an upward trend in recent years. Perhaps more than any other geophysical hazard, major earthquakes are likely to produce almost complete social disruption in modern urban areas. All life-supporting technologies of a city both above and below the ground may be shattered, and quick repair of below-ground life lines is almost impossible. Individuals may suffer physical deprivation, psychological trauma, pain, and death. Family life patterns may be altered for days, weeks, or even months as the economic loss and physical dislocation take their toll on the social web into which each family was embedded.

Some business organizations may profit from an earthquake or tsunami-produced disaster, but many more businesses would suffer economic loss. Many other organizations would be seriously disrupted. Loss and disruption at the family and organization level take their toll on the community as a total system. Needs for most governmental services would increase drastically, while the tax base would be decimated.

Mechanisms used in the United States to cope with the consequences of earthquakes and tsunamis include: 1. attempts at reduction/prevention of earthquakes per se; 2. earthquake and tsunami-resistant construction; 3. land use management; 4. attempts to forecast and disseminate earthquake and tsunami warnings; 5. insuring structures against earthquake and tsunami damage; 6. efforts to prevent or minimize associated hazards such as fire and landslide; and 7. efforts to prepare the community to respond promptly and adequately when disaster does strike.

Public investment in research related to earthquakes and tsunamis has been focused primarily on geophysical, seismological, and engineering research. Only nominal amounts have been invested in research on insurance and community preparedness.

An analysis of significant research needs suggests that the emphasis should be shifted if economic loss and social disruption are to be reduced.

## Land Use Management

Of all the potential mechanisms to cope with earthquakes, the simplest and most direct would be the avoidance of high-risk areas wherever economically practicable. However, San Francisco cannot be relocated, and undeveloped high-risk areas may be potentially very valuable, (as in some parts of the San Francisco Bay Area). The degree of risk is not always obvious. Several courses of action are indicated: 1. risk zoning of critical parts of the already developed areas to turn them into park land or other nonhazardous use as opportunity arises; 2. risk zoning of high-risk undeveloped areas to prevent future hazardous development; and 3. development of systematic techniques for collection and evaluation of data for use in microzoning (zoning of comparatively small areas), and the establishment of criteria for microzone levels of risk.

Research should be done on microzoning procedures with some detailed case studies, collection of local seismicity data and local fault mapping as needed, and the identification of especially hazardous areas, including potential landslides and soil liquefaction. Expenditures to support 200 person years of effort over ten years are required.

A research effort designed to point out ways in which restriction of building in fault zones might be encouraged and adopted would have considerable payoff. This restriction of building could begin in actual fault zones and other areas of high hazard such as those in which the soil is known to be subject to liquefaction, and could be extended to other areas as microrisk zones are assessed.

The study would analyze the question of how such zoning could be adopted, especially for structures and facilities of vital importance.

Social, political, and economic constraints to land use management would be assessed, as well as its consequences. The study of zoning adoption for the earthquake hazard may be similar to such studies for other hazards such as flood plain management.

Research on zoning and subdivision regulation could be combined, in certain instances at least, with experimental research on building code adoption. Undeveloped areas subject to high seismic activity could be used for certain economically feasible purposes if improved building codes were first adopted and used as a basis for seismic-resistant design.

An adequate investigation would run for a period of five years at a cost of 40 person years.

Similar studies on a much smaller scale are needed for coastlines where tsunami hazard is large or where invasion by urban development is rapid. Two person years should be spent on problems of local provision for tsunamis in land use management, and ten person years should be given to risk zoning.

## Earthquake-Proofing

Few structures can be made completely earthquake-proof, especially against the shaking produced by giant earthquakes. Most buildings could be designed and constructed to resist significant structural damage, the possibility of total collapse. Loss of life and injury could be greatly reduced.

Most of the research attention to date has been applied to the more spectacular and analytically interesting types of structures, for example, many-storied buildings, large dams, nuclear power plants, and storage tanks. Relatively little attention has been paid to lesser structures. While this approach has produced positive results, it has neglected several important problems: 1. potential weaknesses in certain methods (lift-slab construction, prefabricated construction, and other methods which may result in lack of adequate structural continuity) have not been investigated sufficiently; 2. low structures, with the exception of school buildings in California, generally have not been given attention commensurate with their property value and the human risks involved; 3. many-storied buildings that have been adequately designed and constructed to withstand the motion of major earthquakes without serious structural damage are not necessarily safe for human occupancy if the elevator system fails or if fire breaks out; and 4. a dam and the valley below it, which seemed safe at the time of construction of the dam, may later prove to be unsafe due to increased density of human population in the valley, deterioration of the dam and its foundation, or the occurrence of a greater-than-expected earthquake.

Engineering research is needed on: 1. development of continuity in structural systems; 2. earthquake resistance of low buildings; 3. overall safety of multistoried buildings, including structural integrity, safe evacuation routes, and fire resistance; and 4. overall safety of dams and the valley below, and restructions on land use in areas subject to flooding. Research is also needed for greater understanding of foundation conditions.

Additional funding of about 200 person years over the next ten years would be appropriate. The movement toward improving earthquake-resistant construction has been generally successful, with some exceptions, and needs further support.

The upgrading of building codes should be studied in light of the fact that estimates of increased costs to *new* construction rarely exceed 6% of the total cost of the structure. Building codes for all classes and structures and the political, social, and economic constraints to their adoption and enforcement should be considered.

Some high-risk cities appear to be significantly more progressive in the upgrading of building codes than other cities. If this is true, a series of comparative case studies would provide answers on how this upgrading takes place, and what the secondary consequences are. Experimental efforts should be made to provide incentives to the local powers who could influence building code upgrading. For example, communities could be identified where the mortgage lenders are somewhat progressive. A small team of professionals (economists, structural engineers) could carry out a careful effort to demonstrate to the lenders why supporting an improved building code would be in their own best interest. Other approaches could be tried in other cities to see which approach was most effective in producing the desired change. It is suggested that such a study should run for a period of five years at a cost of 25 person years.

Old buildings probably present the most difficult problem of all. They may be lucrative rental property or tax write-offs for the owners, homes and community foci for a great number of persons who cannot or will not live anywhere else, and may also be potential death traps due to the danger of collapse or fire. The two general classes of problems concern the physical condition of the structures and the social and economic constraints on doing anything about the conditions.

Research into ways of strengthening old buildings could scarcely be expected to lead to general procedures because of the great differences in construction and conditions. However, it might be possible to arrive at suggested procedures for particular classes of buildings.

Both types of research--survey and evaluation, and procedures for strengthening--might well be carried out in connection with programs of demolition for urban renewal and community conservation or other purposes if arrangements can be made well in advance of the start of demolition. Funding of about 100 person years over ten years would support a useful program of investigation.

Research is needed which will contribute to quicker adoption of policies that will sharply reduce the risk from old buildings. Economic constraints to the phasing out of dangerous structures include not only costs to the individual owner, community, state, or Federal subsidies, but also shifts in the tax base. Social costs include the disruption of established neighborhoods, a possible rise in social instability associated with urban renewal, and the problems inherent in the relocation of families and businesses. Long Beach, California, has undertaken a program designed to specify the seismic risk for each structure and the social costs and benefits of regulating future use or rehabilitation of each structure. Such a program could provide the basis for a valuable case study carried on by an interdisciplinary team.

It is difficult to estimate how dangerous a threat older buildings pose to lives and property. Study is needed to determine the risk they present, as well as how this risk might be lessened. Such work might start by determining how many old buildings exist in hazardous areas, as well as their conditions and use patterns. Of those that are dwelling units, knowledge of their inhabitant density would clarify the degree of risk they present. Research could be designed to determine how the risk might be reduced. Determination of their natural rate of abandonment could be followed by an investigation of how that rate might be affected and what would be the cost of remodeling appropriate structures to some level of acceptable safety. All alternatives should be examined. In addition to alternatives for reducing the risk, the research should address the social, economic, and political constraints to the adoption of each alternative.

The research would vary in time and cost with the size and density of the areas selected for analysis. However, a study costing on the order of 30 person years over five years should provide a good basis for action.

In addition, the analysis of tsunami-resistant structures with a view to improving design and code provisions should be undertaken. Costs of seven person years are warranted.

## Earthquake Prediction and Warning

Specific forecasts of damaging earthquakes may be available in less than a decade, but it is not clear whether the forecasts will be more of a blessing or a curse. Empirically based research on the social, economic, political, and legal consequences of earthquake forecasts and warnings must be given a high priority. Research of this type is under way at the University of Colorado.

Specific forecasts of damaging earthquakes will have lead times on the order of a few months to ten years, and will be relatively specific as to location and magnitude. Such forecasts are qualitatively different from those used in other hazard warning systems.

A reliable method of reasonably precise prediction, with a low false alarm rate, could reduce earthquake casualties significantly, and might reduce property losses. It seems very likely that earthquake prediction will have additional large-scale impacts, some will be positive, and others negative.

There may be two types of forecasts and therefore the possibility of two types of "false alarms." The first is a forecast that an earthquake *will* take place, the second is a forecast that an earthquake will *not* occur. Furthermore, the very existence of an earthquake prediction and warning system may to some extent generate a false sense of security and a tendency on the part of the public to infer that *no* warning means that *no* damaging earthquakes will occur.

There are no existing social mechanisms to assist responsible officials and organizations in arriving at plausible and realistic estimates of responses to the forecasts. If the results of careful research on the probable response of organizations and the public are reported to all responsible officials, they will have adequate, realistic knowledge upon which to develop their plans. It is imperative to learn how to cope with earthquake prediction as early as possible.

Support for at least 50 person years over five years is required.

The Pacific-wide Tsunami Warning System detects tsunamis rapidly and effectively. Where lead time is sufficient, dissemination of relevant information to the threatened communities is generally adequate. The actual forecast is handicapped by difficulties in estimating the flood depth or "run up", and in calculating the generation of waves from seismic data. Preparedness at the local level to disseminate needed information for prompt evacuation appears to be lacking in most cases. This may be due in part to the rarity of a tsunami warning in any given community. It is not known what incentives are required to insure that vulnerable communities maintain adequate local warning-response capability. Information on that question could be gathered by a research effort on the order of ten person years over a five-year period. Ideally such an effort would be part of a more comprehensive study of warning response.

The tsunami warning problems are more like those for flash floods and tornadoes than for earthquakes. The current studies of their geophysical and engineering aspects should be supplemented by ten person years on ways of improving the response and the socioeconomic consequences.

## Insurance

While insurance against earthquake damage is generally available, relatively few property owners have taken out such policies. In California, less than 5% of the property insured against fire is also insured against earthquakes, and the percentage is even smaller in Alaska.

The reasons for this low rate of adoption should be analyzed. Insurance companies are concerned about the possibility of severe losses. The industry now is handicapped by lack of a sound reinsurance program. The low rate of adoption may also result from insufficient awareness of the earthquake hazard, or misinformation on the availability of coverage and the rates. The factors affecting decisions to buy or refuse insurance, as well as those affecting how it is made available, are being examined at the University of Pennsylvania. So long as the insurance adoption rate remains below a socially desirable rate, these issues will require probing. It seems likely that current studies should be extended by at least ten person years over a period of five years.

Investigation is needed to assess the opportunities and pitfalls in providing earthquake coverage in all-risk insurance. A study of the feasibility and possible design of an all-risk insurance program would cost 20 person years over a period of five years.

The difficulties encountered with tsunami insurance are of a different character. Because of the very long recurrence interval for tsunamis and the short history of damages, it is suggested that a review of historical evidence be joined with review of insurance use and limitations.

Community Preparedness, Relief and Rehabilitation

Risk in an area is a function not only of the geological and topographical features, but more importantly of the types and density of human use to which the area is subject. Detailed community-specific vulnerability studies which define risk in terms of special physical problems such as buildings and gas and water lines, and community function problems such as transportation and health, are needed to complete risk definition and subsequent preparedness. Such studies should also take into account the compound hazards associated with earthquakes. These studies might be modeled after those for the San Francisco Bay area and the Los Angeles area conducted by NOAA. The cost would depend on the size and density of the community analyzed. It is estimated that a total of 30 person years would be required for such research.

At least three person years also should go into pilot studies of a similar character in tsunami areas.

Community preparedness for earthquake disasters is vital for adequate community response, especially since secondary hazards such as fire require immediate attention after an earthquake. In most communities, however, present levels of preparedness fail to provide for all the eventualities of an earthquake disaster. A study should be conducted on how emergency planning and levels of preparedness could be improved. The study might be incorporated into ongoing preparedness programs at a level of 25 person years over a period of five years.

Research should be conducted on the long-range social costs of relief and rehabilitation programs in which costs are defined more broadly than those involving administrative organizations. It would examine the extent to which present loan and grant practices are successful in aiding individual recovery and which aid programs retard the adoption of other adjustments, thereby possibly increasing the hazard potential in an area. It should be possible to restructure present programs to improve the character of the services offered. In selected communities relief efforts should be assessed for their consequences in rehabilitation, which in turn could be assessed for long-term social and economic costs and interaction with the adoption of other adjustments. The study would also determine the major policy issues involved in implementing the adjustment and their effects on economic costs, social disruption, and the speed of recovery. Such a study would cost about 25 person years over five years.

More specific case studies of earthquake impact could contribute needed baseline data that would be relevant to many of the adjustments to earthquakes, as well as to other lines of hazard research. The most efficient and fruitful way to perform the studies is through the organization of interdisciplinary postdisaster field teams. Such a comprehensive effort should also: 1. develop a methodology for estimating earthquake loss (social, economic, and political); 2. document comprehensive interdisciplinary field observations; 3. maximize information flow to responsible officials; and 4. develop comprehensive field research techniques. A start in this direction has already been initiated by the Earthquake Engineering Research Institute.

## Earthquake Reduction

The general aim of earthquake reduction is to release by physical means the energy in relatively small steps to bring about many small earthquakes, rather than one or a few major earthquakes. There are unevaluated risks in attempting to reorder the forces of nature; there is no certainty that attempts to trigger small earthquakes will not release a large one, nor is it known to what extent the results of experiments conducted in one geological area can be applied to another.

Earthquake reduction is an ongoing field of geophysical and engineering research which may have potential long-term benefits, but its ultimate success cannot be predicted at this time. Such research should be done with provision for an interdisciplinary research program, including investigation of the social and economic consequences of earthquake reduction. If and when techniques for earthquake reduction become feasible, knowledge will be needed on how those techniques might be implemented. If many small earthquakes cost less socially and economically than one or a few large ones, questions of implementation become paramount.

Research should focus on the constraints operating to thwart implementation, and the means by which these may be overcome. The economic consequences should be addressed. If an area were to shut down temporarily in order to accommodate a series of artificially triggered, small earthquakes, what would the costs and effects be? It would be desirable to analyze how conflict between special interest groups might be resolved, the amount and cost of any resultant social disruption, and the level and structure of necessary community preparedness. The political implications of implementation and liability for damages should also be addressed. It should also look into the means for implementation, to indicate who would decide when such an event would occur. At such time as reduction techniques seem promising, the research might run for a period of five years at a cost of 25 person years.

# PART I

# EARTHQUAKES

## CHAPTER I

## DIMENSIONS OF THE EARTHQUAKE PROBLEM IN THE UNITED STATES

### Landmarks

It was not until the latter part of the 19th Century that seismology began to emerge as a quantitative science, perhaps first in Japan; generally it was not until the second quarter of the 20th Century that engineers and building officials began to give serious consideration to earthquakes in building designs. The social sciences have only recently concerned themselves with earthquakes. The most comprehensive social scientific analysis of an earthquake appears in The Great Alaska Earthquake of 1964: Human Ecology (Committee on the Alaska Earthquake, 1970).

The 1906 disaster by earthquake and fire in San Francisco resulted in the preparation of extensive reports (California State Earthquake Investigation Commission, 1908-10; United States Geological Survey, 1907; Whitney, 1906), but few adjustments were adopted for the future. The Seismological Society of America was founded after the 1906 disaster and soon started publication of its Bulletin. There is relatively little to be found on the earthquake problem in engineering literature until the 1930's, and not until the 1950's did the volume of literature become significant.

The Tokyo-Yokohama catastrophe of 1923 and the moderate earthquake at Santa Barbara in 1925 stimulated engineering interest (Jacobsen, 1929; Suyehiro, 1932; Freeman, 1932).

The Long Beach earthquake of 1933, although relatively moderate in magnitude, was in some ways the most significant North American earthquake up to that time because of its long-range effects on the adoption of adjustments to earthquakes. The most immediate effect resulted from the widespread damage to over-ornamented and inadequately designed school buildings. The California Legislature, as a consequence, passed very quickly the well-known Field Act, which placed stringent requirements on the earthquake resistance of new public school buildings, and the Riley

Act which applied to a wide range of buildings. An important result was the impetus for the incorporation of earthquake resistance into building codes.*

The Long Beach earthquake was the first for which useful records of strong ground motion were obtained. The U. S. Coast and Geodetic Survey had developed suitable instruments, and in 1932 started a small network of stations capable of recording the strong motions of earthquakes. This network, recently under the direction of National Oceanic and Atmospheric Administration (NOAA), has grown to hundreds of stations. As of September, 1973, all earthquake research and services programs formerly provided by NOAA became the responsibility of the U. S. Geological Survey (USGS). The strong-motion instrument network is now operated by USGS in cooperation with the National Science Foundation.

Another result of the Long Beach disaster was the stimulation of research in earthquake engineering, principally at universities. A recent historical paper by Blume (1972) summarizes the "Early Research in the Dynamic Aspects of Earthquake Engineering."

A sequence of damaging earthquakes occurred in the United States over the following 20 years: one at Helena, Montana in 1935, a reminder that strong earthquakes are not limited to the Pacific Coast; one in the Imperial Valley, California in 1940; the Puget Sound earthquake of 1949, which did substantial damage in Seattle; and the Kern County, California earthquake of 1952. During the period 1932-1952, in which these relatively moderate occurrences were taking place in the United States, a series of devastating earthquake disasters occurred in China, India, Chile, Turkey, Japan, and Ecuador resulting in a total loss of life in those six countries of nearly 200,000. These earthquakes, in the United States as well as abroad, helped to develop an increased awareness of the seriousness of the problem.

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*The Long Beach earthquake occurred on March 10. The Field Act became effective on April 10, 1933, and the Riley Act applied to buildings constructed after May 26, 1933. The Riley Act required that all buildings, except certain types of dwellings and farm buildings, be designed for certain specified lateral forces (upward revisions were made in 1953 and again in 1965). See the report Meeting the Earthquake Challenge (Joint Committee on Seismic Safety, 1974) for the history of these legislative acts and the development of local California building codes with requirements for seismic safety.

The Earthquake Engineering Research Institute was founded in 1949. Among its early activities was the sponsorship of the First World Conference on Earthquake Engineering, held in 1956. Later conferences have been held under international sponsorship (World Conference on Earthquake Engineering, 1956, 1960, 1965, 1969, 1973).

The principal developments of the 1950's and 1960's were the improvements in engineering capability for analyzing the increasingly available strong-motion earthquake records, the improvements in the mathematical modeling of complex, nonlinear structural systems having many degrees of freedom, the development of high capacity automatic computers which could handle the mathematical models, and the increasing interest and activity on the part of Federal agencies.

The Alaska earthquake of 1964 introduced a new range of engineering problems especially in regard to soil and foundation conditions. Studies of the Alaskan disaster are far broader than engineering ones, however, including the fields of oceanography, geology, seismology, biology, hydrology, geography, and human ecology (Committee on the Alaska Earthquake, 1969, 1970, 1971, 1972, 1972a; Eckel, 1970; Kunreuther and Fiore, 1966).

The San Fernando earthquake of 1971 has also been widely studied (U. S. Senate, 1971; Jennings, 1971; Lew, Leyendecker, and Dikkers, 1971; U. S. Geological Survey, 1971; Joint Panel on the San Fernando Earthquake, 1971; National Bureau of Standards, 1971; Los Angeles County Earthquake Commission, 1971; Steinbrugge, *et al.*, 1971; Joint Committee on Seismic Safety, 1971a; McClure, 1973). Among the major developments arising from the Alaska and San Fernando earthquakes is the consideration of adjustments other than structural ones, namely land use zoning, insurance, and community preparedness. The Alaska and San Fernando disasters have also been influential in stimulating increased activity in research on the dynamics of structures including the further development of earthquake simulator laboratory equipment of very large size (Earthquake Engineering Research Center, 1972a).

Much has been learned from earthquake disasters abroad which is of interest in the United States. These include the disasters in southern Chile in 1960 (Saint-Amand, 1961); at Agadir, Morocco in 1960 (AISI, 1962); Skopje, Yugoslavia in 1963 (Berg, 1964); Chile in 1965 (Kennedy, 1971); Niigata, Japan in 1964 (Dynes, *et al.*, 1964; International Institute of Seismology and Earthquake Engineering, 1965);

Caracas, Venezuela in 1967 (Sozen, *et al.*, 1968; Hanson and Degenkolb, 1969); western Sicily in 1968 (Haas and Ayre, 1969); and Managua, Nicaragua in 1972 (Earthquake Engineering Research Institute, 1973; Kates, *et al.*, 1973; National Bureau of Standards, 1973a). Many others could be mentioned (World Conference on Earthquake Engineering, 1956, 1960, 1965, 1969, 1973). The North Atlantic Treaty Organization's Committee on The Challenge of Modern Society held an international conference in 1971 on topics related to earthquake hazard and disaster, emergency relief, rehabilitation, and the role of various levels of organizations.

Studies and publications by social scientists on earthquakes were generally very few before 1964 when, under the impetus provided by the Disaster Research Center at The Ohio State University and by the National Academy of Sciences, an increase in interest was shown. The publications by Dynes, Haas, Kates, Kennedy, and Kunreuther have been referenced above.

In addition to the many reports on the effects of particular earthquakes which have appeared in recent years, several comprehensive studies by special commissions (Ad Hoc Panel on Earthquake Prediction, 1965; Federal Council for Science and Technology, 1968; National Academy of Sciences, 1969), and at least two major books on earthquake engineering (Wiegel, 1970; Newmark and Rosenbleuth, 1971) have been published. Recently a comprehensive manual on seismic design for buildings has been published through the joint effort of U. S. military agencies (U. S. Departments of Army, Navy and Air Force, 1973).

Among recent technical conferences of special interest have been the National Workshop on Building Practices for Disaster Mitigation (National Bureau of Standards, 1973) and the International Conference on Microzonation for Safer Construction (National Science Foundation, 1972).

In a study of a somewhat different sort, Urban Geology: Master Plan for California (California Division of Mines and Geology, 1973), a comparison is made of ten "geologic problems" and their quantitative effects on the State of California, "earthquake shaking" generally appearing as foremost among the problems.

The volume of technical literature regarding earthquakes and their effects has become so large that a third edition of the Bibliography of Earthquake Engineering has been published by the Earthquake Engineering Research Institute (Hollis, 1971). Furthermore, publication of the annual Abstract Journal in Earthquake Engineering was started in 1971 (Earthquake Engineering Research Center, 1972).

What is potentially the most far-reaching study is that reported in Meeting the Earthquake Challenge, which is the Final Report to the Legislature, State of California, by the Joint Committee on Seismic Safety (1974). Part One, entitled "A Comprehensive Approach to Seismic Safety," consists of definite recommendations to the legislature regarding needed action. The primary recommendation made by the legislative committee is as follows:

> The State should establish the California Commission on Seismic Safety with responsibility and authority to develop seismic safety goals and programs, help evaluate and integrate the work of State and local agencies concerned with earthquake safety, and see that the programs are carried out effectively and the objectives accomplished.

The report then proceeds to describe needed legislative action, including further definition of the proposed Commission's activity and authority with respect to the following areas of interest: land use planning measures, building construction (including standards and codes); abatement of hazardous buildings; critical and high-exposure facilities (schools, hospitals, dams); emergency preparedness measures; and research. These are followed by additional recommendations with respect to the following: land use controls; structural design measures for seismic safety; the furthering of preparedness, response and recovery; training and education; and earthquake insurance. The report is of great value not only in its exposition of the earthquake management problem in California, but also as a model of governmental study of a natural hazard.

## Affected Population

1. The World

Several million earthquakes, ranging from barely perceptible tremors to catastrophic shocks, occur in the world each year (OEP, 1972, Volume 3, p. 75). The entire land rim of the Pacific Ocean (from New Zealand through the Philippines, Japan, the Aleutian Islands, southern Alaska, and the coast of North, Central, and South America) is the Circum-Pacific Belt. The Alpide Belt extends from New Guinea, through the Himalayas, across southern Eurasia, through the Mediterranean, to the Azores in the Atlantic Ocean. The third major belt extends across the Arctic Ocean to Spitsbergen, then southward along the middle Atlantic ridge to the Antarctic Ocean and around the tip of Africa into the Indian Ocean. However, earthquakes of great magnitude are not confined to these belts alone.

The major earthquake areas include densely populated regions, e.g., the Pacific Coast of the United States, Japan, and areas bordering on the Mediterranean Sea. It has been "estimated that over 500 million persons could suffer damage to their property in seismic risk areas" (OEP, 1972, Volume 3, p. 77).

2. The United States Risk Zones

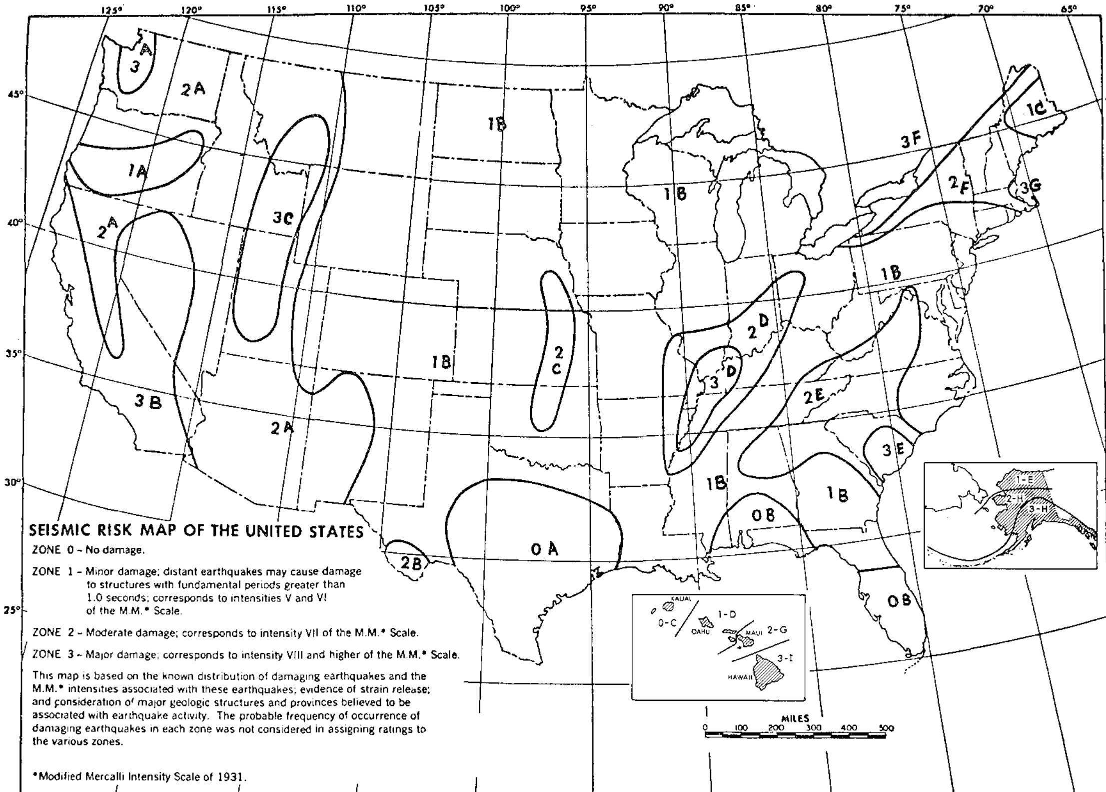
The most earthquake-prone areas of the United States belong to the Circum-Pacific Belt: those areas which are adjacent to the San Andreas Fault system of coastal California; the fault system in east-central California that separates the Sierra Nevada from the Great Basin; and the fault system along the southern coast of Alaska. Great earthquakes have occurred during the past three hundred years along the Atlantic Coast and in the central Mississippi Valley.

Seismic risk maps, developed by seismologists and engineers, have been used to define, in an approximate way, zones of varied degrees of risk. Figure I-1 is a map for the United States, Hawaii, and Alaska. The levels of risk range from Zone 0--no damage, to Zone 3--major damage. A recent study (Furomoto, *et al.*, 1972) proposes increases in zoning for the Hawaiian Islands. A new publication by U. S. military agencies includes a higher level, labeled Zone 4--great damage, for parts of California, Nevada and Alaska (U. S. Departments of Army, Navy, and Air Force, 1973).

It must be emphasized that "the probable frequency of occurrence of damaging earthquakes in each zone was not considered in assigning ratings to the various zones" (see notes on Figure I-1). There is doubt about the most effective way of analyzing recorded shocks, geologic structure, and evidence of recent faulting to estimate risk. A place which has had no pronounced seismic activity in the period of record may be the seat of a great earthquake during the next decade. The risk maps presented here are the best available at the time of publication, but it is generally agreed that much more research is needed on how to prepare risk maps that reflect all significantly relevant factors.

FIGURE I-1

SEISMIC RISK MAP OF THE CONTERMINOUS UNITED STATES




(Office of Emergency Preparedness, 1972, Volume 1)

Note: For significance of added letters A, B, etc., see Table I-1.

3. Estimates of Population-at-Risk

In an attempt to estimate population-at-risk in the United States by seismic risk zone, risk maps were superimposed on a map of counties. Population estimates were based upon the 1970 Census. When a county was in more than one risk zone, a population density map was used to position the population of that county among the appropriate zones. Table I-1 presents population estimates by seismic risk zone as defined in Figure I-1; population estimates by zone for each state; and population estimates for each of the four zones for the entire country.

The criticism in Section 2 above regarding the shortcomings of the risk maps must be applied also to the estimates of population-at-risk based on those maps.

The distributions of population-at-risk shown in Table I-1 compare favorably with the results of a study of housing-at-risk units based on the 1970 census and supplied to us by Johnson (1974). Johnson's analysis of year-round housing units, in standard metropolitan statistical areas and places of 10,000 inhabitants or more, resulted in finding the following percentages of such units located in the various seismic risk zones: Zone 0, 8.5%; Zone 1, 56.5%; Zone 2, 16.4%; Zone 3, 18.5%. His analysis covered 75.6% of the total of approximately 67,700,000 housing-at-risk units.

## Impact on Human Social Systems

The interrelationships between the earthquake and the social system can occur at six different levels: (1) the individual, (2) the small group, (3) organizatons, (4) the community, (5) the region, and (6) the nation (Barton, 1970, pp. 50-51). The impact of earthquakes may be felt, and adjustments adopted, at each of these levels. This section discusses briefly some of the relationships and their costs and benefits.

Earthquakes, like other natural hazards, place stress on human social systems. A system experiences stress when its capacity to meet demands is less than the level of demands made upon the system (Haas and Drabek, 1973). Of special interest for earthquakes is that impact comes without warning, and aftershocks may last for extended durations of time. These factors have special implications for the hazard's influence on the social system.

TABLE I-1

U. S. POPULATION-AT-RISK BY SEISMIC RISK ZONE AND STATE

| State | Total Population | Estimated Population-at-Risk by Seismic Risk Zone[1] | | | |
|---|---|---|---|---|---|
| | | Zone 0 | Zone 1 | Zone 2 | Zone 3 |
| Alabama | 3,444,165 | 1,056,000 | 1,126,000 | 1,263,000 | 0 |
| Alaska | 300,382 | 0 | 6,000 | 25,000 | 270,000 |
| Arizona | 1,772,482 | 0 | 0 | 1,742,000 | 30,000 |
| Arkansas | 1,923,295 | 0 | 1,473,000 | 166,000 | 284,000 |
| California | 19,953,134 | 0 | 0 | 2,636,000 | 17,317,000 |
| Colorado | 2,207,259 | 0 | 2,207,000 | 0 | 0 |
| Connecticut | 3,032,217 | 0 | 2,948,000 | 85,000 | 0 |
| Delaware | 548,104 | 0 | 548,000 | 0 | 0 |
| Florida | 6,789,443 | 5,503,000 | 1,286,000 | 0 | 0 |
| Georgia | 4,589,575 | 0 | 1,777,000 | 2,812,000 | 0 |
| Hawaii | 768,324 | 30,000 | 637,000 | 39,000 | 63,000 |
| Idaho | 712,567 | 0 | 0 | 513,000 | 200,000 |
| Illinois | 11,113,976 | 0 | 9,951,000 | 895,000 | 268,000 |
| Indiana | 5,193,669 | 0 | 2,350,000 | 2,608,000 | 236,000 |
| Iowa | 2,825,041 | 0 | 2,825,000 | 0 | 0 |
| Kansas | 2,249,071 | 0 | 1,907,000 | 342,000 | 0 |
| Kentucky | 3,219,311 | 0 | 1,349,000 | 1,467,000 | 403,000 |
| Louisiana | 3,643,180 | 0 | 3,643,000 | 0 | 0 |
| Maine | 993,663 | 0 | 318,000 | 675,000 | 0 |
| Maryland | 3,922,399 | 0 | 3,734,000 | 189,000 | 0 |
| Massachusetts | 5,689,170 | 0 | 0 | 1,980,000 | 3,709,000 |
| Michigan | 8,875,083 | 0 | 8,875,000 | 0 | 0 |
| Minnesota | 3,805,069 | 0 | 3,805,000 | 0 | 0 |
| Mississippi | 2,216,912 | 269,000 | 1,674,000 | 217,000 | 57,000 |
| Missouri | 4,676,501 | 0 | 3,079,000 | 1,389,000 | 209,000 |
| Montana | 694,409 | 0 | 240,000 | 313,000 | 142,000 |
| Nebraska | 1,483,791 | 0 | 1,206,000 | 278,000 | 0 |
| Nevada | 488,738 | 0 | 0 | 300,000 | 189,000 |
| New Hampshire | 737,681 | 0 | 0 | 738,000 | 0 |
| New Jersey | 7,168,164 | 0 | 7,168,000 | 0 | 0 |
| New Mexico | 1,016,000 | 0 | 536,000 | 480,000 | 0 |
| New York | 18,236,967 | 0 | 13,211,000 | 2,481,000 | 2,545,000 |
| North Carolina | 5,082,059 | 0 | 2,172,000 | 2,910,000 | 0 |
| North Dakota | 617,761 | 0 | 618,000 | 0 | 0 |
| Ohio | 10,652,017 | 0 | 7,863,000 | 2,789,000 | 0 |
| Oklahoma | 2,559,253 | 0 | 2,399,000 | 160,000 | 0 |
| Oregon | 2,091,385 | 0 | 539,000 | 1,539,000 | 13,000 |
| Pennsylvania | 11,793,909 | 0 | 11,347,000 | 183,000 | 264,000 |
| Rhode Island | 946,725 | 0 | 84,000 | 863,000 | 0 |
| South Carolina | 2,590,516 | 0 | 0 | 1,577,000 | 1,013,000 |
| South Dakota | 665,507 | 0 | 666,000 | 0 | 0 |
| Tennessee | 3,923,687 | 0 | 1,165,000 | 1,810,000 | 949,000 |
| Texas | 11,196,730 | 9,859,000 | 1,325,000 | 13,000 | 0 |
| Utah | 1,059,273 | 0 | 40,000 | 48,000 | 972,000 |
| Vermont | 444,330 | 0 | 0 | 444,000 | 0 |
| Virginia | 4,648,494 | 0 | 2,435,000 | 2,213,000 | 0 |
| Washington | 3,409,169 | 0 | 0 | 1,240,000 | 2,169,000 |
| Washington, D.C. | 756,510 | 0 | 757,000 | 0 | 0 |
| West Virginia | 1,744,237 | 0 | 1,509,000 | 236,000 | 0 |
| Wisconsin | 4,417,731 | 0 | 4,418,000 | 0 | 0 |
| Wyoming | 332,416 | 0 | 308,000 | 19,000 | 5,000 |
| Total | 203,223,000 (100%) | 16,717,000 (8%) | 115,091,000 (57%) | 40,442,000 (20%) | 30,973,000 (15%) |
| | | A 9,859,000 | A 539,000 | A 8,831,000 | A 2,169,000 |
| | | B 6,828,000 | B 113,591,000 | B 13,000 | B 17,535,000 |
| | | C 30,000 | C 318,000 | C 780,000 | C 1,319,000 |
| | | | D 637,000 | D 11,340,000 | D 2,349,000 |
| | | | E 6,000 | E 13,010,000 | E 1,013,000 |
| | | | | F 6,404,000 | F 2,545,000 |
| | | | | G 39,000 | G 3,709,000 |
| | | | | H 25,000 | H 270,000 |
| | | | | | I 63,000 |

[1]Figures rounded to nearest thousand.

[2]The numbers 0, 1, 2, 3 indicate the seismic risk zones; the letters A, B, etc., the geographical locations on Figure I-1.

Population estimates based on 1970 census.

On the individual level, an earthquake may disrupt normal activities and relationships. The loss of personal possessions and economic security, the death or injury of relatives and friends, as well as the possible exposure to aftershocks, can result in increased psychological depression and anxiety. The long-term effect of disaster-related anxiety is now known.

Earthquakes disrupt the family unit by threatening the family's economic security, and causing death or injury to family members. The economic loss resulting from the destruction of family-owned structures, however, does not provide as great an impetus for relocating out of high-risk areas as other natural hazards, perhaps because high-risk earthquake areas cover large geographical areas. Relocation out of high-risk areas would require severing economic and social ties not only with a part of a community, but with a geographical region itself. It is interesting that most emigration out of the Los Angeles area after the 1971 San Fernando earthquake was by new residents whose economic and social ties to the area were weaker than those of native residents (Nichols, 1972, p. 16).

Persons whose residences are temporarily uninhabitable must obtain temporary housing which is likely to be inconvenient with respect to comfort and accessibility to their old house. In contrast, inhabitants of dilapidated housing destroyed by an earthquake are likely to receive temporary housing that is of higher quality than their preimpact quarters. In addition to shelter, recreational activities are sacrificed.

Earthquakes affect organizations involved in disaster activities, as well as other organizations. In the former case, continued functioning of the organizations (a fire department or a hospital) after impact is crucial, whereas in the latter case, activities can be temporarily suspended in deference to higher-priority tasks.

Disaster-relevant organizations may have reduced capacity to meet demands, due to injured or absent personnel and damaged or inaccessible equipment. Furthermore, demands are likely to increase in quantity, as well as in novelty, after the earthquake. Performing new tasks and the absence of key personnel may cause an organization to lose its essential capability for coordinated and effective action. Possession of disaster-related skills influences response (Barton, 1970); organizations whose members' disaster tasks are comparable to their normal activities are more likely to respond efficiently. Utility organizations (water, electricity, gas) provide an example.

Stress may provide opportunities for the internal restructuring of an organization that may result in improvements (Anderson, 1970). Organizations specializing in repair and construction of buildings can expect increased business and profits following earthquakes. Some firms may adopt new technologies during the recovery period (Dacy and Kunreuther, 1969, pp. 168-75).

In many ways communities suffer the most serious effects of earthquakes. Not only are community buildings, schools, and public services damaged, but the destruction of private property results in a diminished local tax base. This reduction in revenues may be compensated partially by city sales taxes; the revenues collected from this source increase during the post-disaster reconstruction period. However, many marginal businesses may not have the capital to rebuild--regardless of forgiveness clauses in SBA loans--causing a temporary or permanent loss of revenues for the area (Committee on the Alaska Earthquake, 1970).

The adoption or revision of building codes may result from structural damage or destruction experienced in an earthquake. Another positive consequence of earthquakes at the community and regional levels is that the experience can provide a basis for the adoption, or revision, of local and regional preparedness planning for future impact response.

Figure I-2 illustrates some of the relationships between the different aspects of the physical and social environment, the earthquake, and their influence on a social system.

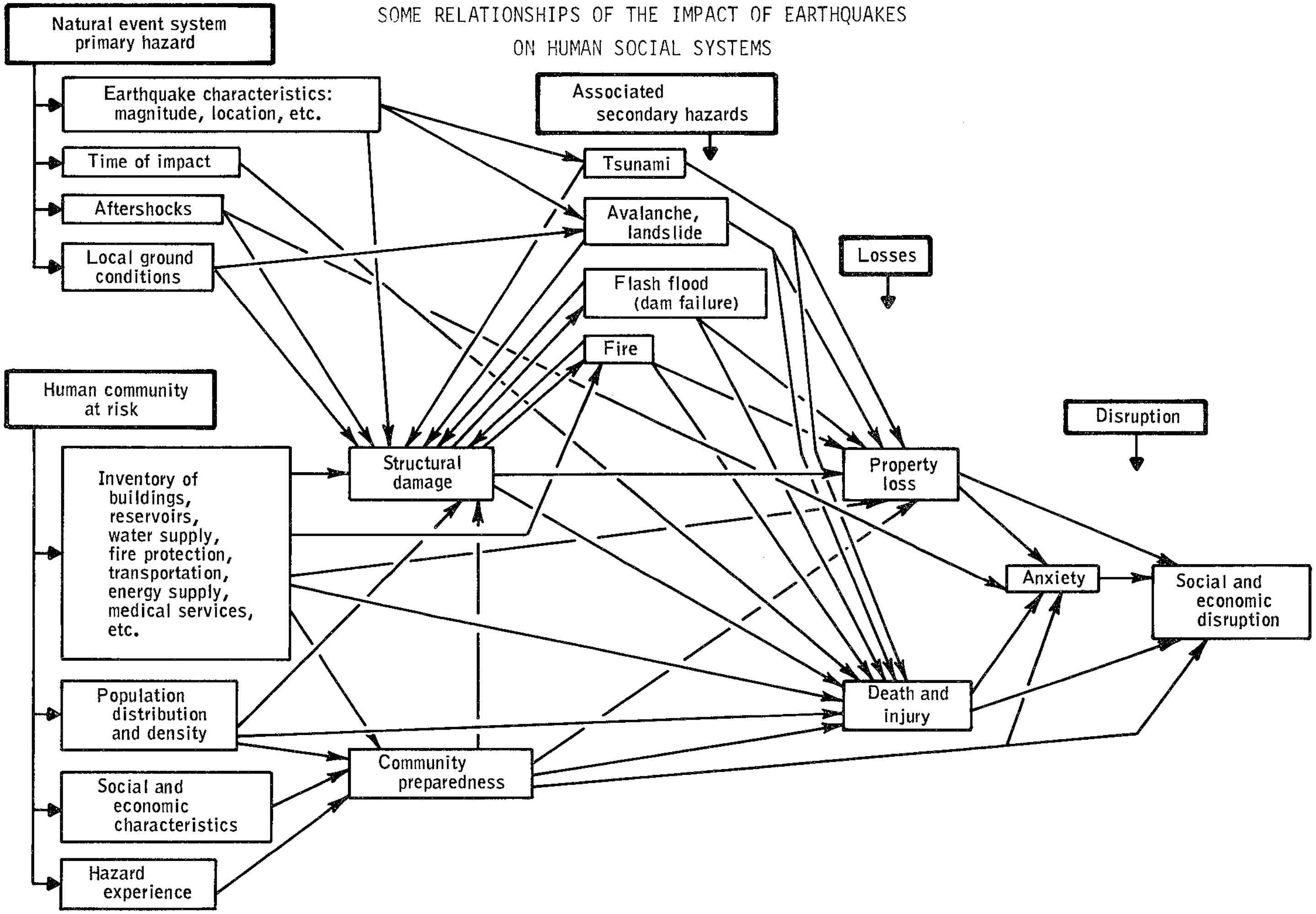
In these and other ways the earthquake provokes far-reaching impacts in society that go beyond dollar and fatality estimates. We turn next to a discussion of adjustments to earthquake hazard.

## Adjustments to Earthquakes

The adjustments which comprise the adaptive process to earthquakes include: (1) earthquake reduction and prevention; (2) earthquake-resistant construction; (3) land use management; (4) forecast and warning systems; (5) insurance; (6) adjustments to associated hazards (fire, landslide) triggered by an earthquake; and (7) community preparedness, relief, and rehabilitation. Of these, (2), (6), and (7) are partially effective; (1) and (4) are under consideration but have had little application; and (5) is available, but there has been relatively little demand for it.

FIGURE I-2

SOME RELATIONSHIPS OF THE IMPACT OF EARTHQUAKES ON HUMAN SOCIAL SYSTEMS



1. Earthquake Reduction

Regarding the controversial subject of earthquake reduction, we quote directly from the Office of Emergency Preparedness (1972, Volume 3, p. 86):

> At present and for the foreseeable future, the possibility of preventing earthquakes is extremely remote. The discovery of the correlation between deep-well waste disposal at the Rocky Mountain Arsenal and the minor earthquake activity in the nearby Durham, Colorado, area has led to the Rangely, Colorado, experiment being conducted by the U. S. Geological Survey. Results to date have indicated that it is possible to 'unlock' interfaces between rock strata by pumping fluid under pressure down a bore hole so that it is forced between the layers. Whether this lubricating action can be applied to areas of shallow earthquake activity to dissipate stresses gradually by causing many microtremors is indeed problematical. However, it provides a very fertile area for research in the immediate future.

The subject of earthquake reduction is interesting, but too little is known at present to justify prediction of its ultimate success. Were man able to implement in a reliable manner a trade of more frequent smaller earthquakes for one or a few large earthquakes, the hazardousness and costs of earthquakes could possibly be reduced. However, a diversity of constraints could thwart adoption of the technique: who would make the decision; how it would be decided; if damage resulted, who would be liable; and what social and economic disruption would result from a scheduled and announced earthquake. Such issues may serve as strong constraints to implementation of the technique, were it to become available.

It is by no means certain that a series of smaller earthquakes--unless they are, indeed, microtremors--will necessarily result in a smaller total social and economic disruption than a single major earthquake. The most probable benefits to come from research into earthquake reduction are greater knowledge of the processes by which earth strains accumulate and are released, and the application of this knowledge to prediction. This subject needs research in the social sciences, if it is to be researched in the physical sciences and engineering.

2. Earthquake-Resistant Construction

Optimum structural resistance to earthquakes involves responsible action by the owner, financing agency, architect, engineer, builder, foreman of construction, manufacturer of components, insuror, and appropriate government officials. The chief concern is with fixed structures--residences, buildings, ways for transportation, industrial plants, and dams.

Building codes and other regulations regarding safety, loading, and quality of materials and construction are vital in protection against earthquake, fire, and other hazards, but they are only as good as their enforcement. Furthermore, codes and regulations establish no more than minimum requirements. For a building code to be workable, it must be general enough to apply to residences, commercial buildings, and industrial structures.

There are many special problems in structural design for resistance to earthquakes which it is not possible to cover satisfactorily in a building code. It is the responsibility of the architect and engineer to recognize these problems. It is the responsibility of the contractor to ensure that the materials and construction practices meet the full intent of the contract and codes, since structures may fail as a consequence of poor materials and workmanship as well as poor design. The limitations on liability, with respect to construction in hazard-prone areas in general, have been discussed briefly by Kunreuther (1973a, pp. 28, 29).

Fire-resistant construction and other fire safety practices are required by building codes and insurance underwriters. Lending agencies require that full coverage fire insurance be carried by the mortgagee. Most communities have some sort of organized fire protection system.

For the hazard of earthquakes, however, there is at present only one reasonably effective check--building codes--but the codes themselves are often inadequate and in need of improvement. Earthquake insurance is available but seldom used. Furthermore, it is doubtful that lending agencies exert any generally significant influence on earthquake-resistant construction.

The problem of earthquake damage is not technically obscure for the standard types and sizes of structures. The implementation of resistant design to its full potential, however, is not widely practiced. This is evidenced by the fact that some recently constructed public structures were virtually a total loss as a result of the San Fernando Earthquake of 1971. In general, however, the older "pre-earthquake code buildings" are much more liable to be seriously damaged than buildings constructed after earthquake-resistant provisions began to be adopted.

The existence of an earthquake code does not guarantee that all new structures will remain completely undamaged; codes establish no more than minimum requirements, and cannot cover all types of structural assemblies and configurations. Furthermore, codes are not designed to prevent all damage--that would be prohibitively expensive.

The aim of a code is to reduce damage and human casualties to a tolerable minimum: (1) all persons involved need to become more aware of the possible damaging effects of earthquake ground motion, the dangers of fault zones, and the limitations of building codes (what codes do and do not do); (2) architects and engineers who design structures to be built in seismically active regions should be qualified in the theory and practice of earthquake-resistant design; (3) greater knowledge is needed regarding the theory and actual behavior of structures and their foundations in response to damaging earthquake ground motion; (4) greater knowledge is needed regarding the ground motions; (5) building codes need to be made much more effective; and (6) programs for the strengthening or demolition of existing hazardous buildings need to be adopted. These suggested courses of action are not new. Considerable progress has been made in some of them, if one considers that the applied knowledge as of 1933 was nearly nonexistent.

Little progress has been made in the strengthening or demolition of old, hazardous buildings except in the City of Long Beach, California, which has a program for doing away with such structures. Old hazardous buildings pose a very serious problem in some cities because many of them have evolved into densely occupied housing for the low-income population.

Suggested actions (1) and (2) require the establishment of continuing programs of education. Some universities and professional groups, particularly in California, have taken steps in this direction. Actions (3) and (4) require intensified, continuing programs of research. Actions (5) and (6) involve law and its enforcement, and require the adoption of ordinances and effective means for their implementation. All six types of action, especially (3) and (4), have been discussed in the report by the Committee on Earthquake Engineering Research (National Academy of Sciences, 1969).

At least two cities, Los Angeles and Long Beach, and two states, California and Massachusetts, are actively pursuing the improvement of their building codes. The balanced risk concept adopted by Long Beach for existing buildings, is new. In it, "each building is assigned both an *expected lifetime* and an *importance* (or exposure) *factor*" (Wiggins, 1972).

An extremely important matter is the consideration of the earthquake-resistance of special structures, mechanical equipment, and other facilities. Damage or destruction to these could lead to increased disaster through the associated hazards of flood, fire, explosion, and release of toxic substances, or to the interruption or failure of vital community functions such as transportation, energy flow, communication, water supply, waste disposal, food supplies, medical services, fire fighting capability, police, and other emergency services (Veterans Administration, 1974). The damage and destruction of many facilities during the San Fernando earthquake contributed to the overall magnitude of the disaster. Aside from buildings, dams and certain other structures, codes generally do not cover these specialized facilities. Much of the damage to special structures and equipment can be prevented by relatively inexpensive changes in design, provided they are introduced at the time of preliminary design. Numerous examples are available (Jennings, 1971; National Academy of Sciences, 1969).

The needlessness of much destruction and loss of life is evident when one considers that the additional cost of earthquake-resistance in most ordinary structures may be a small percentage of the total cost of the structure, provided good materials, design, and workmanship are used, and any modifications for earthquake design are *introduced at the time of preliminary design*. The percentages estimated by engineers vary considerably although they are ordinarily small, depending on the risk zone, type of structure and other considerations. Estimates of additional cost ranging from 0-6%, for ordinary structures, have been seen. The cost of strengthening a structure *after* it has been built, however, is generally very high and may equal a high percentage of the value of the structure. Nevertheless, the potential loss incurred in an earthquake event can far exceed such alteration.

Constraints operating to inhibit the adoption of building codes are diverse. Economically, they represent an increased cost to individual owners, the community, and the various levels of government. Socially, condemnation of old buildings disjoints neighborhoods, poses problems of relocation, and can precipitate conflict from special interest groups. Furthermore, the economic and social constraints may interact with the political and administrative systems to breed additional constraints. Perhaps the biggest constraint is getting experts to agree upon what is adequate yet simple enough to be workable.

Of particular interest to the reader of this section are the proceedings of the National Workshop on Building Practices for Disaster Mitigation (National Bureau of Standards, 1973).

3. Land Use Management: Risk Maps and Zoning

The implementation of land use management requires identifying the degree of hazardousness of geographical areas on both large and small scales. Since earthquake-induced loads are generated in buildings through the motion of the supporting ground, the required scale of investigation of ground conditions must ultimately be reduced to that of the particular buildings.

Subsurface conditions, which are important in evaluating earthquake risk, are not readily visible and can be determined only by local subsurface investigation. Engineers, as a group, know far more about the analysis and design of the part of the structure which is above ground, that is, above the level of transfer of the structural loads to the layers of soil and rock, than they do about the subsurface conditions. Any serious attempt at microzoning for earthquake risk requires the professional backgrounds of the soils engineer, geologist and seismologist, as well as the foundation-design engineer.

Little has been done in the United States in delimiting earthquake risk on either a macro- or micro-scale. The map shown in Figure I-1 reflects only one mode of analysis and should be supplemented by maps showing other parameters of risk such as Quaternary faulting.

There have been relatively few publications on local zoning for earthquake risk until very recently. Brief discussions are found in reports by the Committee on Earthquake Engineering Research (National Academy of Sciences, 1969, pp. 23. 71, 115, 117), by the Los Angeles County Earthquake Commission (1971, pp. 33-35), by Petak, *et al.* (1973), and in Disaster Preparedness (OEP, 1972, Volume 1, pp. 84-85). The most comprehensive collection of studies is in the Proceedings of the International Conference on Microzonation for Safer Construction (National Science Foundation, 1972); some of the most valuable conference papers have been republished in Contributions to Seismic Zoning (National Oceanic and Atmospheric Administration, 1973). See also the publications by Olson and Wallace (1969), and Mader (1972).

The OEP (1972) Report, cited above, states among its findings the following:

(1) The greatest potential for reducing the loss of life and property from earthquakes lies in restricting the use of land in high-risk areas and in imposing appropriate structural-engineering and materials standards upon both new and existing buildings.

(2) The greater use of instruments is essential to increasing knowledge, to providing risk maps, and to developing a theory of prediction . . . and perhaps control . . . of earthquakes.

(3) The development of seismic risk maps is an essential first step in hazard reduction and preparedness planning.

Zoning can proceed only as the result of further investigation and mapping of specific micro-areas, including identification of fault locations, the soil liquefaction hazard, and the landslide hazard.

The technical aspects of zoning are only one part of the problem if zoning is to be restrictive of property use. Consideration also must be given to the social, political, economic, and legal problems concerning its implementation.

Constraints operating to inhibit the adoption of land use management begin with the lack of micro-risk maps which provide the technical base for zoning. In addition, legislation may be necessary on which to base the implementation of zoning. A high degree of existing economic development, or of potential development in a high-risk zone, would encourage opposition to zone definition and the ensuing reduction in property values. Zoning on any basis is difficult, and in the opinion of some persons, natural hazard considerations are least likely to govern any zoning plan (see Baker and McPhee [1975] for expanded treatment of land use).

4. Forecast and Warning Systems

Earthquakes strike essentially without natural warning. They are felt no more than a few seconds or minutes, although there may be foreshocks and aftershocks spread over months. The time problem is vastly different for earthquakes compared to hurricanes, floods, and distantly generated tsunamis.

At this point a distinction between prediction and forecast must be made. Prediction may be defined as the evaluation of the probability of occurrence of an earthquake of given magnitude in a seismically active area in some number of years. However, it is the forecast of the specific time and place of occurrence and magnitude of an earthquake, including the accuracy of that forecast, that is the necessary prerequisite to an earthquake warning system. Forecast is relevant not only for the occurrence of an earthquake, but also for aftershocks. The latter use of forecast would be important to decision-making concerning the reoccupation of buildings after an earthquake.

Considerable study has been devoted by seismologists to theory and instrumentation for earthquake forecasting. At present, American, Japanese, and Russian seismologists are independently engaged in research on different methods. While there are still differences of view regarding the feasibility of earthquake forecasting (OEP, 1972, Volume 1, p. 85), there seems to be more optimism now than there was a year or two ago. Some persons anticipate a breakthrough within years rather than decades.

In this connection, one of the recommendations of the Committee on the Alaska Earthquake (1969, pp. 7-8) is especially interesting. It reads in part as follows:

> Studies are needed to make earthquake forecasting and hazard evaluation practicable; not only the feasibility but *also the socioeconomic implications of such forecasting need to be studied.*
>
> At the same time that means of forecasting earthquakes are sought, research should be directed to the probable economic, political, and social consequences of more accurate earthquake forecasting. Forecasting would be welcomed by scientists and engineers, but for the general public in a seismic area it is not clear whether the ability to forecast earthquakes would solve more problems than it would create. For example, a recent probabilistic earthquake warning or forecast for an area in Japan is said to have resulted in great tension and damage to the local economy.

Forecasting, when credible, would be valuable in reducing casualties, saving easily moved property, and preventing losses from some of the secondary effects of earthquakes such as fire. Whether or not reliable forecasting will be realized may be debatable; whatever the conclusion, it seems questionable to continue research for forecast capability without researching the social and economic aspects associated with forecasts. An investigation of the socioeconomic consequences of earthquake prediction is underway at the University of Colorado, with support from NSF (Haas and Mileti 1975).

Constraints to the adoption of forecast systems are numerous. Decision-makers may not want the responsibility of issuing what could turn out to be a false alarm. Evacuation of an entire area may be infeasible without extensive planning. The economic costs of temporarily "shutting down" a city may exceed the cost of the earthquake. Little information is available on effective methods for insuring, to some acceptable level, that the public will react in a predictable and desirable manner when a warning is received.

The Federal Disaster Assistance Administration has shown special interest in the outlining of needed research on the possible socioeconomic consequences of earthquake forecasting. At the request of FDAA, the National Academy of Sciences has established a panel on the Public Policy Implications of Earthquake Prediction.

5. Earthquake Insurance

In damage per capita, the damage from the 1906 San Francisco earthquake--including fire--was $5,000 in 1970 dollar value, while the damage per capita from the 1964 Alaska earthquake and tsunami was $7,500. Although much of the nation's seismic activity occurs along the Pacific coast, every state is vulnerable to earthquakes and has experienced them. A list of damaging earthquakes for the United States is given in Table I-2.

Insurance against earthquake damage is generally available. Coverage is available under the following insurance forms:

(1) Earthquake Form--Eastern and Pacific Form.

(2) Difference in Condition Form--Where not excluded by policy.

(3) Manuscript Form--A Lloyds type of policy written to include specific hazards not found in standard form. Inclusion in form would be based on recognition of need by insured and degree of risk underwriter attached to peril.*

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*The above information was supplied by Johnson (1974). Further details can be obtained from the F. C. & S. Bulletins, Earthquake Insurance and Difference in Conditions Contrasts, published by the insurance industry.

However, Dacy and Kunreuther (1969, p. 237) point out that relatively few property owners have been encouraged to avail themselves of its protection. One reason is that insurance companies are concerned about the possibility of severe losses if a great many buildings in one area are destroyed or damaged. Earthquake insurance is looked on "as a special service to customers holding other policies with the company, rather than as a profit-making operation." As a consequence, earthquake insurance has generally not been promoted, nor have property owners expressed much interest in it. The "5% deductible", based on the cash value of the earthquake policy, may discourage many owners of wood frame houses, damage to which may often be minor, from purchasing a policy.

For California in 1972, the "total premiums written for earthquake insurance were $9.0 million compared to $214.5 million for fire insurance" (Kunreuther, 1973a). These figures are for the year *following* the San Fernando earthquake. For Alaska, between the years 1960-1966, the total premiums for earthquake insurance were never greater than 1.2% of the total premiums written for fire insurance. This lack of coverage cannot be attributed to unusually expensive policies, since most houses are constructed of wood for which the rate is the lowest. Even after the 1964 earthquake, however, most homeowners did not take out insurance.

Except for nine Western states where damage potential is relatively severe, there is one standard manual used to determine insurance rates. The country is divided into zones on the basis of risk, with premiums varying according to type of construction. Rates for the Western states are calculated by the Insurance Services Office on the basis of three different hazard zones and eight types of residential construction. These types range from wood frame structures (the least vulnerable), to buildings of clay tile, hollow unreinforced concrete blocks, or unreinforced adobe walls (the most vulnerable). Rates for wood frame houses in California, for example, are about 15¢ per $100 coverage (with a 5% deductible clause). Rates for similar construction in the central and eastern parts of the country are considerably lower, perhaps about one-fourth of those in California. Rates for highly vulnerable types of construction may be many times greater.

The problem of insuring against a natural hazard having very high catastrophe potential, such as a great earthquake striking a large metropolitan area, is an extremely difficult one financially. At least one source has made the following gloomy observation:

> ... as things stand now, the seismic region of California may be virtually *uninsurable* as a whole. The potential losses from a single strong earthquake are very great--on the order of $5-$50 billion--and there is no certainty that the next such earthquake will be delayed long enough for the insurance industry to build up adequate reserves to cover the losses (Joint Committee on Seismic Safety, 1974).

Facing the insurance industry is the key question: what type of *reinsurance* can the industry obtain to protect it against a great earthquake catastrophe?

In the future, some collaborative form of government/industry earthquake insurance may be a solution to the problem of financial protection against earthquakes. The program might be similar to the flood insurance now generally available throughout the United States. Strong views, both for and against such a program, may be found. Coupled with the program there must be strong incentives for property owners to purchase the insurance.

In addition to the monographs by Dacy and Kunreuther and the Insurance Information Institute, discussions related to the earthquake insurance problem may be found in the report on Earthquake Engineering Research (National Academy of Sciences, 1969); in papers published in the proceedings of the Earthquake Risk Conference (Baker, 1971; Kunreuther, 1971); and in other references (Kunreuther and Fiore, 1966; Committee on the Alaska Earthquake, 1969; Friedman, 1970; Kaplan, 1971-72; Steinbrugge, *et al.*, 1971; Los Angeles County Earthquake Commission, 1971; Mukerjee, 1971; OEP, 1972, Volume 1; Kunreuther, 1973; Steinbrugge, 1973). A recent paper by Theodore H. Levin (1973) is particularly useful. The hazard "insurance" program of the New Zealand Earthquake and War Damage Commission has been discussed by Bennett (1965), O'Riordan (1971), and others. The book, Earthquake Damage and Earthquake Insurance (Freeman, 1932) is of historical interest.

The constraints mitigating against the adoption of earthquake insurance are closely linked to some other adjustments. Public relief and rehabilitation policies probably influence individual use of insurance in some way. A recent monograph by Kunreuther (1973a) considers this question in detail. No one knows precisely, however, the total social costs of insurance, why insurance is so sparsely adopted, and how it encourages or discourages other adjustments. In 1974 Kunreuther began an extensive survey research effort to determine what factors influence the decision of homeowners whether or not to purchase earthquake insurance. The survey has been planned to include 1000 house-to-house interviews in California, including both insured and non-insured homes in the sample.

6. Adjustments to Associated Hazards Triggered by Earthquakes

The problems of compound disasters of associated hazards have been introduced. We will discuss the adjustments to associated hazards only very briefly.

The standard adjustments to fire are well known. What often is not understood, however, is the need for *all* facilities required for the fighting of fire to be completely safe against significant earthquake damage. Furthermore, the fire-fighting organization must be adequately staffed, trained, and prepared to cope with operations under the conditions of an earthquake disaster (National Oceanic and Atmospheric Administration, 1972, pp. 208-212; Earthquake Engineering Research Institute, 1958; Steinbrugge, 1968).

The adjustments to tsunamis are treated under Part II of this report. Adjustments to flash floods, landslides, and avalanches will be found in separate reports of the Assessment of Research on Natural Hazards series (White, *et al.*, 1975; Sorensen, Ericksen and Mileti, 1975; ARNH Staff, 1975).

The failure of a dam usually results in a flash flood. Dams located in seismically active areas, therefore, must be designed and constructed with great care. (This has been a matter of concern to the State of California for many years.) Furthermore, it would be wise not to allow vulnerable development to take place in a flood path downstream from such a dam. A bill passed in March, 1973, by the California State Legislature (California Senate Bill 896, as amended) provides that the California Department of Water Resources will inform the California Office of Emergency Services of those dams which, if they broke, would cause loss of life. One thousand two hundred such dams have now been designated. Exemptions for building in the area at risk may be applied for by dam owners, but the burden of proof of no loss of life with dam breakage is on the owner. Four hundred such exemptions have been granted. The review of all exemptions is required every two years.

Some of the less risky landslide and avalanche areas, which under non-seismic conditions may be controllable through stabilizing or diversion structures, under the dynamic triggering action of an earthquake may release masses of uncontrollable size. Landslide and avalanche paths in seismically active areas should be zoned for open space or other non-vulnerable purposes.

7. Community Preparedness, Relief, and Rehabilitation

Community preparedness, relief, and rehabilitation encompass the related actions of three time phases of preparation for, or actual response to an earthquake disaster. Community preparedness is a component of relief and rehabilitation in that, to a significant extent, what occurs in the former determines the efficacy of the latter. In this context community preparedness anticipates the eventual but undetermined impact of an earthquake. Relief is the immediate response after impact to provide required services and commodities to the community, groups, and individual victims. It consists basically of remedial processes originating within the community itself, as well as those from outside the community. Rehabilitation consists of those *long-term* efforts to restore stability to a stricken community once immediate needs have been met in relief. In relief people are fed, sheltered, and clothed; in rehabilitation, employment, physical health, and buildings are restored (see Mileti [1975] for further discussion).

Community preparedness for earthquakes must proceed on the assumption that an earthquake occurs without warning (given the present status of our forecast ability), and that the demand for decision-making in leadership roles immediately after impact will be greater than for most other natural hazards. With these assumptions recognized, preparedness for an earthquake disaster begins with an understanding of the threat in a specific community and how best to respond: community-specific vulnerability analysis; potential damage assessment; and detailed plans to cope with situations of varying degrees of shock impact. Seldom, however, can one plan provide for all eventualities. An adequate and usable plan must be adaptable to most situations.

The Interim Federal Earthquake Response Plan (OEP, 1973) for the San Francisco Bay Area is an attempt to specify such details into a plan for Federal response to a major earthquake in the greater San Francisco region. Based on a detailed vulnerability analysis of the area (National Oceanic and Atmospheric Administration, 1972), the plan is designed to complement a yet-to-be-developed state plan for response. The plan assumes that various levels of response will be required, depending upon the magnitude of the earthquake, location, season of year, and the time of day of the impact.

A comprehensive program for the development of preparedness is currently being conducted in many California cities and counties. The program is sponsored by the Defense Civil Preparedness Agency and the California Office of Emergency Services, and is being implemented by the University of Southern California Institute for Disaster Preparedness. Among the goals of the program are: the training of officials and personnel; increasing the awareness that individual area capability for response is not enough for large scale disasters; and the development of a local capability to carry out simulation exercises (Meyer, *et al.*, 1969).

The consequence of the viability of community preparedness is the actual operation of the relief effort. However, other factors may disrupt the effective functioning of the processes of relief and rehabilitation. These can be grouped into those conditions stemming from the relief-giving organizations (public service organizations, religious service organizations, local governmental units, and state and Federal agencies) and those factors involving the population requiring relief.

There are several incentives for the active participation of relief and rehabilitation organizations, not the least of which is the community's desire to remove the added economic burden placed on local revenues by structural damage of business and personal property, as well as to avert possible unemployment.

There is a recurrent dilemma intrinsic in the relief and rehabilitation process: decisions to act quickly to relieve suffering and to get the economy going again often tend to undermine those actions that should be taken for longer-term recovery. This is especially critical in the provision of temporary housing, which is rarely replaced.

## Costs and Benefits of the Hazard

### 1. Estimating Earthquake Losses and Adjustment Costs

Estimating earthquake losses is an inexact science. There can be considerable variation among estimates, depending on the method used. For example, dollar losses can be estimated on the basis of replacement costs, or on the basis of actual cash value. The difference can be highly significant, as illustrated by the fact that the actual cash value of the buildings damaged at Bakersfield, California at the time of the 1952 shocks was 36% of the replacement value of these buildings (National Oceanic and Atmospheric Administration, 1972, p. 5).

The U. S. Coast and Geodetic Survey has published a chronological catalog of United States earthquakes, Earthquake History of the United States, which includes damage figures for major United States earthquakes and tsunamis, compiled in Table I-2. A comparison between these damage estimates and other estimates from different sources illustrates the degree of difference between sources. The initial damage estimate by the Office of Emergency Preparedness for the Alaska Earthquake of 1964 was $620 million; its damage estimate of September, 1964, was $335 million (Kunreuther, 1970, p. 430); and the estimate published by the National Earthquake Information Center in 1969 was $500 million (National Earthquake Information Center, 1969, p. 52). The Office of Emergency Preparedness' estimate includes shortfall of revenue and extraordinary operating expenses, whereas the Earthquake Information Center's estimate apparently does not, even though it is the higher estimate. Kunreuther makes the observation that initial damage estimates are generally much higher than later estimates, as illustrated by the Office of Emergency Preparedness' estimates.

Another example of differing earthquake damage estimates is the OEP estimate of the San Fernando, 1971 earthquake damage at $553 million (OEP, 1972, Volume 3, p. 82), and the National Bureau of Standards estimate of the damage at $436 million (National Bureau of Standards, 1971, p. 15).

We have found no published listings of earthquake dollar damages which include damage from minor earthquakes. Although the economic loss from cracked plaster, damaged chimneys, and broken dishes is readily absorbed by the local community, the economic accumulation of loss over many small earthquakes may be significant.

In estimating earthquake losses, it should be noted that property damage is only one aspect of loss due to earthquakes. Other losses include loss of life (see Table I-2), injuries, mental health problems, economic loss due to injuries, loss of income due to business disruption, and the cost of emergency operations.

Possible benefits of earthquake-stimulated Federal programs must also be taken into consideration. An economic study of the Alaska Earthquake of 1964 indicates that there were no long-term economic effects resulting from the earthquake, although a temporary increase in employment occurred following the earthquake (Rogers, 1970, p. 35).

TABLE 1-2

PROPERTY DAMAGE AND LIVES LOST
IN MAJOR U.S. EARTHQUAKES (Including Tsunamis)*

| Year | Locality | Damage ($M)[1] | Constant Dollars ($M)[2] | Lives Lost[1] |
|---|---|---|---|---|
| 1811 | New Madrid, Missouri | | | Several |
| 1812 | New Madrid, Missouri | | | Several |
| 1812 | San Juan Capistrano, California | | | 40 |
| 1865 | San Francisco, California | .5 | .7 | |
| 1868 | San Francisco, California | .4 | .7 | |
| 1868 | Hayward, California | | | 30 |
| 1872 | Owens Valley, California | .3 | .6 | 27 |
| 1886 | Charleston, South Carolina | 23.0 | 73.8 | 60 |
| 1892 | Vacaville, California | .2 | .7 | |
| 1898 | Mare Island, California | 1.4 | 5.3 | |
| 1899 | San Jacinto, California | | | 6 |
| 1906 | San Francisco, California | 24.0 | 71.1 | 700 |
| | Fire loss | 500.0 | 1481.9 | |
| 1915 | Imperial Valley, California | .9 | 2.4 | 6 |
| 1918 | Puerto Rico (tsunami damage from earthquake in Mona Passage) | 4.0 | 5.6 | 116 |
| 1918 | San Jacinto and Hemet, California | .2 | .3 | |
| 1925 | Santa Barbara, California | 8.0 | 14.1 | 13 |
| 1926 | Santa Barbara, California | | | 1 |
| 1932 | Humboldt County, California | | | 1 |
| 1933 | Long Beach, California | 40.0 | 111.2 | 115 |
| 1934 | Kosmo, Utah | | | 2 |
| 1935 | Helena, Montana | 4.0 | 9.1 | 4 |
| 1940 | Imperial Valley, California | 6.0 | 14.0 | 9 |
| 1941 | Santa Barbara, California | .1 | .2 | |
| 1941 | Torrance-Gardena, California | 1.0 | 2.1 | |
| 1944 | Cornwall, Canada-Massena, New York | 2.0 | 3.5 | |
| 1946 | Hawaii (tsunami damage from earthquake in Aleutians) | 25.0 | 37.8 | 173 |
| 1949 | Puget Sound, Washington | 25.0 | 29.9 | 8 |
| 1949 | Terminal Island, California (oil wells only) | 9.0 | 10.8 | |
| 1951 | Terminal Island, California (oil wells only) | 3.0 | 3.1 | |
| 1952 | Kern County, California | 60.0 | 63.8 | 14 |
| 1954 | Eureka-Arcata, California | 2.1 | 2.3 | 1 |
| 1954 | Wilkes-Barre, Pennsylvania | 1.0 | 1.1 | |
| 1955 | Terminal Island, California (oil wells only) | 3.0 | 3.0 | |
| 1955 | Oakland-Walnut Creek, California | 1.0 | 1.0 | 1 |
| 1957 | Hawaii (tsunami damage from earthquake in Aleutians) | 3.0 | | |
| 1957 | San Francisco, California | 1.0 | | |
| 1958 | Khantaak Island and Lituya Bay, Alaska | | | 5 |
| 1959 | Hebgen Lake, Montana (damage to timber and roads) | 11.0 | 10.9 | 28 |
| 1960 | Hawaii and U.S. West Coast (tsunami damage to Hilo from earthquake off Chile coast) | 25.5 | 25.3 | 61 |
| 1961 | Terminal Island, California (oil wells only) | 4.5 | 4.5 | |
| 1964 | Alaska and U.S. West Coast (includes tsunami damage from earthquake near Anchorage) | 500.0 | 497.5 | 131 |
| 1965 | Puget Sound, Washington | 12.5 | 12.2 | 7 |
| 1966 | Dulce, New Mexico | .2 | .2 | |
| 1969 | Santa Rosa, California | 6.3 | 5.6 | |
| 1971 | San Fernando, California | 553.0 | 474.3 | 65 |
| | | 1862.1 | | |

[1](Office of Emergency Preparedness, 1972, Volume 3)

[2] 1957-59=100

*The compilation is not complete; an earthquake in Utah in 1962 which caused nearly $1 million damage (U. S. Coast and Geodetic Survey, 1965, p. 71) is not included.

However, as Rogers pointed out, the Alaska economic pattern was unusually dependent upon Federal expenditures. One cannot draw comparisons between the Alaska Earthquake and, for example, a major California earthquake. According to another source, Alaska did benefit from the earthquake (Eckel, 1970, p. 31). Some of the benefits cited are: (1) the permanent stabilization of part of the business area of Anchorage by gigantic earth buttresses, (2) new and better port facilities in the affected seacoast towns, (3) the acquisition of new fishing boats and modern canneries under favorable financial terms, (4) the discovery that the port of Anchorage could be used year-round, and (5) the discovery that plastic tents over construction projects permitted construction in the sub-Arctic winter. Eckel states that the total amount of Federal aid to Alaska was greater than the damage, although Kunreuther's figures (Kunreuther, 1970) disagree.

There is little information on the costs and benefits of particular adjustments, although a paradigm for estimating them has been published (Mukerjee, 1971). The costs of structural changes have been discussed briefly in another part of this report. A study on the benefits from engineering seismology predicts a great potential benefit from this source (Crumlish and Wirth, 1967). The prediction may be correct, but benefit predictions limited to a single class of adjustments are apt to be misleading.

2. Trends in Earthquake Losses

Trends in earthquake losses are difficult to estimate because (1) the recurrence period of damaging earthquakes is large and in some areas may be as large or larger than the period for which data are available, and (2) many factors other than the magnitude and duration of the earthquake will influence the extent of the earthquake's effects. The more densely populated the area, the greater the destruction, and the trend has been toward increasing population. Whether or not a major fire occurs will influence the amount of damage and loss of life. Time of occurrence may be very important.

In spite of the difficulty in interpreting damage trends, there is some evidence that earthquake damage has been increasing in the United States. The average annual increase in earthquake damage has been calculated at 5.8% (Dacy and Kunreuther, 1969, p. 17). Dollar loss on a per capita basis seems to show an upward trend in recent years (see Figure I-3).

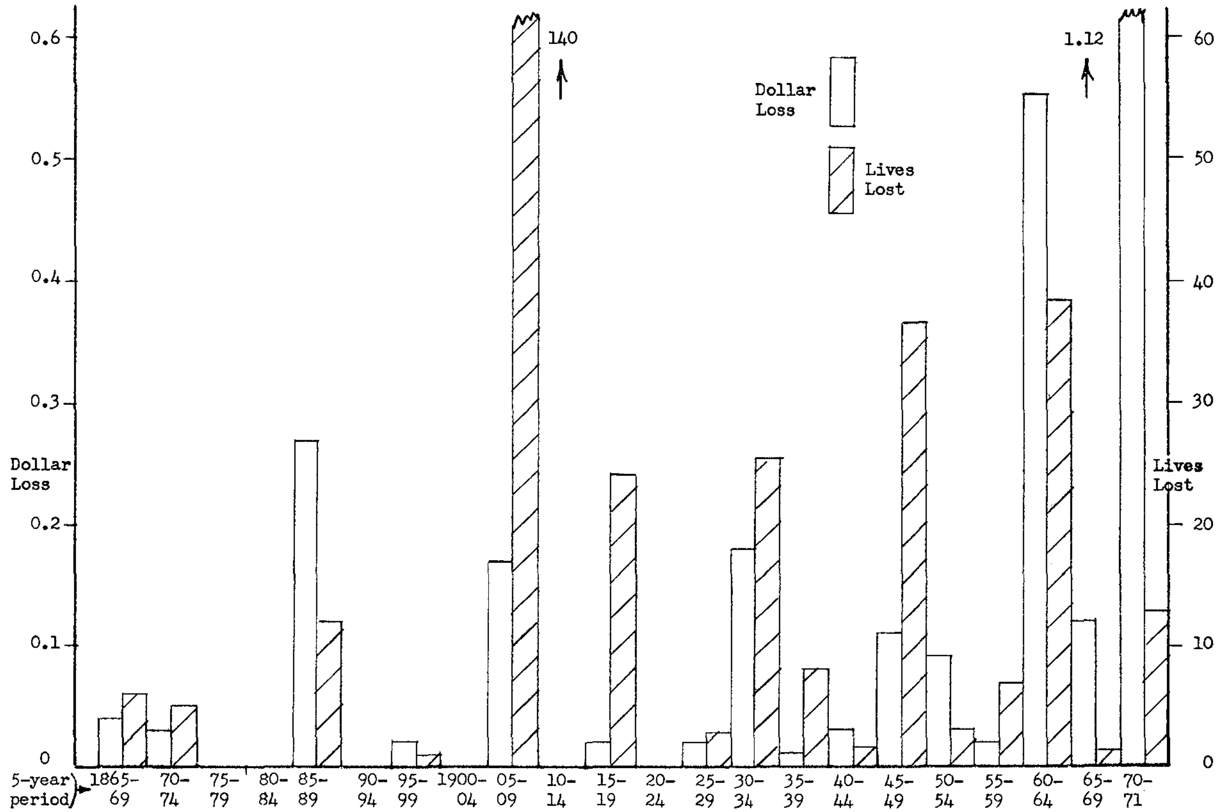



FIGURE I-3

MEAN ANNUAL PROPERTY DAMAGE AND LIVES LOST IN U.S. EARTHQUAKES

Dollar loss is per capita of U.S. population. Deaths expressed as average per year. Calculations based on 5-year periods.
(Based on Office of Emergency Preparedness, 1972, Volume 3)

Another approach to the problem of earthquake trends is to estimate, for a given area, the amount of damage that would occur from an earthquake of a certain magnitude. For areas in which it is known that major earthquakes will occur, this approach is useful in estimating the potential benefits of particular adjustments. An example is the study of the San Francisco Bay Area for earthquakes of a Richter magnitude of 8.3, 7.0, and 6.0 (National Oceanic and Atmospheric Administration, 1972). The estimated damages for *dwellings* in California as a whole over various time spans, for regions of California for a 100-year span, and for various California counties for a 100-year span have been calculated using a present-day level of construction. The damage estimate for dwellings in the state of California over 100 years is about $6.5 billion.* For a single San Francisco earthquake similar to that of 1906, the damage for dwellings is estimated at $1.2 billion (Algermissen, *et al.*, 1969, pp. 49-55). The result of these calculations, for dwellings alone, is staggering.

It may be impossible to get agreement on estimates of future losses, except in terms of broad ranges of loss, particularly in the case of hazards such as severe earthquakes for which the recurrence interval is long and for which the catastrophe potential is great. It may be worthwhile, however, to compare some of the estimates which have been made.

In the case of the highly vulnerable San Francisco Bay region, a present-day repetition of the 1906 earthquake can be assumed to result in damage measured in billions, even tens of billions of dollars. The population of the region has grown from approximately 500,000 in 1906 to approximately 5 million in 1970, that is, by a factor of about ten.

Furthermore, the dollar investment in construction *per capita* is now much larger than it was in 1906, possibly by a factor of five to ten. There are several reasons for the increase, including economic inflation, growth of technology, and increased demands for services. Offsetting to some extent the effects of these increases are the improved resistance of modern construction to earthquake and fire and the presumably improved fire-fighting capability. (At least 80% of the total

*This figure is apparently for direct damage to dwellings alone.

damage in San Francisco in 1906 has been attributed to fire.)

Even if one uses the most conservative estimates regarding growth in population and investment, and assumes, furthermore, a relatively negligible fire loss (which isn't likely), the cost could be of the order of $5 billion or more in direct damages.

A recent, detailed prediction of the economic impact on the San Francisco Bay region of a repetition of the 1906 earthquake (Cochrane, 1974) resulted in an estimate of *direct* losses of $7 billion, plus *indirect* costs of $6 billion, for a total cost of $13 billion. It is interesting to note that another source (Duke, 1974) has estimated that direct damage from an earthquake centering in Los Angeles, of a severity comparable to the 1906 San Francisco earthquake, would result in $20 billion damage.

Levin (1973) reports that studies sponsored by the Federal Insurance Administration and the Office of Emergency Preparedness result in the "estimate that a recurrence in San Francisco of such a catastrophe (the 1906 shock) would cause $25 billion in losses in the metropolitan area." He further points out that should a shock of similar magnitude "hit the Los Angeles area, (the) total could be doubled." One can interpret this to mean that the loss might be as much as $50 billion. Some authorities find this estimate too high.

In the recent publication, Meeting the Earthquake Challenge, The Final Report to the Legislature, State of California, by the Joint Committee on Seismic Safety (Joint Committee on Seismic Safety, 1974), it is estimated that "the potential losses from a single strong earthquake (in California) are very great--on the order of $5-$50 billion...." It is not clear whether these estimates were intended to include indirect losses.

These estimates indicate that tabulations of historical dollar damage, as in Table I-2, are apt to be very misleading as bases for prediction of future losses, unless they are accompanied by estimates of population and investment growth. It is evident that a *single great earthquake in a large metropolitan area could result in damage greater than the total historical dollar damage* shown in Table I-2.

The Los Angeles and San Francisco urban areas are by no means the only candidates for such catastrophic losses, although history indicates that their probabilities are highest. Evidence shows that the Seattle, Boston, and Charleston areas, and the region north from Memphis along the Mississippi and Ohio Rivers (Figure I-1) may also be candidates.

Some comments regarding categories of construction and damage are in order. Cochrane (1974) shows the following breakdown of his estimated $7 billion direct loss: residential structures, $2 billion loss; commercial/industrial structures, $1.5 billion loss; public sector (presumably including utilities and transportation), $3.5 billion loss. Algermissen, *et al.* (1969) reported an estimated loss of $1.2 billion for dwellings alone for a repetition of the 1906 earthquake. Duke (1974) points out the importance of "city lifelines" (utilities and transportation systems), and reports that "they constitute around 50% of the constructed value vulnerable to earthquakes, the other 50% being buildings." There seems to be reasonable agreement among these several sources.

Predictions of human injury and loss of life are at least as difficult to make as predictions of dollar damage. The United States has been extremely fortunate in the relatively few casualties from earthquakes. Human casualties in an earthquake are caused primarily by structural damage, structural collapse, or falling masonry unless a fire storm develops, as in Tokyo in 1923.

Most seriously damaging earthquakes in the United States have occurred at times of day when most people were in their homes. If a major earthquake were to strike a large metropolitan area during rush hour when crowds of people are on the sidewalks or entering or leaving buildings, the number of casualties could be enormous.

Casualty predictions have been published by several authors. It is not always clear whether these estimates have been arrived at independently, but evidently there is some agreement, at least in order of magnitude. Duke (1971a) has predicted that an expectable, great earthquake in the Los Angeles area would result in 10,000 deaths. In regard to the San Francisco Bay Area, it has been predicted that an earthquake of 8.3 Richter magnitude on the San Andreas fault near San Francisco--essentially a repetition of the 1906 earthquake--could result in as many as 10,000 deaths and 40,000 hospitalized injuries if the shock occurred at about 4:30 p.m. (working-day rush hour) (Algermissen, *et al.*, 1972). Furthermore, it has been estimated that 30,000 additional deaths could result from failures of dams, induced by the earthquake, in the Bay Area (Algermissen, *et al.*, 1972). The foregoing estimates have also been included in the report, Urban Geology (California Division of Mines and Geology, 1973).

An article by Levin (1973) reports that loss of life "could approach 10,000" as the result of a major shock of the magnitude of the 1906 earthquake striking either the San Francisco or the Los Angeles metropolitan area. He points out that the numbers would depend, also, on the "location, duration, and time of day of the shock."

Urban Geology (California Division of Mines and Geology, 1973) is perhaps the most comprehensive report available on the projection of quantitative direct damages due to a variety of geologic problems in a large geographic area. Earthquake shaking is shown as having "projected total losses, 1970-2000, without improvement of existing (1970) policies and practices," equal to about $21 billion. The estimated "possible total loss reduction 1970-2000, applying all feasible measures" is about $10.5 billion, in other words a reduction of 50%. The "estimated total cost of applying all feasible measures, at current state of the art, 1970-2000", is believed to be $2.1 billion, which is 10% of the projected total loss and 20% of the estimated possible loss reduction. These results lead to an estimated benefit/cost ratio of 5. More complete explanation is available in the sources (California Division of Mines and Geology, 1971, 1973). The estimates of loss and reduction in loss include estimates of lives lost at $360,000 per death.

The loss calculations were based on an hypothetical "urban unit" containing 1000 dwellings with appropriate service facilities and business community, in an area of 0.377 square miles, and having a population of 3000 persons. This corresponds to a population density of approximately 8000 persons per "developable square mile." It was assumed that 50 persons are killed in each urban unit "per earthquake in the MM (Modified Mercalli) intensity range of IX or more, and five persons are killed . . . during intensity MM VIII shaking." It was assumed that no deaths occurred at MM intensities of VI or less. The authors point out that "these assumptions are based on little more than conjecture." They state, furthermore, "Injuries are not included because an estimate of the number of people affected is much more difficult than for life loss, and the costs of injuries are still more difficult to estimate" (California Division of Mines and Geology, 1973). Indirect losses apparently were not included.

The death-ratio assumptions are equivalent to one death in 60 persons at earthquake intensities of MM IX or above, one death in 600 persons at MM VIII, and no deaths at MM VI or below. Using these ratios and making some very crude assumptions regarding the percentages of population exposed to the various ranges of earthquake intensity during a great earthquake in either the San Francisco or Los Angeles areas, an estimated death toll of the order of 10,000 is determined. The authors of the report predict a "90% reduction of life loss" due to "earthquake shaking" provided "all feasible measures" to reduce loss are applied during the period 1970-2000.

Loss of mineral resources due to urbanization is scarcely a natural hazard in the sense of the other geologic problems listed. Comparing the projected losses, loss reductions, remedial costs and benefit/cost ratios for the various geologic problems, one notes the very high position it has been given.

Fault displacement has been separated from earthquake shaking. Damage may occur as a result of very slow fault displacements, called fault creep, without strong earthquake shaking motions, as well as by sudden fault displacements accompanied by earthquakes. The projected total losses for the 30-year period due to all fault displacements, either slow or sudden, are only about 0.35% of the projected total losses due to earthquake shaking. The earthquake shaking problem is of immensely greater consequence than the fault displacement problem as far as economic losses are concerned.

Next to the bottom rank is the tsunami hazard, with projected total losses only about 0.2% of those due to earthquake shaking. It must be remembered, of course, that the data used in this comparison apply only to the state of California and that they have been limited to a 30-year projection. If similar studies were made for Hawaii and Alaska, the tsunami hazard would assume a more prominent rank.

3. Federal Expenditures for Earthquake Adjustment

Federal expenditure for earthquake adjustment can be divided into pre- and post-disaster responses, with post-disaster responses predominating. Much of the pre-disaster activity of the Federal government has been in the area of seismological and engineering research and seismological monitoring. The amount spent for Federal earthquake research in 1972 was over $3,408,000, according to information from the Smithsonian Science Information Exchange. This figure is low because the level of support was not disclosed for a substantial amount of earthquake research funded by the Department of Defense and the U. S. Geological Survey.

The total amount spent for post-earthquake adjustments by the Federal government has not been compiled, but the amount spent by the Federal government following the Alaska earthquake, $321 million (Kunreuther, 1970, p. 430), gives some indication of the level. The expenditures of the Small Business Administration, the major source of financial assistance to the private sector in earthquake disasters, is another indicator of Federal involvement. The average annual amount loaned by the SBA for earthquakes from 1960-1972 has been $25 million.

## Role of the Federal Government

In the 19th and early 20th Century, the Federal government had little to do with natural disasters except on an ad hoc basis through the armed forces. In the San Francisco disaster of 1906, Army units were sent in on patrol and on various special missions.

In 1932, as already mentioned, the U. S. Coast and Geodetic Survey started the "strong motion" instrument program, now grown to hundreds of stations in a widely spread network. As a result of this system, we have a record of 40 years of the recording of strong motion earthquakes. The results are invaluable for use in estimating the response of structures.

The Federal government has funded research in structural dynamics for more than 25 years. Some of it has been directed especially toward the problems of earthquake resistance of structures. Development in earthquake-resistant design has been carried on within some Federal agencies, for example, the Bureau of Reclamation designs dams for seismically active locations. Research in seismology and geology receives Federal support within the agencies, and also for sponsored research by university and other groups. Among the subjects are seismicity and earthquake prediction. Fire research has long been an activity of the National Bureau of Standards; this work is indirectly important to the earthquake hazard problem.

In comparing the roles of the Federal government related to the flood and the earthquake hazards, significant differences are found. For the earthquake hazard there is no expenditure comparable to the vast sums which have gone into capital investment in dams, levees, and other control works related to floods. No significant role is played by the Federal government in earthquake insurance similar to what it has done in flood insurance. Far more research, however, is supported by the government in fields concerned with the earthquake problem than in those directly concerned with floods.

1. Community Preparedness

Federal involvement in community preparedness for earthquakes has largely been integrated with community preparedness programs. It operates on the assumption that the programs must be a combined effort of Federal, state, and local governments. The Federal effort is based in the Office of Emergency Preparedness (now Federal Disaster Assistance Administration), whose task (OEP, 1972a) is to foster the development of state and local organizational plans to cope with disasters. It also serves as a source of assistance to the states in developing plans and programs for assisting individuals suffering losses as a result of major disasters (OEP, 1972, Volume 1, p. 1). State plans must be in accordance with Federal ones; plans of political subdivisions within states must be in accordance with both Federal and state emergency plans and operations.

While the Federal government can indicate appropriate state actions, it is the responsibility of the state governments to provide the additional constitutional or statutory support, organization, and procedures for the conduct of those activities. Through a contract with the Office of Emergency Preparedness, the Council of State Governments prepared the Example State Disaster Act (OEP, 1972, Volume 2), as well as Guidance for State Disaster Planning (OEP, 1972, Volume 2), illustrating features of a state disaster plan. Guidance for the Development of a County Emergency Plan, as issued by the California Community Emergency Planning Program--part of the California Office of Emergency Services--serves as an illustration (California Disaster Office, 1969).

In October of 1969, the Federal government began providing matching funds of as much as $250,000 for the development of state disaster plans. In addition, matching funds not to exceed $25,000 per year may also be provided for improving, maintaining, and updating state disaster assistance plans. However, by the end of 1971, fewer than one-third of the states were participating. Such funds are still available to the states.

In 1971, OEP issued the Outline Plan for Federal Response to a Major Earthquake, which outlines planning responsibilities of varied Federal agencies in response to a major earthquake. In the same year, OEP commissioned a damage assessment study on the assumption that community preparedness for a major earthquake in a metropolitan area requires a detailed vulnerability analysis. Focusing on the San Francisco Bay area, A Study of Earthquake Losses in the San Francisco Bay Area (National Oceanic and Atmospheric Administration, 1972) is a prototype of a planning program based on a highly detailed community-specific vulnerability analysis. The Interim Federal Earthquake Response Plan (OEP, 1973) is the current product of that study. The plan is to extend such action to other high-risk earthquake areas. Viewed as a pilot project in the eventual formulation of integrated national planning for disasters, the study is the first attempt at basing preparedness planning on specific localized vulnerability analysis (OEP, 1972, Volume 1, p. 9; OEP, 1972a, pp. 1-2).

2. Relief and Rehabilitation

a. The Expanding Scope of Involvement

Public Law 81-875, enacted in 1950, provided for the first permanent program of Federal disaster assistance to the state and local governments. This law, principally concerned with Federal assistance to state and local governments, also provided for aid to individuals, but only through cooperation with the Red Cross in the distribution of relief supplies. Public Law 107, enacted in 1951, amended Public Law 81-875 and authorized the use of emergency housing for disaster victims. Public Law 134, enacted in 1953, further amended Public Law 81-875 to allow for the donation and loan of Federal surplus commodities to state and local governments and individuals. Public Law 87-502 was enacted in 1962. It expanded the definition of a state, and made Public Law 81-875 applicable to all of the United States and its possessions. It also authorized the emergency repair and temporary replacement of damaged state government facilities; theretofore, only public facilities owned by local governments were able to receive such aid.

The expansion of Federal programs for assisting disaster victims accelerated after the Alaskan earthquake of 1964. Public Law 88-451 increased Federal contributions from 50% to 94.9% for highway construction, authorized the matching of state funds for paying mortgages, provided additional assistance for public facilities through FHA loans, and permitted the Small Business Administration to make 30-year loans on dwellings. PUblic Law 89-41, the Pacific Northwest Relief Act of 1965, authorized $70 million for the repair and reconstruction of damaged highways not eligible under Public Law 81-875.

In 1965, Public Law 89-339 was passed and for the first time a forgiveness clause was included in SBA disaster loans. A $1,800 forgiveness was provided for after the first $500 of the loan was paid. Public Law 89-769, enacted in 1966, further amended Public Law 81-875 by including rural communities, unincorporated towns, and villages as units capable of applying for Federal disaster aid through some state or local government. It was this law which established a Federal liaison with state and local governments for community preparedness.

In 1969, Public Law 91-79, The Disaster Relief Act of 1969, was enacted. An increased range of Federal involvement included disaster unemployment insurance, grants for debris removal, and food coupons to low income victims. The Disaster Relief Act of 1970, Public Law 91-606, increased the forgiveness amount in SBA loans to $2,500.

Public Law 92-385, enacted on August 16, 1972, further revised the Federal disaster loan program to forgive up to the first $5,000, and to lower the interest rate to 1% on any additional balance. This financial resource was available to disaster victims not only after a Presidential disaster declaration (as was the case prior to Public Law 92-385), but also after the SBA and the FHA made their own disaster declarations in smaller disasters not declared by the President. The forgiveness feature was repealed by the Disaster Relief Act of 1974 (Public Law 93-288); it repealed all but the loan section of the Disaster Relief Act of 1970 (Public Law 91-606), and chartered a number of new programs and features, as well as furthering many provisions of the old law.

The Federal government now assumes many of the costs previously incurred by the Red Cross. When a Presidential declaration of disaster is made, the Federal government may pay the costs of bulk cleaning supplies distributed by the Red Cross, assume the cost of rentals for temporary housing when its housing program is established, and may pay for the cost of household accessories given by the Red Cross (Popkin, 1972).

b. The Present Involvement

Federal resources are made available to disaster-stricken areas through the provision of services, supplies, equipment, and manpower, and by the allocation of congressionally authorized funds for relief, rehabilitation and reconstruction purposes. Four definitions of disaster exist which define the mode of Federal involvement: major disasters declared by the President; emergencies declared by the President; disasters declared by either the Small Business Administration (SBA) or the Farmer's Home Administration (FHA); and disasters in which no formal declaration is made.

The President, at the request of the governor of an affected state, can declare a major disaster if damage is of sufficient severity and magnitude to exceed state resources and capabilities for effective response. Until recently, Public Law 91-606, as amended, provided the range of benefits available to state and local governments, individuals, non-profit enterprises, and businesses. Some of the primary benefits included home loans, temporary housing, the restoration of public facilities, community disaster grants, debris removal, unemployment compensation, coordination of relief organizations, and emergency relief support teams.

Recently, Public Law 92-288 added certain new benefits and modified others, for example, 100% grants for repairing or reconstructing disaster-damaged public educational, park, and recreational facilities. Other noteworthy changes included a 25% community loan program, the establishment of a Recovery Planning Council for affected areas, and an individual and family grant program for disaster-related needs and expenses.

The benefits provided by the Federal government in cases of a Presidential declaration of a major disaster are subject to the following major considerations: (1) Federal assistance can be applied in a manner to suit the level of destruction incurred, which is subject to concurrence with the governor, and in amounts necessary to supplement individual, state and local resources, including equipment and personnel as well as monetary aid; and (2) Federal assistance to individuals, non-profit organizations, and businesses is conveyed directly, as in the case of loans and temporary housing, and indirectly through state and local agencies, as with grants to individuals, unemployment payments, and food stamps.

The President can declare an emergency, rather than a major disaster, when the governor of a state certifies that danger from, or damage caused by, a natural hazard requires Federal emergency assistance to supplement state and local efforts to save lives, protect property, public health and safety, or in order to avert or lessen the threat of a disaster. Although extensive Federal help is available when such an emergency is declared, benefits provided for individual and governmental losses are not as inclusive or sizable as those in a major disaster.

The Federal government may also become involved in disasters in which neither a Presidential declaration of a major disaster or an emergency is made, because of statutes which authorize the heads of the Small Business Administration or the Farmer's Home Administration--on their own prerogative--to make loans to individuals and small businesses, and to provide other aid to agriculture in stricken areas.

In cases in which no disaster declaration of any sort is made, other Federal programs (such as urban renewal) may still involve the Federal government in relief and rehabilitation. These programs can be a significant part of local long-range rehabilitation efforts. However, they are not brought into action by existing disaster legislation; they continue to function in their normal pre-disaster capacities. For example, heavily damaged areas of a city can be incorporated in a new or enlarged urban renewal program. Estimates of the portion of Federal expenditures for these programs which are directed at post-disaster activities are not available.

Approximately 30 volunteer agencies and groups, such as the American National Red Cross--which is Congressionally chartered as a disaster relief agency--and the Salvation Army, have played a very significant role in both declared and undeclared disasters, and continue to do so. The increasing involvement of the Federal government in major disasters (with food stamps, for example) has relieved some of the financial burden formerly borne by these organizations and further commits Federal expenditures to disaster relief.

In the 1961-1970 period, 2% of all major disaster declarations were for earthquakes and their associated hazard, tsunamis. These declarations for the 1964 Alaskan earthquake and tsunami, and for the 1965 Puget Sound, Washington earthquake represented a total of 8% ($60.85 million) of all allocations for the period from the President's disaster fund (OEP, 1972, Volume 1, p. 176). The annual average amount loaned by the SBA for earthquakes for the period 1960 through 1972 was $25.26 million.

c. Implications for the Future

Table I-3 presents the distribution of SBA home loan size for selected disasters. It can be seen that the introduction of forgiveness clauses in SBA home loans caused disaster loans to cluster around an amount approximating the amount of forgiveness. Prior to the introduction of forgiveness clauses, obvious modal frequencies are absent in the

TABLE I-3

DISTRIBUTION OF SBA HOME LOAN SIZE

FOR SELECTED DISASTERS

| LOAN SIZE | ALASKAN[1] EARTHQUAKE 1964 | NORTHWEST[1] FLOODS 1965 | PALM SUNDAY[1] TORNADOES 1965 | HURRICANE[2] BETSY 1965 | SAN FERNANDO[3] EARTHQUAKE 1971 | HURRICANE[4] AGNES 1972 |
|---|---|---|---|---|---|---|
| 0- $500 | .5% | .7% | 2.0% | 1.4% | 1.9% | 1.7% |
| $501- $1,000 | 5.1 | 8.7 | 9.5 | 5.3 | 5.9 | 3.4 |
| $1,001- $2,500 | 7.7 | 17.9 | 19.3 | 63.3[5] | 27.5 | 17.0 |
| $2,501- $5,000 | 14.5 | 25.1 | 20.0 | 14.6 | 62.1[6] | 52.3[5] |
| $5,001- $10,000 | 16.3 | 24.9 | 20.7 | 11.6 | 1.9 | 17.0 |
| $10,001- $25,000 | 22.0 | 20.8 | 24.7 | 3.4 | .5 | 6.6 |
| $25,001- $50,000 | 25.7 | 1.9 | 2.0 | .1 | .1 | 1.9 |
| $50,001- $100,000 | 7.2 | --- | 1.4 | --- | --- | .1 |
| $100,001- $150,000 | .7 | --- | --- | --- | --- | --- |
| $150,001- $250,000 | .2 | --- | .3 | --- | --- | --- |
| $250,001+ | .1 | --- | --- | --- | --- | --- |
| TOTAL % | 100% | 100% | 99.9% | 99.7% | 99.9% | 100% |
| TOTAL N | 809 | 414 | 295 | 26,192 | 67,860 | 75,339 |

(Dacy and Kunreuther, 1969, p. 190; the Small Business Administration, 1972 and 1972a)

[1] No forgiveness clause

[2] $1,800.00 forgiveness clause

[3] $2,500.00 forgiveness clause; $3,000.00 needed to be borrowed to obtain the full forgiveness amount

[4] $5,000.00 forgiveness clause

[5] Modal category equal to the category including the forgiveness maximum

[6] Modal category equal to the category of the forgiveness maximum plus that much again, loans sized $2,501.00 to $3,000.00 accounted for 24.8% of the total while those sized $3,001.00 to $5,000.00 accounted for 37.3%.

data. Aside from the ever-increasing commitment of the Federal government in relief and rehabilitation, it appears that the nation may expect disaster victims to borrow the maximum amount of forgiveness (or an amount equal to twice that of the forgiveness maximum as was the case with the 1971 San Fernando Earthquake) with a greater frequency than loans of any other size. Further discussion of the effect of forgiveness clauses may be found in a recent monograph by Kunreuther (1973a, pp. 19-21). Current law (Public Law 93-24) does *not* provide forgiveness; the interest rate is 5% (Kunreuther, 1973a, p. 13).

## CHAPTER II

## SIMULATION OF EARTHQUAKE LOSS MANAGEMENT

### Simulation Models

The importance of being able to assess the likelihood of earthquake loss, the magnitude of loss that may be incurred, and the means of adjustment to that loss can scarcely be overestimated.

The purposes of this chapter are two-fold. One is to discuss the simulation of earthquake loss management from a very general point of view (static versus dynamic modeling, samples, adjustments, reference systems). The other is to present the computed results of the simulation of a large selected sample of earthquakes (44) acting on a large, diverse community (approximately the lower half of the State of California, greater Los Angeles region, as of about 1970). There is some overlap in the presentations related to the separate purposes.

In the computed simulation the community as a whole is static in time (no changes in total population, building inventory or adjustments). The earthquake sample is composed of events which are historical in earthquake magnitude and epicentral location, but the sample is biased in that emphasis was placed on earthquakes of damaging magnitudes having epicentral locations potentially damaging to the most densely developed part of the community (Algermissen, *et al.*, 1973). The earthquake sample varies widely, however, in magnitude (approximately 5.0 to 7.8 Richter) and in epicentral location (approximately 15 to 250 miles from Los Angeles center). The part of the community subject to loss varies widely in location, area, local intensity, and local population and building inventory.

Our interest in the simulation results has been chiefly in *relative values* rather than absolute values of loss. As a matter of fact, the absolute values of loss seem low, even taking into account the fact that the computed dollar losses are for damage to privately owned buildings alone.

Only the loss results are presented. The losses have been projected, by methods based on several different assumptions, to assumed maximum earthquakes. No account, however, has been taken of possible secondary effects such as fire, flash flood or landslide, or of timing of the impact on the community. A theoretically "worst case" thus has not been estimated. While such a case may well be possible, the probability of its occurrence seems low.

For information regarding the details of the modeling, assumptions, and loss functions the reader is referred to Friedman (1975). The details of the computation may be obtained on request from the Institute of Behavioral Science, University of Colorado.

Adjustments may be arranged in groups: (1) modifying the natural event system by reducing the magnitudes of earthquakes originating along a particular fault, if that should prove some day to be reliable; (2) modifying the human-use system through programs of strengthening or removal of hazardous buildings, improving the earthquake resistance of new buildings by the upgrading of building codes and ordinances, avoiding hazardous developments in dangerous land areas through land use management and zoning, and earthquake forecasting and warning if those processes should become reliable in the future; and (3) modifying the loss distribution system through programs of insurance, and relief and rehabilitation.

Social and economic pressures may exist or develop for or against certain types of adjustments. Some of these pressures may be quantifiable, while others may be treated only in a qualitative manner. To our knowledge they have not been included in the simulation of adjustments for natural hazards. Some of the factors which need consideration follow: (1) the social, economic and political forces* involved in the adoption or change of building ordinances and zoning which are restrictive as to the earthquake hazard; (2) if forecasting of earthquakes were to prove feasible, what social and psychological factors are pertinent to effective human action in the warning, and what might result from a false alarm in timing; (3) if the control (reduction) of magnitude of earthquakes in certain source regions were to become feasible, what the

*The directions of these forces, their magnitudes in terms of negligible, weak, strong, or some arbitrary scale, and their functional relationships if they can be estimated.

long-range results might be on the effectiveness of building ordinances and land use zoning, and what the effects of human error might be in the control process; (4) what social and economic forces are involved in establishing an effective insurance program for protection against natural events as rare as earthquakes; (5) what the effect on the adoption of other adjustments is of the traditional reliance on federally funded relief and rehabilitation; (6) what the interactions are among the various types of adjustments and the human community; and (7) what the long-range effects of education and experience with respect to the earthquake hazard are on the community.

These questions imply the existence of a complex network of linkages, both direct and indirect, among the various units of the community, the adjustment system and the natural event system. They also imply that the entire system is a dynamic one and that a simulation of it, except for certain limited questions which may be explored with a static model, should include consideration of dynamic modeling, with feedback loops accounted for in the linkages.

## General Modeling Diagram

A diagram showing in a general way the linkages among the human community, the adjustments, and the natural event system is presented in Figure II-1. This diagram is too general to be of direct application in modeling, but it has two values. One is to depict the overall system and the major types of linkages for any natural disaster-prone community. The other is to provide a basic network from which may be extracted subsystems for detailed study, either as static or dynamic models.

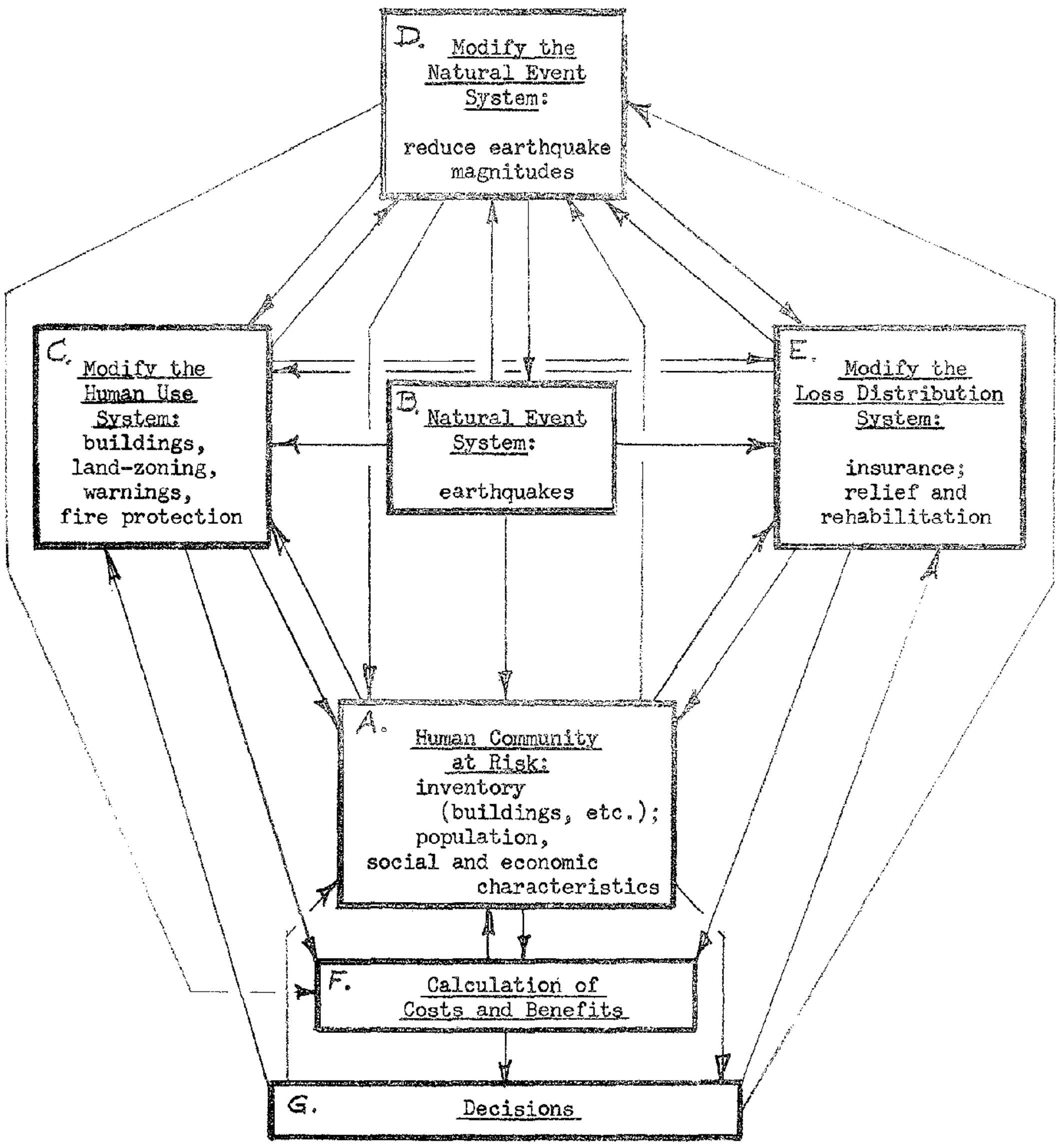
### 1. Static Models

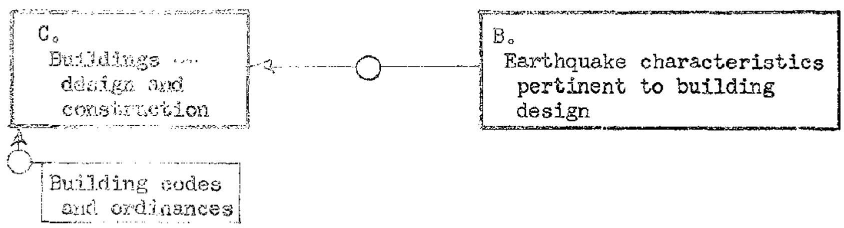
An example of a static simulation might be a technical investigation of the upgrading of building design through a change in codes and ordinances. This would involve pertinent parts of blocks B and C (see Figure II-2a), and linkage of these blocks and sub-blocks through functional relationships symbolized by the circles. A more expanded study including estimation of change in costs of design and construction imposed by a change in building resistance, and change in benefits in terms of dollar damage to buildings and loss of life would involve parts of A, B, C, and F (see Figure II-2b).

Both of these studies, as diagrammed, are essentially static because feedback relationships have not been included. They are useful,

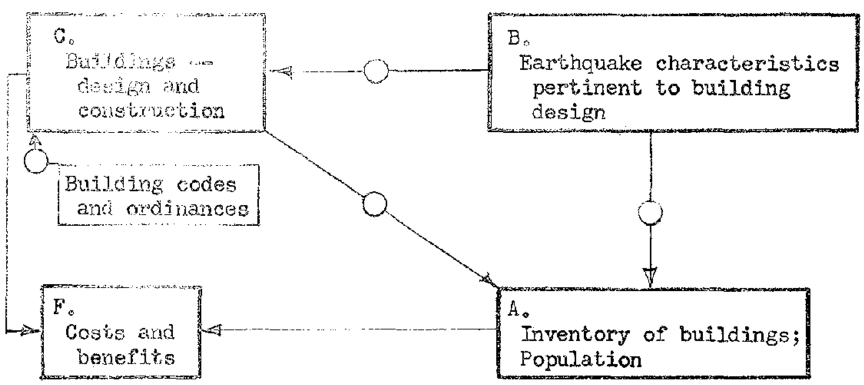
FIGURE II-1

GENERAL DIAGRAM FOR SIMULATION MODELING






(a)




(b)

FIGURE II-2

TENTATIVE DIAGRAMS FOR STATIC SIMULATION MODELS

Note: Circles indicate the existence of functional relationships.

however, in the quantitative evaluation of certain actions when those actions and their directly linked results may be separated from the time stream and the system as a whole and viewed as though with a snapshot camera.

2. Dynamic Models; Feedback

Assume that we want to investigate the continuous and possibly varying interaction of the building-resistance adjustment with the community. The possibility of feedback has now been included; the model is dynamic and we start to view it as though with a motion picture camera. The functional relationships may change with time and load due to long-range social and technological processes. The diagram becomes somewhat more complicated, as shown in Figure II-3a.

When we are concerned with the interaction of two or more different types of adjustments, dynamic effects will become even more important. A network for simultaneous operation of adjustments in building resistance and earthquake insurance has been shown in Figure II-3b.

The networks presented are complete enough to include some of the major linkages among the community-at-risk, the natural event system, and the adjustment systems, but they do not show the relationships necessary within the natural event system to define the sequence of earthquakes (timing, locations, magnitudes), nor do they present the relationships which influence changes in population, building inventory, and economic condition in the community-at-risk. The most significant of these relationships must be included if a reasonably accurate dynamic simulation is to be achieved.

## Design of the Model

We now consider some of the more detailed matters relating to the design of simulation models for the earthquake hazard.

1. Selection of the Study Area

The selection of the study area depends on the purpose of the study, the characteristics of the natural hazard, and the population-at-risk. For the United States, the area types might include (for macro-studies):

(1) the entire land area, including associated islands;
(2) the conterminous United States;
(3) an entire seismic risk zone, say zone 3 (see Figure I-1); and

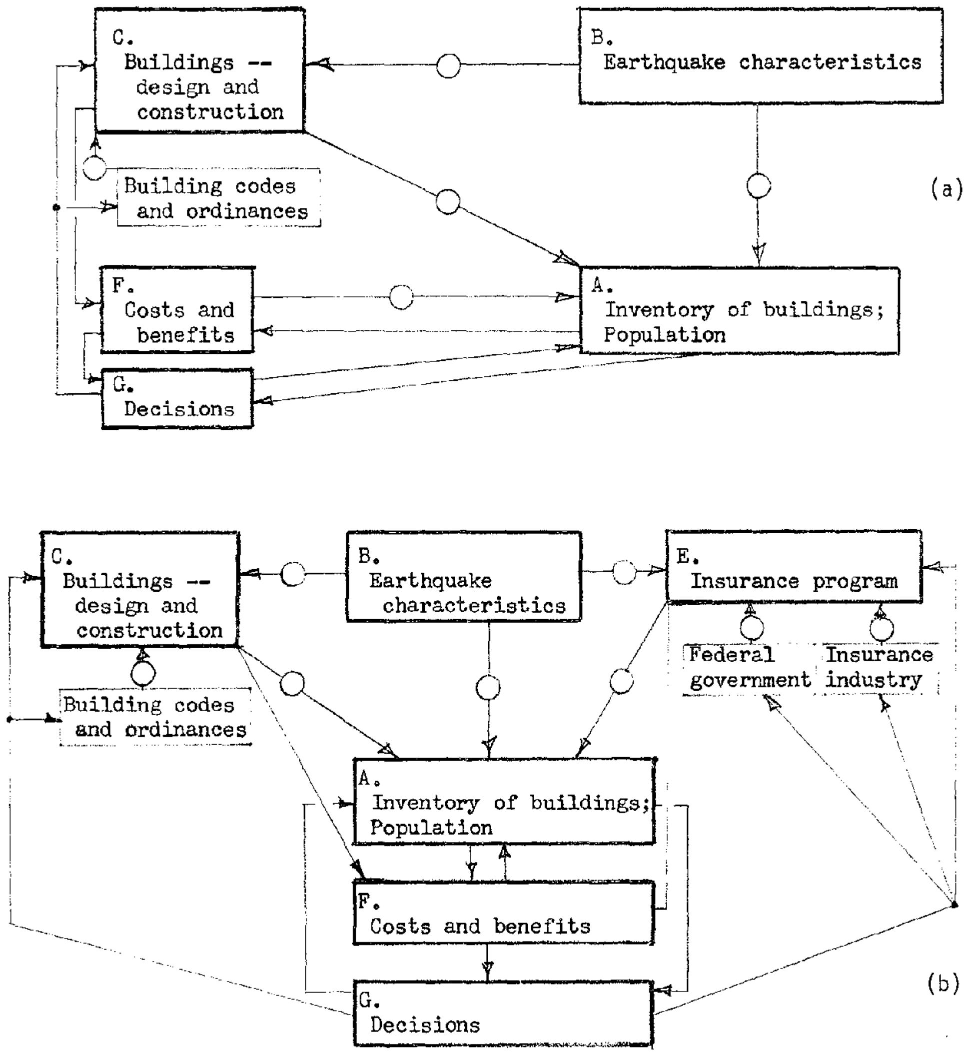



FIGURE II-3

TENTATIVE DIAGRAMS FOR DYNAMIC SIMULATION MODELS

Note: Circles indicate the existence of functional relationships.
Note the presence of feedback loops.

(4) the parts of zone 3 west of the Rocky Mountains in the conterminous United States.

For micro-studies, the types include:

(5) limited regions of possibly high vulnerability, for example, the State of California, the San Francisco Bay Area counties, the greater Los Angeles area, the Puget Sound area, the area along the Ohio and Mississippi Rivers from southern Illinois to Memphis, the southern coastal cities of Alaska, the island of Hawaii, or an aggregate of such regions; and
(6) particular locations of great vulnerability, for example, San Francisco, Los Angeles, Seattle, Boston, or an aggregate of such locations.

Macro-simulations for area types (1) to (3) might be of use in a study of costs and benefits for the country as a whole, but they involve extreme diversity in the natural event system, as well as in the community-at-risk. Type (4) is more homogeneous in the natural event system but it involves great diversity in the community.

Types (5) and (6) are intended for micro-simulations. Each example is relatively homogeneous in its earthquake natural event system, but there are great differences in severity and frequency of occurrence between examples; they all include concentrations of population and development, although they differ considerably in size.

After considering the difficulties inherent in the simulation and interpretation of such non-homogeneous types as (1) to (4), we chose as an example a simulation of a type (5) location, namely, the State of California, with emphasis on the Los Angeles region. The limits of the study area are the boundaries of the State but the earthquake sample is composed of earthquakes most likely to affect the Los Angeles region.

2. Natural Event System; Data Base

a. Types of Earthquake Samples

The most unbiased sample would probably result from a random statistical selection of a sequence of earthquakes, based on the known earthquake history pertinent to the Los Angeles region. This would involve variations in magnitude, time of occurrence, location of epicenter and depth of focus, and would not be simply a reordering in time of occurrence.

Four other approaches, involving the arbitrary selection of the earthquake sample, are: (1) repeat the sequence of earthquakes known to the Los Angeles region; (2) repeat any earthquake of particular interest known to have occurred in the Los Angeles region, for example, the San Fernando earthquake of 1971; (3) repeat the earthquake known to have resulted in the greatest intensities in the Los Angeles study area; and (4) apply the earthquake having greatest expected intensities based on a study of known earthquakes in areas geologically similar to the Los Angeles region.

A sample of type (1) has been chosen. It consists of 42 earthquakes having Richter magnitudes estimated at 5.0 or greater, known to have occurred in the period 1769 through 1971. Two additional earthquakes having magnitude 4.8 with epicenters close to central Los Angeles have also been included.

b. Location of Isoseismal Lines

For the purpose of estimating building damage and resulting casualties it is necessary to have, for each earthquake in the sample, a map showing the isoseismal lines (boundaries between areas having assigned ranges of intensity), or information from which such lines can be drawn. Such maps may be based on human observation of effects at specific locations, for example, varying degrees of building damage,* or the maps may be based on calculations carried out by approximate theoretical procedures from information regarding the characteristics of the earthquakes (magnitude, depth of focus, and location of epicenter), and the local ground conditions. An example of an isoseismal map based on local observation and records is shown in Figure II-4.

c. Simulations

The simulations have made use of a static-model (essentially that shown in Figure II-2b), including an attempt to repeat the sequence of damaging earthquakes known to the Los Angeles region applied to current data (approximately 1970) on population and building inventory-at-risk.

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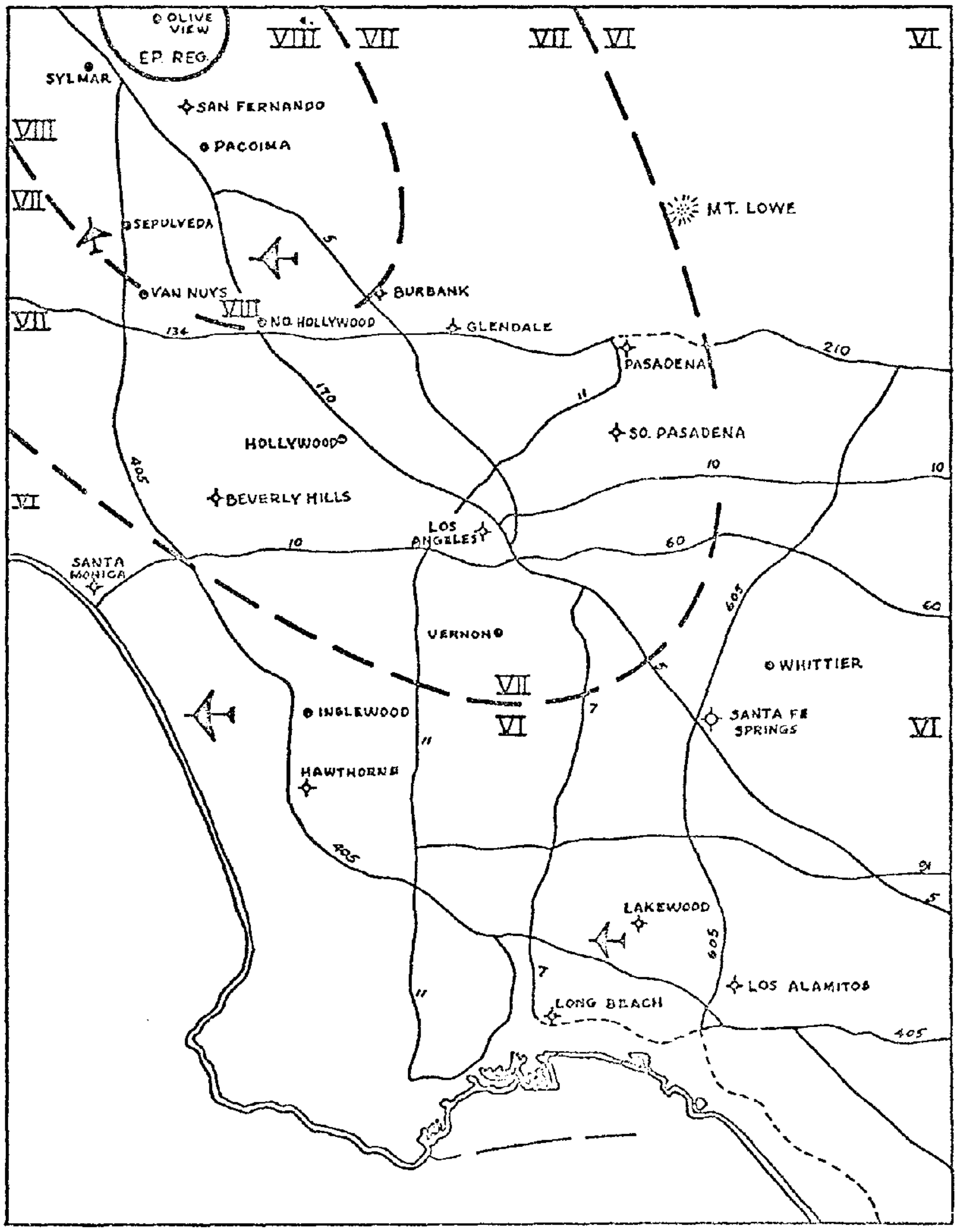
*The method leads to results which may be highly subjective and therefore unreliable as a basis for the prediction of structural damage. It has been used for many years, however, and much historical information is based on it. More refined methods are under development by engineers and seismologists.

FIGURE II-4

LOCAL ISOSEISMAL MAP, SAN FERNANDO EARTHQUAKE, 1971, SHOWING REGIONS OF MODIFIED-MERCALLI INTENSITY




(Whitman, *et al.*, 1973)

3. Community-at-Risk, Data Base, and Loss Functions

Loss functions of earthquake intensity are rare and incomplete. They tend to be S-shaped.

Since casualties in an earthquake follow largely as a result of building damage, it may be assumed that functions of death ratio and injury ratio versus earthquake intensity should be similar in general form to the intensity-damage functions appropriate to the classes of structures in which the casualties occur. It is difficult, however, to establish appropriate scales for death and injury, and large errors in estimation are to be expected. It may be better to relate death and injury directly to building damage rather than indirectly through earthquake intensity.

A detailed discussion of the community-at-risk, data base, loss functions and the assumptions used in the model may be found in the separate report on simulation prepared by Friedman (1975).

4. Data Reference Grid and Unit Cell Size

a. Reference System

For general purposes the standard latitude-longitude system provides the best reference.

b. Cell Size

The question of cell size is less easy to settle, especially because the needs of the data bases for the human community and for the natural event system may be quite different. For our purposes, a 1/10-degree cell size has been chosen. This is equivalent, at the latitude of Los Angeles, to an approximately rectangular area with a north-south length of about seven miles and an east-west width of about six miles.

Results of the California (Los Angeles region) Simulation

The following analysis is based on computer output data supplied to us by Donald G. Friedman of the Travelers Insurance Company. He and his assistants designed the simulation model, programmed the calculations, and carried them out by computer (Friedman, 1975).

The quakes have been assumed to act, one at a time, on a California which remains static in population and building inventories as of about 1970. Public buildings, heavy industry, and transportation and utility systems have *not* been included in the inventory.

1. Earthquake Sample

Since the earthquake sample has been chosen particularly with the potential in mind for damage in the Los Angeles region, the sample is not adequate for places at a considerable distance from Los Angeles. However, the boundaries for the computation are the boundaries of the State of California so that the population and buildings exposed are often drawn from an area much larger than the vicinity of Los Angeles. The sample consists of the 42 earthquakes, apparently having magnitudes of Richter 5.0 or greater, which are listed in the National Oceanic and Atmospheric Administration report, A Study of Earthquake Losses in the Los Angeles, California Area (Algermissen, *et al.*, 1973, Table 1, pp. 5-11). Two additional earthquakes having magnitudes of Richter 4.8, and also listed in the NOAA report, have been included because of the proximity of their epicenters to central Los Angeles. The sample apparently is incomplete even for the fairly recent period of time represented.

a. Characteristics of the Earthquakes

Two values of maximum intensity* are given for each earthquake. One is a theoretical maximum at the epicenter (calculated on a continuous scale). The other is a calculated maximum intensity to which persons and buildings may be exposed. This second value depends not only on the earthquake and ground conditions, but also on the location of the epicenter relative to the geographic boundaries of the calculation.

b. The "Felt Areas"

Exposure to potential damage has been defined as exposure to an intensity of Modified Mercalli scale of 5.0 or greater.

c. Time Distribution

The time distribution of the sample has been shown in Figure II-5. In the early years the sample is sparse, as one would expect, presumably not due to any lack of seismic activity but rather due to a sparseness of population and of concerned observers. Of the 42 earthquakes having Richter magnitude 5.0 or greater, 37 occurred in the 100-year period starting in 1872. We will call these the "100-year sample."

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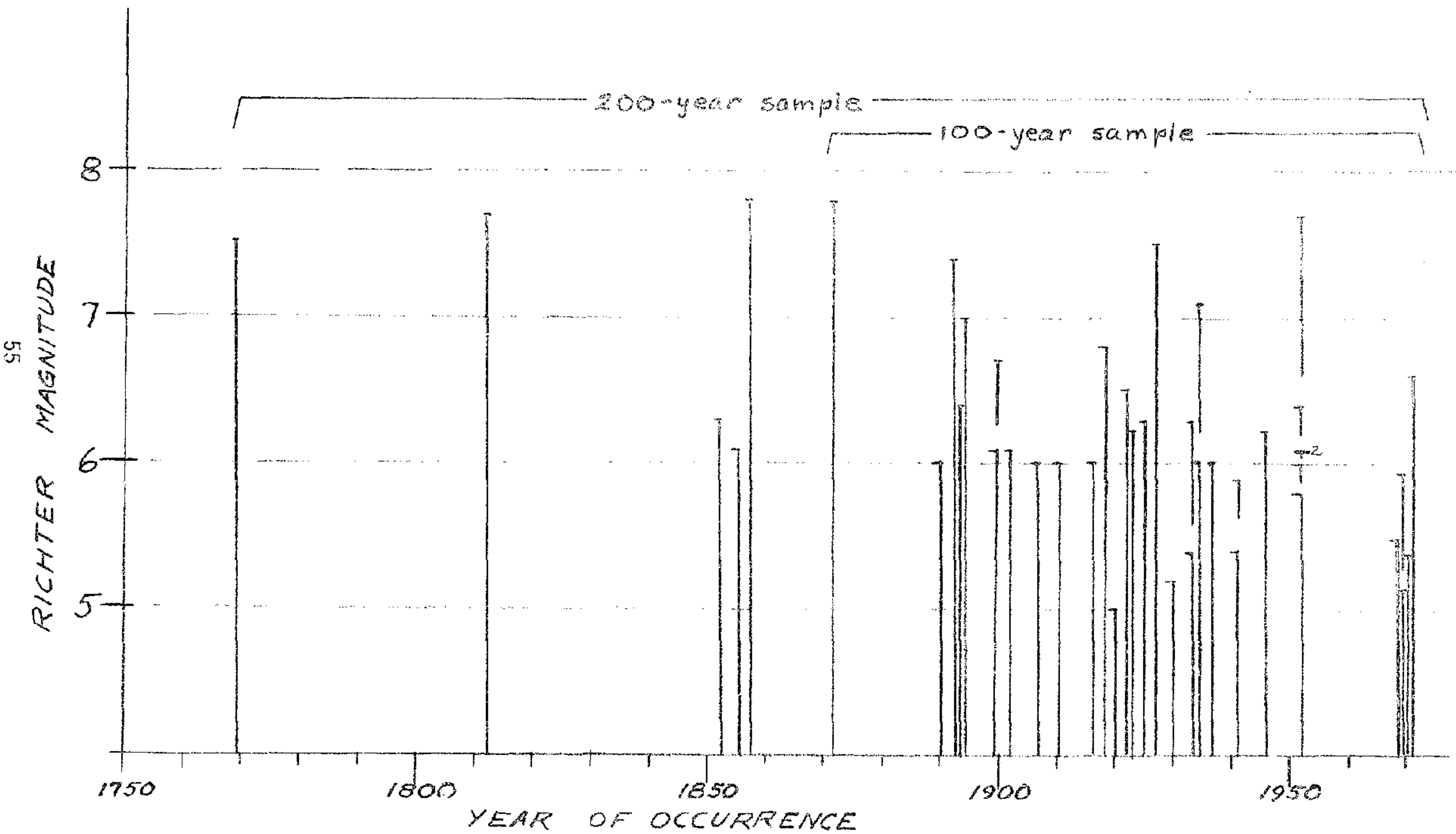
*Intensities have been expressed in the Modified Mercalli Intensity (MMI) scale, but for reasons of convenience Arabic numerals have been used instead of the customary Roman numerals.




TIME DISTRIBUTION OF 42 EARTHQUAKES OF MAGNITUDE 5 OR GREATER

FIGURE II-5

Their time distribution seems to be reasonable. In the period of a little over 100 years prior to 1872, however, there are only five earthquakes in the sample and of these five, three are very large. We will call the total sample of 42 earthquakes the "200-year sample." The difference between the two samples is perhaps made more clear by Figure II-6 which is a frequency diagram for calculated (simulated) total damage to buildings per earthquake.

Magnitudes below 6 are under represented in the sample. This lack should not affect significantly the extrapolations to maximum losses, but it would affect calculated values of averages based on number of earthquakes in the sample. Magnitudes below 5 were omitted in all cases (except two) because of very low potential for damage.

d. The Distance Parameter

For a single measure of distance which is appropriate to earthquake disaster we have used the distance between the earthquake epicenter and the approximate location of the centroid of population and development of the community. Figure II-7 shows the locations of the epicenters, some of the cities and some of the known faults. A crude calculation, based on the major metropolitan populations of the region, places the centroid of population a few miles southeast of Los Angeles center.

e. Isoseismal Patterns

Another basis for grouping the earthquakes within the sample would relate to the faults and to geologic structure, but since we are not geologists we hesitate to venture in that direction. The isoseismal patterns *calculated from the model* are available, however, and a comparison of them shows the existence of groups of somewhat similar patterns. The accuracy of the patterns depends on the accuracy of the model--but they appear to be reasonable. Figure II-8 shows the calculated boundaries of one of six groups of earthquakes for which the boundaries are somewhat similar in shape. (A map for each group is available).

Isoseismal patterns for three earthquakes--Long Beach (1933a), Kern County main shock (1952a) and San Fernando (1971)--were computed, and the one for 1933 is shown in Figure II-9. The pattern is traced from computer printouts. The calculated patterns have been compared with published patterns based on observation and there seems to be at least qualitative agreement. It is conceivable that the calculated

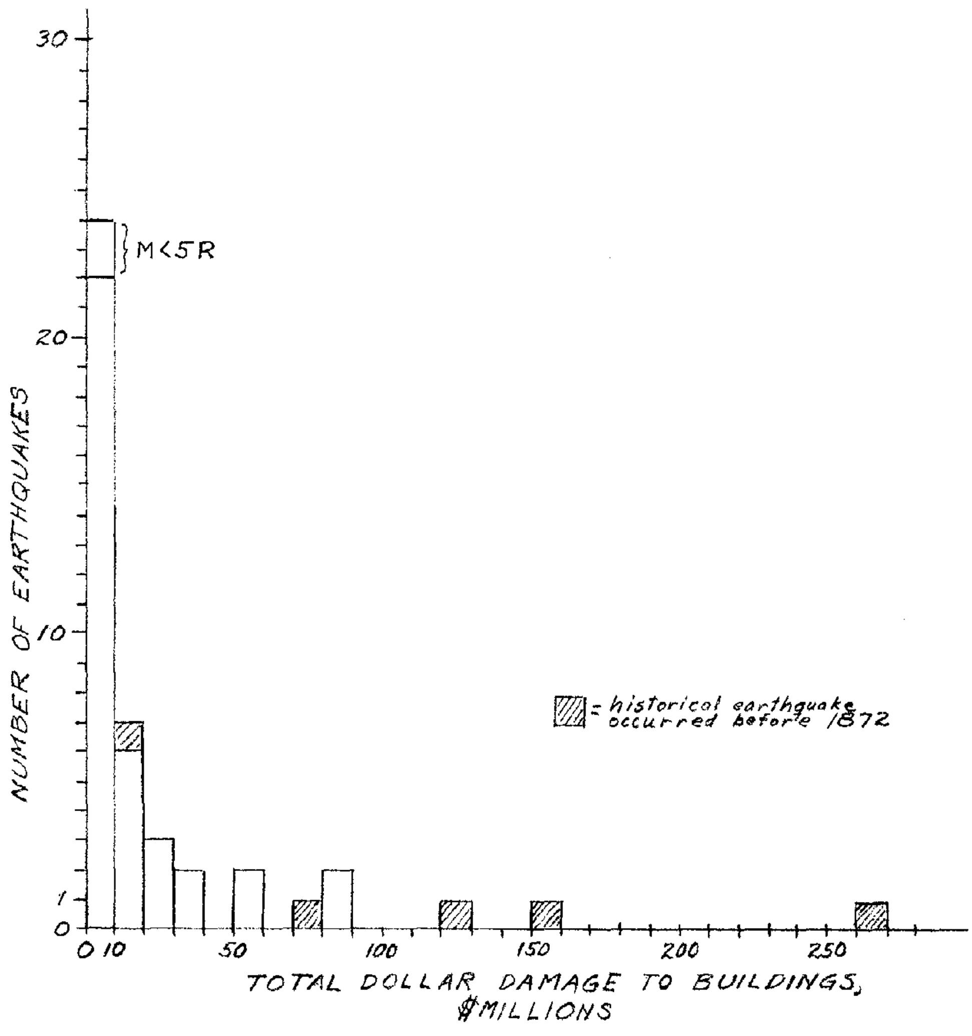
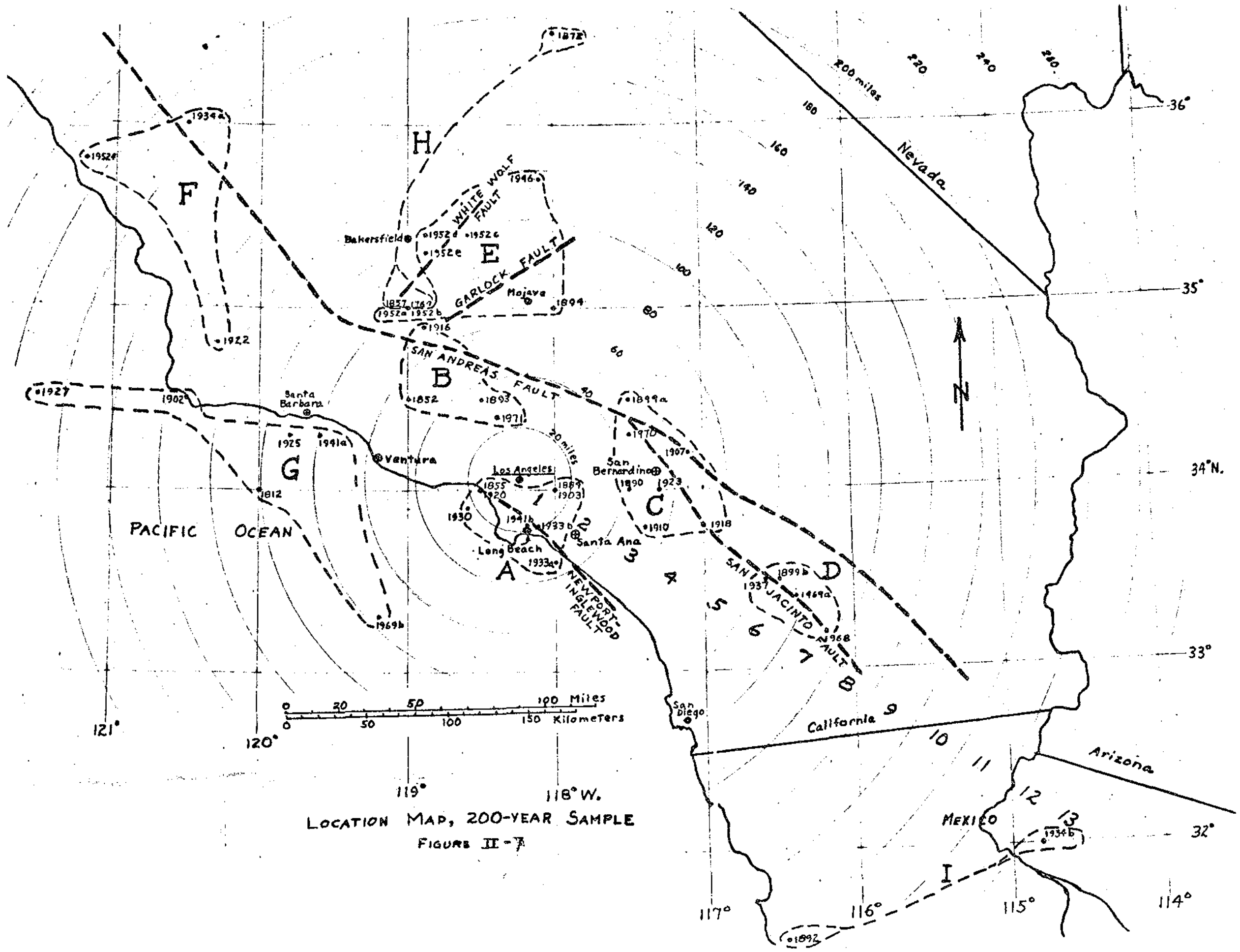
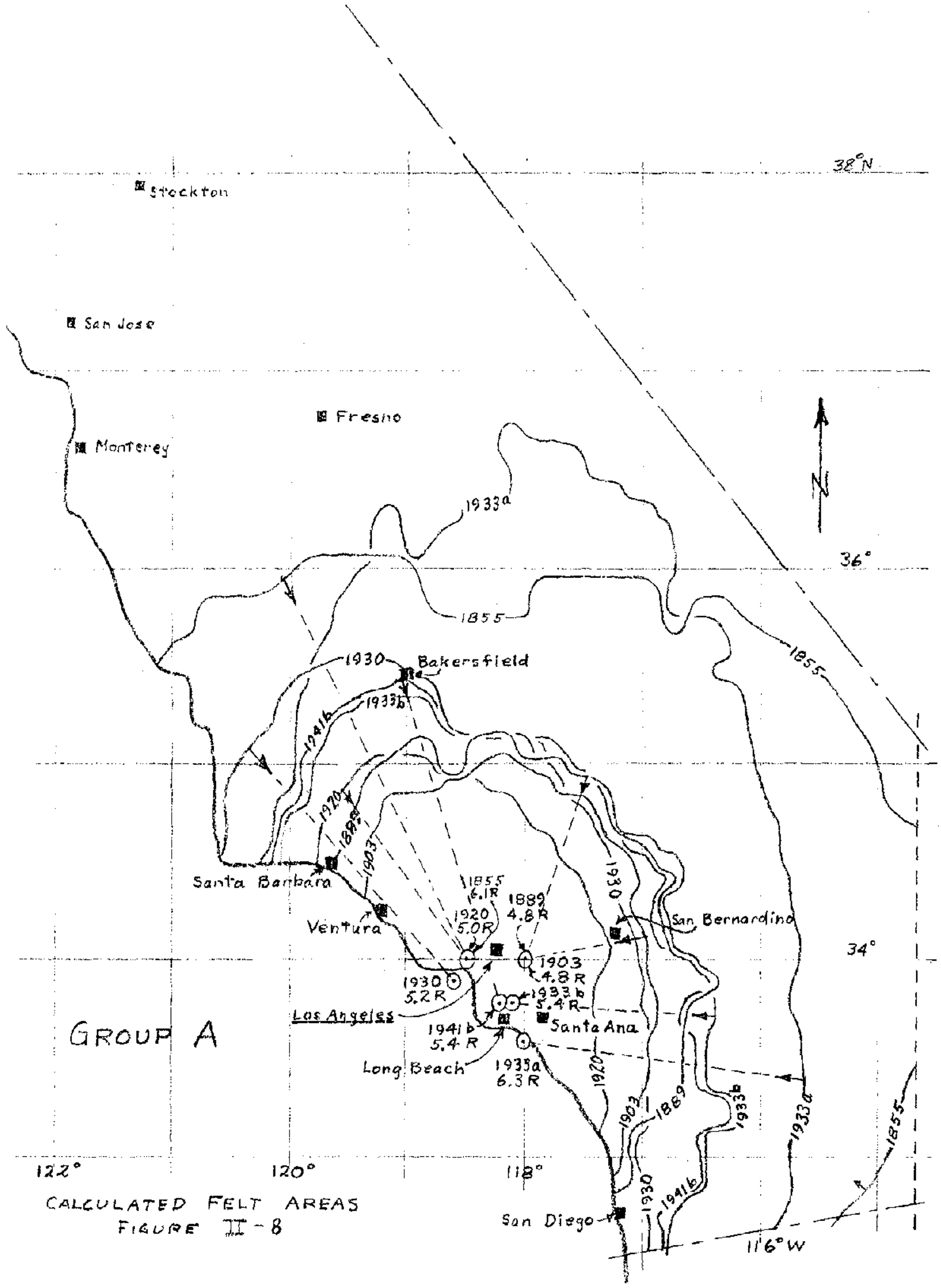



FIGURE II - 6 NUMBER OF EARTHQUAKES VERSUS TOTAL DOLLAR DAMAGE TO BUILDINGS

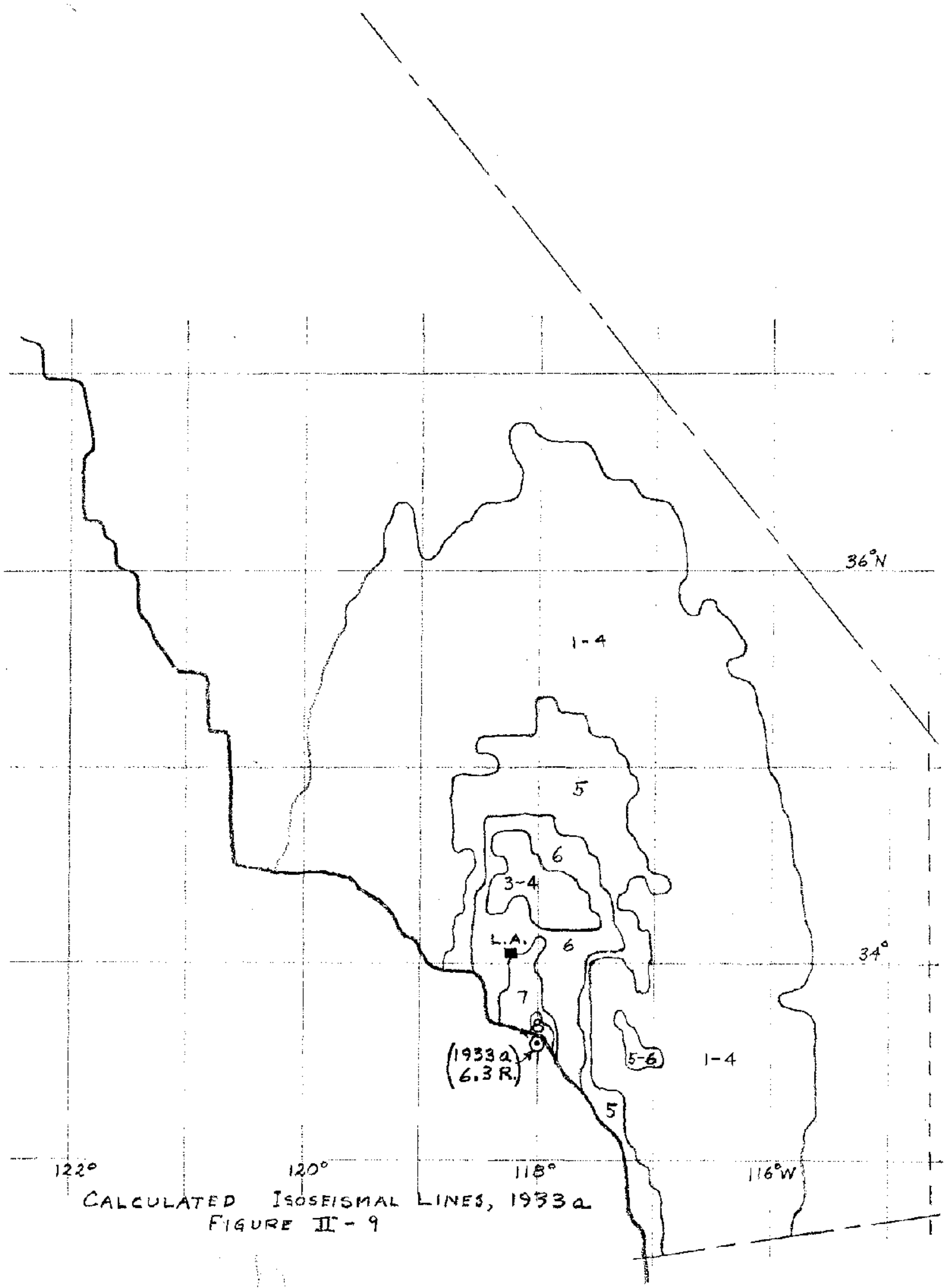



Location Map, 200-Year Sample

Figure II-7




CALCULATED FELT AREAS
FIGURE II - 8




CALCULATED ISOSEISMAL LINES, 1933a
FIGURE II - 9

patterns are more precise representations of the response of the model than the observed patterns are of the response of the prototype. We don't know how well the model represents the prototype. The results, however, seem to be reasonable.

2. Exposure, Damage and Casualties--Calculated Results

32 sheets of graphs were prepared, including a page of graphical projections. Table II-1, which is an index to the graphs, indicates the sorts of information presented. The reader may then skip to the brief summary in Table II-2. If he prefers greater detail he may examine the summaries of upper bounds and projects shown in the working figures which may be obtained on request. An examination of the other figures will indicate the general relationships between exposure, damage, distance and earthquake magnitude and the basis for the upper bounds and projections.

The graphs in the figures carrying starred numbers (see Table II-1) have been plotted directly from the raw computer printout data. The graphs in the other figures are the result of calculation or graphical construction based on the raw data. All graphs have been plotted on a semi-log coordinate system with the exception of those for percent of buildings damaged which were best served by a linear-linear system. While the graphs of response (exposure, damage or casualty numbers, or damage dollars) versus earthquake Richter magnitude have been shown on semi-log coordinate systems, it should be recalled that Richter magnitude is proportional to the log of the energy released by the earthquake, and consequently if the same graphs are thought of as response to the earthquake (exposure, damage, casualties, etc.) versus *energy* released by the earthquake, they are in effect on log-log coordinate systems. It is not surprising that the resulting relationships are often well-approximated by straight lines.

a. Effect of Distance

Plots of exposure, damage or casualties against earthquake magnitude show a general trend from low to high as the magnitude increases, but there is a very wide scattering of points as one would expect from a consideration of the several variables involved. If the points are grouped according to distance from the epicenter, however, then much of the scattering becomes explainable on the basis of distance. In Figure II-10, for instance, the total damage in dollars to single-

TABLE II-1

INDEX TO GRAPHS OF CALCULATED RESULTS AND PROJECTIONS

| Figure Number | Subject |
|---|---|
| | California model; earthquakes affecting Los Angeles region |
| II-21* | Land area exposed to intensity 1 or greater (felt area); number of 1/10° cells |
| | Buildings exposed to intensity 5 or greater; number |
| -22* | Single-unit dwellings |
| -23* | Apartment buildings |
| -24* | Commercial and industrial buildings |
| -25 | Total buildings |
| -26 | Summary of upper bounds (includes persons exposed) |
| | Buildings damaged; number |
| -27* | Single-unit dwellings |
| -28* | Apartment buildings |
| -29* | Commercial and industrial buildings |
| -30 | Total buildings |
| -31 | Summary of upper bounds (includes casualties) |
| | Buildings damaged; percent of number exposed |
| -32 | Single-unit dwellings |
| -33 | Apartment buildings |
| -34 | Commercial and industrial buildings |
| -35 | Total buildings |
| -36 | Summary of upper bounds |
| | Buildings damaged; loss in dollars (approx. 1970) |
| -37* | Single-unit dwellings |
| -38* | Apartment buildings |
| -39* | Commercial and industrial buildings |
| -40 | Total buildings |
| -41 | Summary of upper bounds |
| | Buildings damaged; average dollar damage per building per earthquake |
| -42 | Single-unit dwellings |
| -43 | Apartment buildings |
| -44 | Commercial and industrial buildings |
| -45 | Summary of upper bounds |
| | Population |
| -46* | Total persons exposed to intensity 5 or greater; number |
| -47* | Casualties (not including deaths); number |
| -48 | Percent casualties versus percent buildings damaged |
| | Distance effect |
| -49 | Distance versus Richter magnitude; 200-year sample |
| -50 | Total building damage, dollars, versus distance |
| -51 | Projection of damage to zero distance |
| -52 | Summary of projections--Total building damage, dollars |

The ordinates (number, dollar damage, percent) are indicated above. The abscissae are in *Richter magnitude* unless otherwise indicated.

*Graphs plotted directly from the computer printout data.

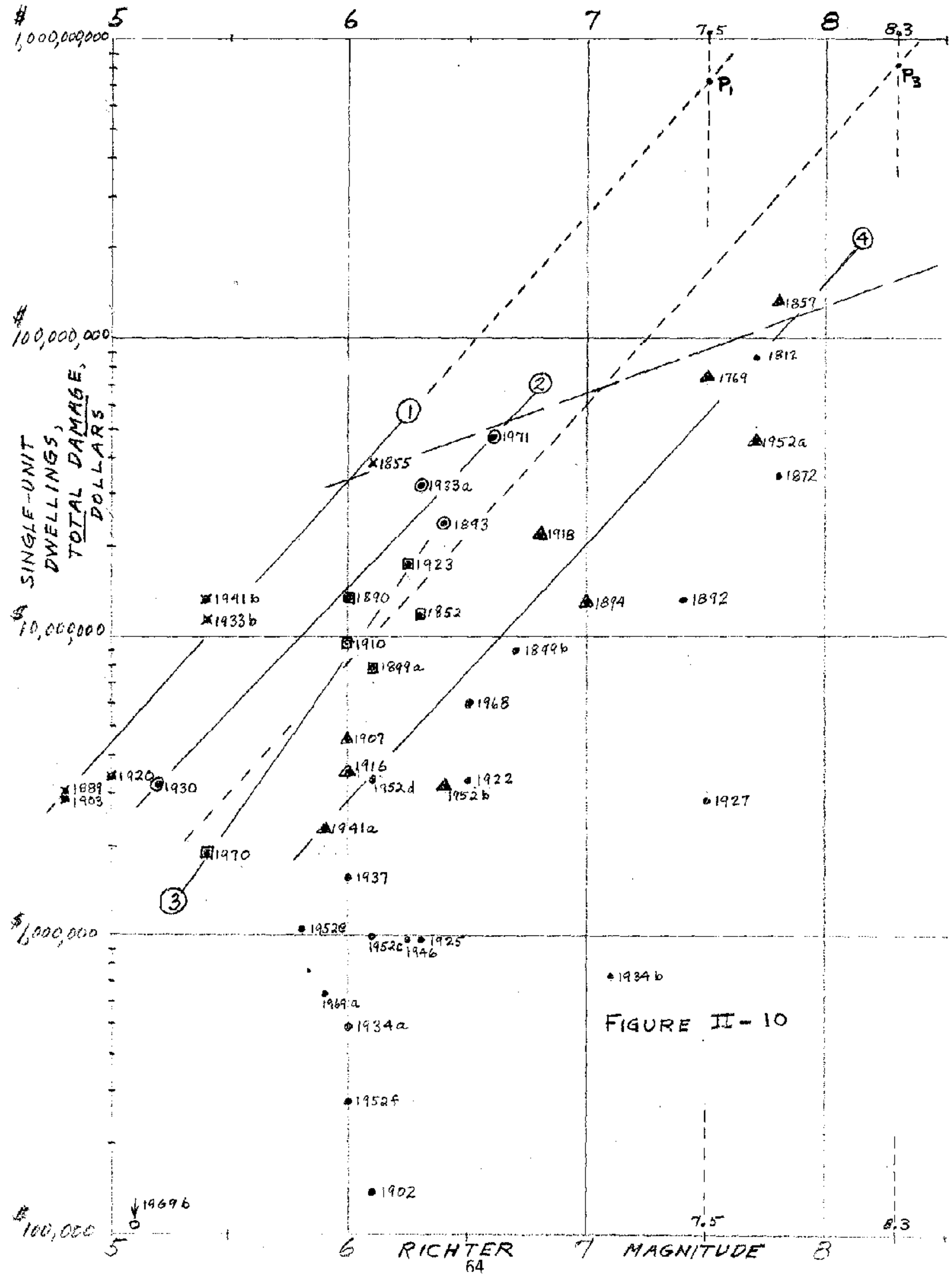
TABLE II-2

SUMMARY

| | 200-Year Sample | | | | 100-Year Sample | | | | Projected Maxima | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Maximum Per Earthquake | Average Per Earthquake | Average Per Year | Total | Maximum Per Earthquake | Average Per Earthquake | Average Per Year | $P_1$ | $P_3$ |
| Number of earthquakes in sample, M ≥ 5R | 42 | | | | 37 | | | | | |
| Richter Magnitude, R | | 7.8 | 6.34 | | | 7.8 | 6.25 | | 7.5 | 8.3 |
| Total buildings exposed | 86,161,700 | 4,700,000 (1857) | 2,051,510 | 430,808 | 68,378,900 | 3,182,700 (1971) | 1,847,940 | 683,789 | 3,550,000 | 6,100,000 |
| Total buildings damaged | 4,707,230 | 369,700 (1857) | 112,072 | 23,536 | 3,432,730 | 223,400 (1872) | 92,768 | 34,327 | 430,000 | 700,000 |
| Percent of total buildings exposed which are damaged | 5.47% | 8.22 (1812) | 5.47 | 5.47 | 5.02 | 7.18 (1872) | 5.02 | 5.02 | 10.4 | 9.3 |
| Total building damage, dollars | $1,204,325,000 | $263,750,000 (1857) | $28,674,400 | $6,021,625 | $570,695,000 | $86,130,000 (1952a) | $15,430,400 | $5,709,650 | $1,800,000,000[1] | $1,800,000,000[1] |
| Single-unit dwellings: | | | | | | | | | | |
| Average $ damage per building damaged | | $480 (1857) | $200 | | | $290 (1952a) | $141 | | $2,200 | $1,100 |
| Average $ damage per building exposed | | | $10.35 | | | | $6.70 | | | |
| Total persons exposed | 315,648,000 | 16,034,000 (1857) | 7,510,000 | 1,578,240 | 254,388,000 | 11,832,000 (1872) | 6,875,000 | 2,543,880 | 13,000,000 | 22,000,000 |
| Casualties[2] (*not* including deaths) | 12,723 | 1,726 (1857) | 302.9 | 63.6 | 7,572 | 804 (1971) | 204.6 | 75.7 | 6,100 | 7,900 |

[1] Projections by another method (projection of the 200-year sample to "zero distance") result in lower values of total building damage of $380,000,000 and $670,000,000 at Richter magnitudes of 7.5 and 8.3, respectively.

[2] It is assumed that the ratio of deaths to casualties without death is 1/30.



$1,000,000,000
$100,000,000
$10,000,000
$1,000,000
$100,000
SINGLE-UNIT DWELLINGS, TOTAL DAMAGE, DOLLARS
5
6
7
7.5
8
8.3
RICHTER MAGNITUDE
P1
P3
1
2
3
4
1857
1812
1769
1952a
1872
1971
1855
1933a
1893
1918
1923
1941b
1933b
1890
1852
1894
1892
1910
1899b
1899a
1968
1907
1916
1922
1952d
1952b
1920
1930
1889
1903
1927
1941a
1970
1937
1952e
1952c
1946
1925
1934b
1969a
1934a
1952f
1902
1969b


FIGURE II-10

unit dwellings is the ordinate, and Richter magnitude is the abscissa. The four full lines, labeled 1, 2, 3, and 4, sloping steeply upward to the right, are straight-line representations of the groups of plotted points associated with rings 1, 2, 3 and 4, respectively, shown on the location-distance map, Figure II-7. (Points $P_1$ and $P_3$ are projections which will be discussed later.) Ring 1 includes the six earthquakes labeled 1855, 1889, 1903, 1920, 1933b and 1941b, having epicenters located approximately within a 20-mile radius of Los Angeles center; ring 2 includes the four earthquakes, 1893, 1930, 1933a and 1971, having epicenters located in the range 20 to 40 miles from Los Angeles center; and so on. The same four groupings, related to rings 1 to 4, have been represented on each graph sheet by straight lines. Groupings related to the outer rings of location, 5 to 13, have not been shown because of greater scattering and sparsity of data, but the same sorts of trends can generally be demonstrated.

b. Exposure, Damage and Casualties

On the plots of *number of units exposed*, whether land area, buildings, or persons, the plotted points related to nearby earthquakes tend to concentrate in a high, relatively narrow band. The simple fact of exposure, however, doesn't tell us whether buildings are damaged or persons become casualties, or, if buildings are damaged, the extent of the damage. If we look at the plots of *number of buildings damaged* or of *number of casualties* we find that the upper band of concentration of plotted points is less dense than in the case of number of units exposed, and that the number of buildings damaged and number of casualties are much more sensitive to the distance from the epicenter than the simple count of number of units exposed.

c. Damage in Dollars

The counts of *number* of buildings damaged and of number of casualties are without regard for the extent of damage to an individual building or the seriousness of injury to a person. A damage or injury could range from slight to very great and still carry the same weight in the count. If, however, we *weight the extent of building damage* (by giving it, for example, a dollar value), it is found that the result is far more sensitive to distance than either of the first two measures described.

d. Deaths

We have not tried to weight the severity of human casualty except to distinguish death. Deaths have not been included in the casualty count, but for every 30 casualties, it has been assumed that there is one death.

e. Percent of Buildings Damaged; Average Dollar Damage

Two additional sorts of quantities have been derived from the basic computer data and plotted against Richter magnitude. They are *percent of number of buildings exposed which are damaged* and *average dollar damage per building per earthquake*.

f. Upper Bounds of Calculated Response to 200-year Sample

In addition to the observations already made, we find that for each of the sheets discussed there is a fairly well defined upper boundary of calculated points. These boundaries trend from lower left to upper right. In the case of plots of exposure counts versus Richter magnitude, the boundary is generally well represented by a single straight line. In other cases, two straight lines are necessary, usually intersecting at about magnitude 6. The boundaries so described are *upper bounds* to the calculated responses of the model of the 1970 community and its geographic site acted upon by the earthquakes in the 200-year sample. They are shown on the plots of response data points and on the summary sheets of which Figure II-11 is a sample.

g. Human Casualties Versus Building Damage

Casualties in earthquakes occur largely as the result of building damage. Omitting from consideration such events as catastrophic fire, dam failure and resulting flash flood, and complete collapse of a large building, which are quite possible but carry relatively low probability, we should expect to find a fairly simple relationship between casualties and damage. Figure II-12 shows percent of total persons exposed who become casualties plotted against percent of total buildings exposed which are damaged. The data are well represented by two intersecting straight lines. There is relatively little scattering of the points.

3. Projection to Maximum Damage

What projections to maximum predicted damage can be made? The study by Algermissen, *et al.* (1973) of earthquake damage in the Los

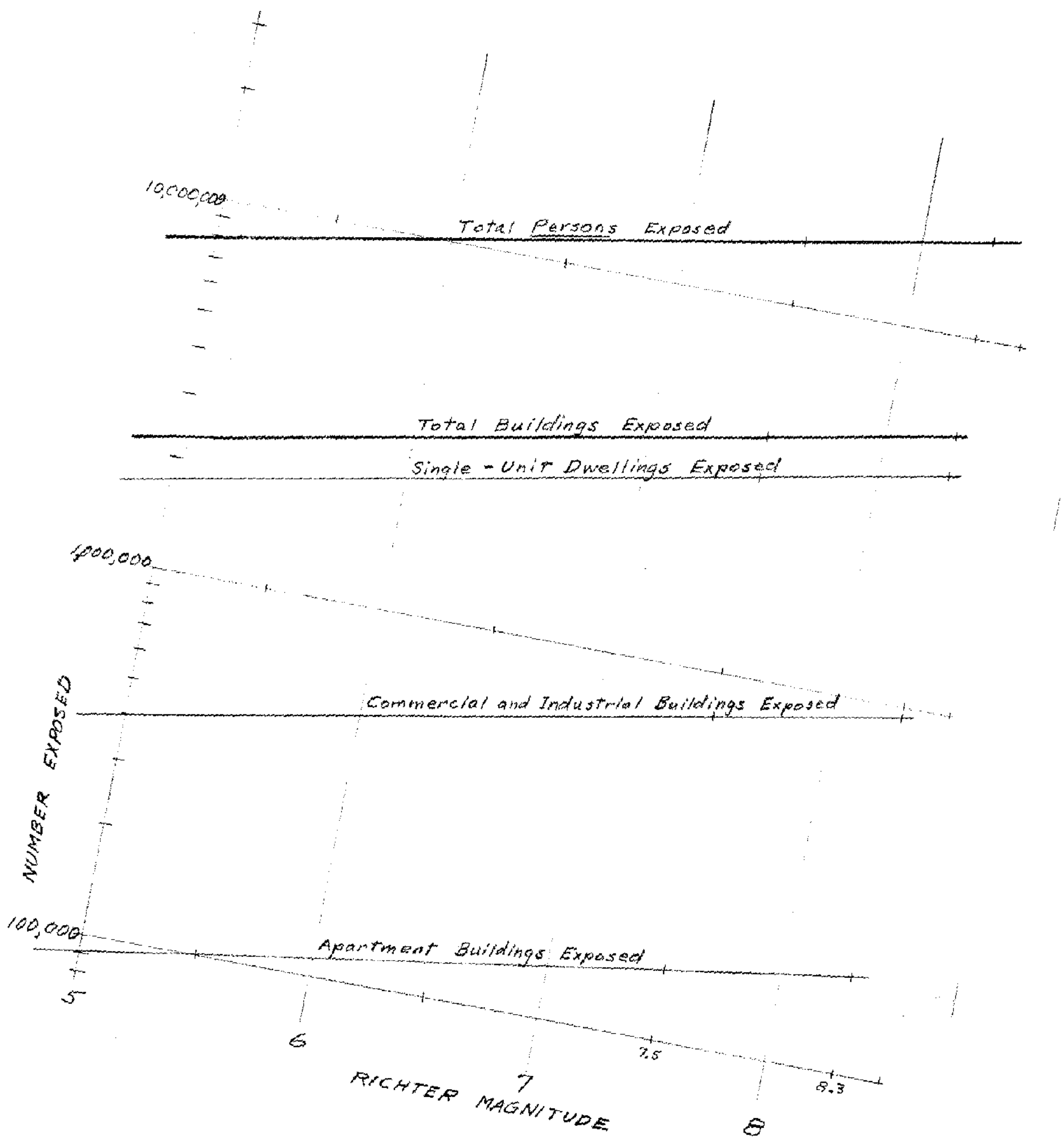

10,000,000
Total Persons Exposed
Total Buildings Exposed
Single - Unit Dwellings Exposed
1,000,000
Commercial and Industrial Buildings Exposed
NUMBER EXPOSED
100,000
Apartment Buildings Exposed
5
6
7
7.5
8
8.3
RICHTER MAGNITUDE

FIGURE II - 11

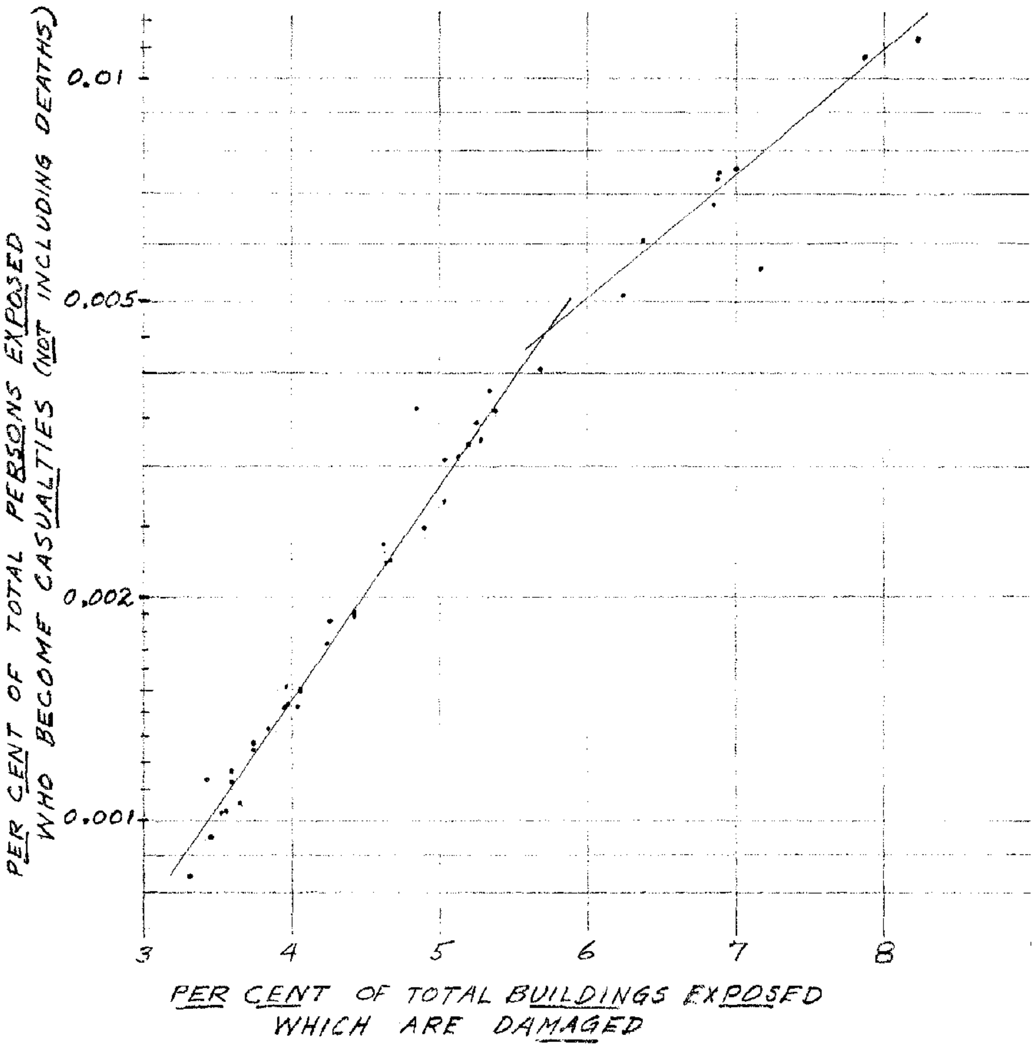

PER CENT OF TOTAL PERSONS EXPOSED
WHO BECOME CASUALTIES (NOT INCLUDING DEATHS)
0.01
0.005
0.002
0.001
3
4
5
6
7
8
PER CENT OF TOTAL BUILDINGS EXPOSED
WHICH ARE DAMAGED

FIGURE II - 12

Angeles region assumes that the largest Richter magnitudes reasonably credible are 8.3 on the San Andreas fault and 7.5 on the Newport-Inglewood fault. The largest magnitude of the earthquakes known to have affected the Los Angeles region has been estimated to be 7.8 (Fort Tejon, 1857, and Owens Valley, 1872). The San Francisco earthquake of 1906, which originated on the San Andreas fault near San Francisco had a magnitude of 8.3.

a. Projection from the Upper-Bound Lines

The upper-bound lines provide the most conservative basis for projection. They have been drawn conservatively through upper groups of points and not necessarily through the uppermost points. They have been projected to magnitude 8.3. The upper-bound projections reflect the influence of the most damaging earthquakes in the 200-year sample, but they do not include the possibility that earthquakes of large magnitude, with epicenters closer to Los Angeles than those known in the past may occur in the future.

b. Lack of Large Earthquakes with Epicenters Close In

No earthquakes of large magnitude and short distance to epicenter have been known to occur in the last 200 years. Two points, $P_1$ and $P_2$, representing hypothetical earthquakes of magnitude 7.5 and 8.3 occurring with epicenters at the closest possible locations on the Newport-Inglewood and San Andreas faults, respectively, have been used. The distances from the epicenters to Los Angeles center would be approximately 10 and 38 miles. A third hypothetical earthquake, having a magnitude of 8.3 and an epicenter distance of 50 miles, also has been represented.

c. Projection to Hypothetical Earthquakes $P_1$ and $P_3$

Arbitrarily, the damage data calculated for the known earthquakes having epicenters within rings 1 and 3 were used as bases for projecting predictions of the damage due to earthquakes $P_1$ and $P_3$. The projections have been carried out graphically on the plots of response data versus earthquake magnitude (Figure II-10 is a sample), resulting in the points $P_1$ and $P_3$ shown at Richter magnitudes 7.5 and 8.3.

It has been assumed in each case that acceptable results may be obtained by straight-line projections from the groups of points labeled 1 and 3 to intersections with the verticals, through the Richter magnitude values 7.5 and 8.3, respectively. Examples have been shown by the short-dashed lines in Figure II-10. In nearly all cases the slope of the line previously drawn, in what seemed to be an acceptable fit of points from ring 3, seemed abnormally steep in comparison with the slopes of the lines through points from rings 1, 2 and 4. In making a projection to point $P_3$, therefore, it was decided to adjust the slope of the projection to more nearly agree with the slopes of lines 1, 2 and 4. This decision resulted in lower values of $P_3$ than would usually have been obtained by direct projection of lines 3.

The projected response values for $P_1$ and $P_3$ are in all cases higher, often much higher, than the values indicated by the upper bounds of the 200-year sample or by the maxima of the calculated responses for individual earthquakes, except for the number of persons or buildings exposed, in which case $P_1$ is lower than either the calculated maximum or the upper bound.

d. Damage Versus Distance

Total building damage in dollars has been plotted against distance in miles between the epicenter and Los Angeles center. In this presentation the plotted points have been grouped according to narrow ranges of Richter magnitude (5.0-5.2R; 5.4R; 5.8-6.1R; etc.). The groups were determined by inspection.

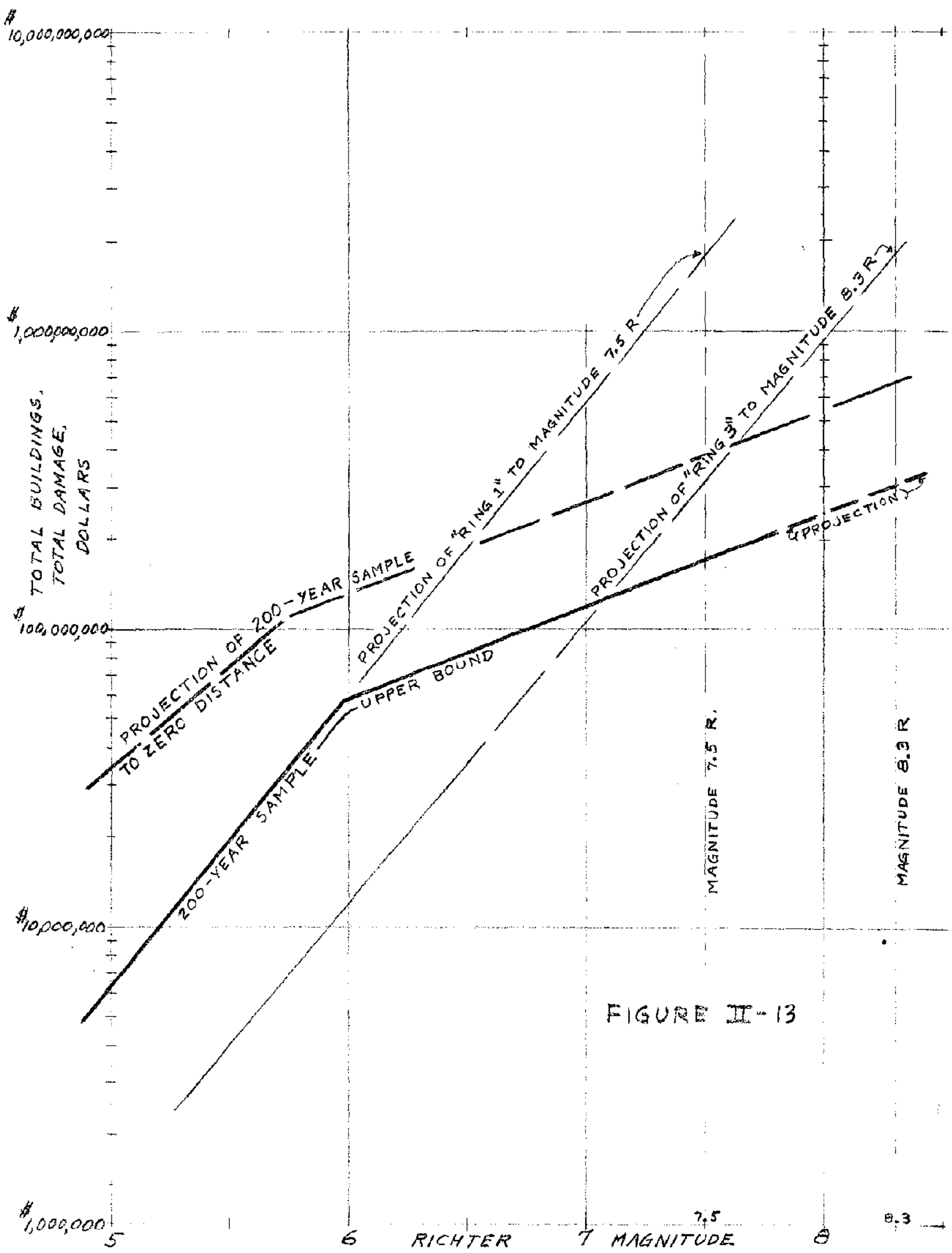
e. Projection to "Zero Distance"

The straight line representing each group of points was extended to an intersection with the damage axis at zero distance. The resulting intersection is a prediction of the total building damage in dollars which would result from a hypothetical earthquake having a Richter magnitude equal to that of the group and having its epicenter located at Los Angeles center. It may literally be impossible for such earthquakes to occur at zero distance because of lack of faulting. Nevertheless, the projection provides still another way of arriving at estimates of maximum damage.

4. Summary

a. Graphical Comparison of Three Methods of Projection

A graphical summary of the projections for total building damage in dollars has been shown in Figure II-13 for the three methods of projection described.



$10,000,000,000
$1,000,000,000
$100,000,000
$10,000,000
$1,000,000
TOTAL BUILDINGS, TOTAL DAMAGE, DOLLARS
5
6
RICHTER
7
MAGNITUDE
8
7.5
8.3
PROJECTION OF 200-YEAR SAMPLE TO ZERO DISTANCE
200-YEAR SAMPLE
UPPER BOUND
PROJECTION OF "RING 1" TO MAGNITUDE 7.5 R
PROJECTION OF "RING 3" TO MAGNITUDE 8.3 R
(PROJECTION)
MAGNITUDE 7.5 R.
MAGNITUDE 8.3 R


FIGURE II-13

The *lowest* predictions are given by the 200-year upper bound. It seems fairly certain that the resulting values are too low because they do not allow for the possibility of future large earthquakes to occur with epicenters located at short distances from Los Angeles center.

The *highest* predictions result from the straight-line projections based on restricted portions of the 200-year sample, namely the "ring 1" earthquakes and the "ring 3" earthquakes. These projections are based on a perhaps erroneous assumption that the total damage increases according to the same law regardless of whether earthquake magnitude is moderate or large.

Predictions of *intermediate level* are obtained by projecting the entire 200-year sample to zero distance. While it may be physically impossible, or at least highly improbable, for these earthquakes to occur with epicenters at zero distance, the resulting estimates seem more realistic than the considerably higher predictions obtained by straight-line projections for the earthquake groups 1 and 3.

b. Summary Table; General Comments

Table II-2 summarizes the results. We have been not so much concerned with absolute values of damage and casualties as with relative values within the sample of many earthquakes. The projected maxima are considerably lower than some other predictions have given, perhaps because of differences in the loss functions used or in the completeness of the inventory of damageable structures. We have included only privately owned buildings. Publicly owned buildings, utility lines and equipment (water, electricity, transportation facilities) and the facilities of heavy industry have not been included; if they were included, the losses might be doubled.

No allowance has been made for indirect damage and social disruption. The principal input variables have been the earthquakes--their locations and magnitudes. They are historic only in the sense that they are known to have occurred at some time in the past. The community has been assumed to remain constant as of about 1970. The damages to buildings, including the projected damage (projections to earthquakes having greater magnitude and closer location), are in dollars of approximately 1970.

While the community was assumed to remain constant in time, the densities of population and buildings within the community are highly variable from place to place (ranging from dense urban development to desert and ocean). The damage response to an earthquake depends not only on the characteristics of the earthquake but also on the parts of the community subject to the impact of the earthquake. The inputs to a given earthquake/community impact consist of many variables and these variables are interactive. The outputs in terms of damage to buildings and injuries to persons--let alone a consideration of indirect damage and social disruption--are very complicated.

## Scenarios of Future Disasters

The complicated community variables mentioned above can be presented for consideration, and possible interactions can be indicated, through scenarios of hypothetical earthquakes striking known communities. Considerable work was done on the scenario methodology by the Assessment of Research on Natural Hazards project, and some of the results may be seen in White and Haas (1975); Cochrane (1974, 1975); and Ericksen (1975).

# CHAPTER III

## RESEARCH RECOMMENDATIONS

In attempting to assess research opportunities, the effort has been to canvass the full range of possible adjustments, the dynamic factors affecting them, the total benefits and costs to society of the current mix of adjustments, and the likely consequences for society of introducing new information and techniques through research. In no case has it been practicable to identify all of the forces at work or to specify the full social impacts of different mixes of adjustments. This fact in itself indicates the desirability of pressing harder for investigation of social response to the hazard. The findings presented here represent a judgment based upon sifting of seasoned experience, a necessarily incomplete cost-benefit analysis, and a critical examination of social and physical factors affecting the mix and adoption of adjustments.

### Earthquake Reduction

1. Geophysical and Engineering Aspects

A sudden release of stored energy within the earth may result in a vibration of the earth which is called an earthquake. The general aim of earthquake reduction is to attempt, by physical means, to release the energy in relatively small steps to bring about many small earthquakes, rather than one or a few major earthquakes. There are, however, unevaluated risks in attempting to reorder the forces of nature: there is no certainty that attempts at the artificial triggering of small earthquakes may not release a large one, nor is it known to what extent the results of experiments conducted in one geological area can be applied to another.

Earthquake reduction is an ongoing field of geophysical and engineering research which may have potential for long-term payoff, but its ultimate success cannot be predicted at this time. If such research is to be continued under Federal sponsorship, it should be done with provision for the establishment of an interdisciplinary program of research, including a strong component of investigation of the social and economic consequences of an earthquake reduction program. This proposal is discussed in the next section.

2. Adoption of Earthquake Reduction

If techniques for earthquake reduction become feasible, it is obvious that knowledge will be needed concerning how those techniques might be implemented. Furthermore, if it is determined that many small earthquakes, in fact, cost less socially and economically than one or a few large ones, questions of implementation become paramount. Research should address the feasibility and consequences of implementation as well as the means of implementation.

Research should focus on the constraints operating to thwart implementation, and the means whereby these may be overcome. The basic economic consequences of implementation should be addressed. If an area were to "shut-down" temporarily in order to accommodate a series of artificially-triggered, small earthquakes, what would the costs and effects be? Since the social consequences of implementation may be far-reaching and serious, careful research is required. It would be mandatory to analyze how conflict between special interest groups might be resolved, the amount and cost of any resultant social disruption, and, most importantly, the level and structure of community preparedness necessary for the event to take place. The political implications of implementation should also be addressed. Liability for damages, especially direct damage to property, would be a vital issue.

The research would examine the total social, economic, and political cost of implementation, identifying major constraints and tactics whereby those constraints might possibly be overcome. We might also expect such research to detail the manner and means for implementation, to indicate who would decide when such an event would occur and how it would be decided. Such research is necessary and promises payoff only to the extent that the actual techniques for reduction exist. At such time as these techniques seem promising, this research might run for a period of five years at a cost of five person years* per year. The research

*Funds needed to support one research worker, including staff and travel, for one year; currently $60,000.

effort might well be incorporated into any existing program of earthquake preparedness.

## Earthquake-Resistant Construction

### 1. Analysis, Design, and Building Codes

Research on earthquake-resistant construction has been carried on for many years, but there is still a large gap between knowledge and practice. The research has resulted in some improvement of building codes, an increased awareness of the earthquake hazard, and improved construction in some classes of structures in the most obviously vulnerable areas. Most of the attention has been applied to the more spectacular and analytically interesting types of structures, for example, many-storied buildings, large dams, nuclear power plants, and storage tanks. Relatively little attention has been paid to more modest structures.

While this practice has indeed had positive results, it has led indirectly to possibly negative effects, among them are the following: (1) potential weaknesses in certain methods (lift-slab construction, prefabricated construction, and other methods which may result in lack of adequate structural continuity) have not been investigated sufficiently; (2) the lower structures, with the exception of school buildings in California, generally have not been given attention commensurate with their property value and the human risks involved; (3) many-storied buildings, which have been adequately designed and constructed to withstand the motion of major earthquakes without serious structural damage, are not necessarily safe for human occupancy if the elevator system fails or if fire breaks out; and (4) a dam and the valley below it, which seemed safe at the time of construction of the dam, may later prove to be unsafe due to increased density of human population in the valley, deterioration of the dam and its foundation, or the occurrence of a greater-than-expected earthquake.

These comments point out the following needs in engineering research: (1) special attention should be given to defining the structural deformations that may occur during earthquakes; (2) greater attention should be paid to the earthquake resistance of low buildings; (3) no multi-storied building should be designed and built without a thorough analysis of its overall safety, including structural integrity, safe evacuation, and fire resistance; (4) no dam should be constructed without full analysis of the overall safety of it and the valley at risk below; and (5) reliable techniques should be developed for making cost-benefit studies of earthquake resistance versus overall cost, especially as affected by building codes. Specific suggestions could be made regarding the need for greater understanding of foundation conditions and other subjects of concern. The safeguarding of life-lines--water, electricity, communications--is greatly in need of study.

It is suggested that additional funding on the order of about 20 person years per year for the next ten years would be desirable. The movement toward improving earthquake-resistant construction has been generally successful, with some exceptions noted, and needs further support. Special support is needed for studying the social and economic constraints surrounding the implementation of building codes. This problem is discussed in the following section.

2. Code Implementation

The implementation of upgraded building codes, in light of the fact that estimates of increased costs of providing earthquake resistance to *new* construction rarely exceed 6% of the total cost of the structure, is seen as an area in need of study, with promise of payoff. The upgrading of building codes for all classes of structures and the political, social, and economic constraints to their *adoption and enforcement* are problems in need of research.

It is our impression that some "high-risk" cities are significantly more progressive in the upgrading of building codes than other cities. If so, a series of comparative case studies would begin to provide answers regarding how movement does and can take place, and what the secondary consequences seem to be. It may not even be out of the question to try some experimental efforts at providing various incentives to the local powers who could influence building code upgrading. For example, one could search for communities where the mortgage lenders were somewhat progressive. A small team of professionals (economists, structural engineers) would carry out a careful effort to demonstrate to the lenders why supporting an improved building code would be in their own self-interest. Other possible approaches could be tried in other cities to see which approach was most effective in producing the desired change. It is suggested that such a study should run for a period of five years at a cost of five person years per year.

3. Old Buildings: Physical Condition

Old buildings present what is perhaps the most difficult problem of all. They may be lucrative rental property or tax dodges for the owners, homes and community foci for great numbers of persons who can't or won't live anywhere else, and potential death traps due to the danger of collapse or fire. The two general classes of problems are the physical condition of the structures, and the social and economic constraints on doing anything about the condition.

Regarding physical conditions, research is needed for (1) systematic ways of surveying and evaluating the structural integrity and general safety of these buildings, and (2) ways of strengthening those where remodeling rather than demolition is justified.

Research on the problem of survey and evaluation would involve techniques for collection and interpretation of data, including criteria for critical weaknesses, direct visual examination, use of photography (including aerial photography ), and drawings and building permit records where available. Indeed, the process might be similar to the examination of buildings after an earthquake. In certain cases, a special technique involving the artificially forced vibration of the structure through the use of a vibration generator might be informative.

Research into ways of strengthening old buildings could scarcely be expected to lead to general procedures because of the great differences in construction and condition. However, it might be possible to arrive at suggested procedures for particular classes of buildings.

Both types of research--survey and evaluation, and procedures for strengthening--might well be carried out in connection with programs of demolition for urban renewal or other purposes, provided arrangements can be made well in advance of the start of demolition. It is suggested that funding of about ten person years per year for ten years would support a useful program of research.

4. Old Buildings: Adoption of Improvements

Buildings built prior to the enactment of earthquake-resistant design codes have a higher probability of suffering structural damage or failure than buildings constructed after the enactment of the codes.*

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*The adoption of earthquake-resistant provisions began to occur in some cities of California in 1933 or later. In many vulnerable areas of the country such provisions have still not been made effective.

It is difficult to estimate the extent of danger older buildings pose to lives and property. Research is needed to determine the risk they present, as well as how this risk might be lessened.

Such research might start by determining how many old buildings exist in hazardous areas, as well as their differential conditions and use patterns. Of those that are dwelling units, knowledge of their inhabitant density would make more manifest the degree of risk they represent. The research might then seek to determine how risk might be lessened. Determination of their natural rate of abandonment might be followed by an investigation of how that rate might be increased. An alternative to abandonment might be the remodeling of appropriate structures to some level of acceptable safety. All alternatives should be examined. In addition to alternatives for reducing the risk, the research should also address the social, economic, and political constraints to the adoption of each alternative.

Economic constraints to the phasing out of dangerous structures include not only costs to the individual owner, community, state, or Federal subsidies, but also might include shifts in the tax base. Social costs would include the disruption of established ongoing neighborhoods and ethnic cohesion, a possible rise in crime rates associated with urban renewal, and the inherent problems in the relocation of families and businesses. Political forces may resist the adoption of such a program, and in some localities current laws may provide no legitimate basis for it. Long Beach, California, is a good example of a city with such a program. It might provide the basis for a valuable case study carried on by an interdisciplinary team.

In terms of potential lives saved, lessening of disaster-related structural damage, and lessening of the economic loss of individuals in earthquake disasters, such research would provide significant payoff. The research would vary in time and cost with the size and density of the areas selected for analysis. However, a study costing on the order of six person years per year, running for five years, should provide a good basis for action.

## Land Use Management

1. Risk Zoning Studies

Of all adjustments, the simplest and most direct would seem to be the avoidance of high-risk areas. However, San Francisco cannot be relocated, undeveloped high-risk areas may be potentially very valuable (as in some parts of the San Francisco Bay Area), and the degree of risk is not always obvious. These comments indicate several courses of action: (1) risk zoning of critical parts of the already developed area to turn them into park land or other non-hazardous use as opportunity arises; (2) risk zoning of high-risk undeveloped areas to prevent future hazardous development; and (3) development of systematic techniques for collection and evaluation of data for use in microzoning, and the establishment of criteria for microzone levels of risk.

A research program on microzoning procedures with some detailed case studies, the gathering of local seismicity data and local fault mapping as needed, and the identification of especially hazardous areas, including potential landslides and soil liquefaction, would involve a considerable expenditure over a long period of time: 20 person years per year for ten years.

2. Zone Adoption Processes

Little attempt has been made to restrict building in fault zones. Building restriction either by the complete non-use of some lands, or by structure type or characteristics is not in practice except in some highly specialized situations.

A research study designed to point out ways in which this innovation might be encouraged and adopted would have considerable payoff. Beginning by restricting land use in actual fault zones and other known areas of high hazard, for example, areas in which the soil is known to be subject to liquefaction, the practice could well spread to other areas as micro-risk zones are assessed.

The study would analyze the question of how to get such zoning adopted, especially for structures and facilities of vital importance in response to earthquakes, for example, fire stations and hospitals. The social, political, and economic constraints to land use management would be assessed, as well as the consequences of implementation. Such consequences, which may constrain adoption, would be reductions in the ongoing economic and physical growth of an area. The study of zone adoption for the earthquake hazard may be similar to such studies for other hazards, flood plain management for example.

Research on the adoption of zoning could be combined, in certain instances at least, with experimental research on building code adoption. Areas not yet developed but subject to high seismic activity could be used for certain economically feasible purposes if improved building codes were first adopted and used as a basis for seismic-resistant design.

An adequate investigation might run for a period of five years at a cost of eight person years per year.

## Prediction and Warning

1. Geophysical Aspects

Prediction and warning of weather conditions and weather-generated hazards have long been a part of our culture, and the public has learned to follow them in the news media and, to some extent, how to interpret them. Earthquakes, however, are unseen phenomena which strike without natural warning. The public has no background of experience for interpreting warnings. On the face of it one would scarcely question the desirability of seismological research in prediction and warning. Judging from the many recent public news releases regarding this research, there are expectations both in this country and abroad that prediction will eventually be successful, perhaps within a few years to a decade. Some efforts at technology assessment of earthquake prediction are underway. The utility of the projections coming therefrom may be open to question, however, since a significant empirical data base is lacking.

Scientifically successful prediction and warning of an event which carries no natural warning cannot be expected to lead of itself to desirable social response. Indeed, in the event of inaccurate or false alarms, which in the nature of the problem will inevitably occur, the social response may be highly undesirable and may lead to greater economic loss and social disruption than an earthquake per se.

It is our understanding that research on earthquake prediction is presently funded at $5 to $6 million per year for a period of ten years. This rate seems reasonable considering the magnitude of the geophysical problem.

2. Warning System Implementation

If seismologists seriously intend to issue warnings of date, place and magnitude of major earthquakes, the communities--general public as well as public administrators and security officers--should first be made fully aware of the possible significance of such warnings: how warnings will be authenticated; given long lead times, how economic dislocation can be minimized; to what extent accelerated strengthening of buildings can take place; and the possible panic selling of real estate. This is a subject for a complete program of social and behavioral research on a warning system, which should be carried on simultaneously with the seismological research program on prediction and forecast, but organized and funded independently.

Very little attention has been paid to the question of what would be done with prediction and warning capabilities. It is not known what agencies would be involved--Federal, state, county, city; to whom advisories or warnings would be issued; what emergency measures should be taken; or who, at each level, should have responsibility. It is our opinion that research should begin which would be designed to answer the questions surrounding the social implementation of earthquake prediction and warning. The study should address itself not only to the question of implementation but also to the probable consequences of that implementation.

To make warnings operational, a variety of alternatives emerge which range on a continuum from alerting only emergency organizations such as hospitals, fire departments, and emergency preparedness agencies, to the evacuation of an entire area-at-risk. Some of these alternatives are presented in Figure III-1.

FIGURE III-1

CONTINUUM OF ALTERNATIVES FOR EARTHQUAKE WARNING

- alert only emergency organizations
- shut down vulnerable activities
- partial evacuation of a city
- evacuate an entire geographical area

The research should address itself to a series of general questions concerning the following: (1) at what point of predicted intensity evacuation would be effected; (2) how such thresholds would be determined for each option on the continuum for varied communities and areas; (3) what the feasibility of evacuating an area is; (4) to where evacuation would be made; and (5) what the economic, political, and social constraints to each alternative of warning implementation are, including what might happen when warnings cross different political units.

In addition, the research might also address the social, economic, and political consequences of the varied alternatives of implementation: (1) what problems false alarms will raise; (2) what a warning will do to the rates at which insurance policies are purchased; (3) what effect it will have on the financing of property; (4) what will happen to buildings under construction; (5) what will happen to the general economic climate of the area; and (6) what positive or negative feedback implementation would have on the adoption of other adjustments to the hazard.

A reliable method of reasonably precise prediction, with a low false-alarm rate, could lead to significant reduction in casualties due to earthquakes and may lead to some reduction in property loss. It seems most likely that additional and perhaps large-scale impacts will also come as a consequence of earthquake prediction. Some of these consequences are likely to be positive and others almost certainly will be negative.

The range of actions that *could* be taken by organizations, families, and individuals is impressive. Estimating what *will* be done, however, is a matter that has not been examined systematically. When the first scientifically credible earthquake forecasts come along there will be a variety of responses from the responsible Federal, state, and local agencies; from the mass media and other interested organizations in the private sector; and from citizens who reside in or near the area to which the forecasts apply. Indeed, even semi-credible forecasts may produce considerable social disruption.

It should be noted that there may be two types of forecasts and therefore the possibility of two types of "false alarms." The first is a forecast that an earthquake *will* take place, the second is a forecast that an earthquake will *not* occur. Furthermore, the very existence of an earthquake prediction and warning system may to some extent generate a false sense of security and a tendency on the part of the public to infer that *no* warning means that *no* damaging earthquakes will occur.

The response to earthquake prediction is, at this point in time, exceedingly difficult to estimate. There are no good parallels to use as a basis for estimating the response. The best sources of information concerning the most likely outcomes of early earthquake forecasts appear to be those persons who are most likely to be involved in the process of initiating a forecast, implementing actions relating to the forecast, and responding to the forecast.

Because earthquake forecasts appear to be qualitatively different from warnings of other hazards, the first few credible forecasts may bring with them some surprising consequences. It is critically important to look in a comprehensive and painstaking manner at the socioeconomic, political, and legal context in which the early forecasts will exist. Whether earthquake forecasts eventually produce a net social benefit or not may be determined in large measure by the response to the first few credible forecasts. From scientifically respectable sources within the United States there have been several earthquake forecasts, but only one forecast for a *damaging* earthquake. The earthquake occurred as predicted, but was below the damaging threshold.

Discussions with seismologists and government officials responsible for handling earthquake predictions have convinced us that once the technology become reliable, no earthquake forecast for a *damaging* earthquake within the United States will be withheld from general circulation for long. If, in advance of credible forecasts for damaging earthquakes, responsible public agencies and private interest groups develop plans and policies which are based on *realistic assumptions about the actions of other organizations and the behavior of citizens at large,* the whole situation will be less volatile, and less likely to produce an economic downturn, unnecessary social disruption, or political upheaval.

What is called for is a research effort which will assess the likely responses to early credible earthquake forecasts. At the present time there are no social mechanisms to assist responsible officials and organizations in arriving at plausible and realistic estimates of responses to the forecasts. If the results of carefully conducted research on the probable response of organizations and the public at large are fed back to all responsible officials, they would have an adequate, realistic knowledge base upon which to develop their plans.

Earthquake forecasts could be one mechanism for reducing potential loss and disruption from earthquakes. With extended lead times, action could be taken to inspect and strengthen buildings, upgrade the seismic component of building code requirements so all new structures would be less susceptible to damage, improve land use zoning regulations so as to limit or prohibit construction in especially hazardous areas, and as the forecast event day approached, plans for partial or complete evacuation could be carried out.

The negative consequences could be enormous if an extended period of uncertainty follows a forecast for a damaging earthquake. Insurance companies may decide to stop selling or renewing earthquake insurance coverage. If that takes place, investment agencies may drastically reduce their commitments to construction and development in the area. That could trigger an extended slowdown in the local economy which would be reflected in increased unemployment and in higher welfare costs. Further, there would be reduced public services due to a shrinking tax base.

Today there is no base of scientific knowledge to provide answers to such questions, but the nation, and especially such states as California, desperately need to have available the best empirically based approximate answers to these critical questions.

Because of the potential for very large-scale negative consequences, it is imperative that we learn as early as possible how to cope with earthquake prediction. Minimum funding of ten person years per year for five years is warranted.

## Insurance

1. Adoption Processes

While insurance against earthquake damage is generally available, relatively few property owners have taken out such policies. In California less than 5% of the property insured against fire is also insured against earthquakes, and the percentage is even smaller in Alaska.

The opportunity to test the reasons for this low rate of adoption exists. It may be that insurance companies are concerned about the possibility of severe losses, or that such insurance is viewed only as a special service to preferred customers rather than as a profit-making operation. It may also be that the low rate of adoption is a function of insufficient awareness of the earthquake hazard, of the ability to externalize costs, of some minimum level of desirable risk as seen by individual property owners, or of misinformation on the availability of coverage and the rates. There is opportunity to determine the factors affecting decisions to buy or refuse insurance, as well as those affecting how it is made available. To the extent that the earthquake insurance adoption rate continues to remain below a socially desirable rate, the results of investigations at a cost of two person years per year for a period of five years will suggest possible modification to increase adoption and protection.

2. All-Risk Insurance

A special line of investigation is needed to assess the opportunities and pitfalls in providing all-risk insurance. It would deal with the whole range of natural hazards, and to be effective would examine possible relationships between insurance and each of the possible types of adjustment. A study of the feasibility and possible design of such a program is estimated to cost four person years per year over a period of five years.

Community Preparedness, Relief and Rehabilitation

1. Micro-Studies of Vulnerability

Risk in an area is a function not only of the geological aspects of the earthquake problem, but more importantly, it is a function of the type and density of human use to which the area is subject. Detailed, community-specific vulnerability studies which define risk in terms of special physical problems such as buildings and gas and water lines, and community function problems such as transportation and health, are requisite to complete risk definition and subsequent preparedness. Such studies should also take into account the compound hazards associated with earthquakes. These studies might be modeled after those for the San Francisco Bay Area and the Los Angeles Area conducted by the National Oceanic and Atmospheric Administration (1972, 1973a). The cost would vary, dependent upon the size and density of the community analyzed. It is estimated that a systematic investigation, including the most earthquake-vulnerable cities in the country, would require five years and an expenditure on the order of six person years per year. The investigation should be coordinated with several of the others suggested, for example those concerned with earthquake-resistant construction and codes, the strengthening or removal of hazardous buildings, land use zoning, and risk mapping.

2. Preparedness Studies

Community preparedness for earthquake disasters, especially since secondary hazards like fire are particularly in need of immediate attention after an earthquake, is vital for adequate community response. In most communities, however, present levels of preparedness fail to provide for all the eventualities of an earthquake disaster. Great earthquakes not only destroy underground services, but disrupt electrical and telephone service as well. Conducting emergency work and clean-up operations under such conditions requires heroic efforts. How emergency planning can be accelerated in a community, and levels of preparedness increased, is worthy of research. The findings of such a study, if implemented, could increase response ability thereby decreasing the impact of secondary hazards--and could aid search and rescue effort and reduce social and economic disruption. Such a study might also consider how constraints which resist increased levels of preparedness might be overcome. The study might be incorporated into ongoing preparedness programs and run for a period of five years at a yearly cost equivalent to five person years.

3. Relief and Rehabilitation

The state of knowledge is insufficient to determine the short- and long-term consequences of relief and rehabilitation on affected social systems. Relief and rehabilitation programs are seldom evaluated in terms of their consequences; no systematic evaluation has ever been conducted. Such knowledge, however, is required in order to determine the actual cost-benefit ratio of programs and services, and how the adjustment influences the hazard potential within an area. It would then be possible to determine the best methods for implementing the adjustment, as well as the nature and combination of services which might best be offered. For example, the location, spatial distribution, density, and type of temporary housing employed may have short- and long-term effects upon the future growth patterns of a community, its employment and welfare programs. These in turn may be related to the level of hazard vulnerability and future losses in the area.

Research should be conducted which would examine the long-range social costs of relief and rehabilitation programs where costs are defined more broadly than those involving administrative organizations. The research would examine the extent to which present loan and grant practices actually are successful in aiding individual recovery, as well as their equitability. The extent to which such programs retard the adoption of other adjustments, thereby possibly increasing the hazard potential in an area, must be determined. It would be interesting, furthermore, to study the income distribution of recipients of loans and grants (Kunreuther, 1973a, pp. 32-35). Once the consequences of relief and rehabilitation efforts are known, it would then be possible to restructure existent programs to determine the nature and combination of services which might be offered.

Realizing the relative infrequency of earthquake disasters, a study designed to assess the adjustment might not be limited only to earthquakes. A series of disaster communities should be studied. In these communities the impact of relief efforts might be assessed for their consequences in rehabilitation, which in turn could be assessed for long-term social and economic costs and interaction with the adoption of other adjustments. The study would also determine the major policy issues involved in implementing the adjustment and their effects on economic costs, social disruption, and the speed of recovery. Such a study might cost an average of five person years per year for five years.

## Post-Audit Analyses

More specific case studies of earthquake impact could contribute needed baseline data which could have payoff relevant to many of the adjustments to earthquakes, as well as to other lines of hazard research. It is proposed that the most efficient and fruitful manner for performing the studies is through the organization of interdisciplinary post-disaster field teams, and that the basic specification, organization, structure, and preparation of those teams and field coordination centers for researchers be established. Such a comprehensive effort should also (1) develop a methodology for estimating earthquake loss (social, economic, and political), (2) document comprehensive interdisciplinary field observations, (3) develop the maximization of information availability, and (4) develop comprehensive field research techniques.

It is difficult to estimate the cost of such a program for any one year. A single event of great magnitude, or a combination of events, can easily unbalance a minimal annual budget for years to come. Furthermore, the budget should provide for case studies of natural disasters in foreign countries whenever the information gained is valuable to the general store of knowledge regarding natural disasters. The program should continue indefinitely and, considering the impossibility of estimating in advance the cost for any one year, it should be financed by a large fund set aside to cover estimated costs for a considerable period of time--ten years or longer.

## A Unified National Research Program

Although lead responsibility for investigation of the geological and geophysical aspects of earthquake hazard reduction is vested in the U. S. Geological Survey, there is not yet a unified national program for hazard reduction. The National Science Foundation has played a vigorous role in promoting research on earthquake engineering, particularly for high buildings, and has pioneered in investigation of social aspects. The National Bureau of Standards carries out a limited amount of research on design and construction of earthquake-resistant buildings. The Department of Housing and Urban Development exercises only weakly its responsibilities for research and technical assistance in land use management. Other Federal agencies, such as NOAA, NASA, and the Energy Research and Development Administration, are involved in one way or another.

If an integrated program of action and supporting research is to be achieved, it would seem essential for one agency to take the lead. The U. S. Geological Survey might be considered to have sufficient authority to do so at present, but ambiguity could be reduced by either executive action or Congressional legislation which specifically directs the preparation and monitoring of an integrated national effort.

## Summary

It should be recalled that the judgments made here are for research related to *earthquakes as a hazard to life and property.* The judgments are not concerned with the basic research of geophysics on occurrence of earthquakes, the nature of ground motions,.etc., important as that research is in the long run.

Tables III-1 and III-2 summarize the results. It should be emphasized that Table III-1 presents estimates for research which are *in addition to currently ongoing and planned research.*

TABLE III-1

FUNDING LEVELS FOR RESEARCH OPPORTUNITY SETS

| Research Opportunities | Estimated Current Annual Level* | Suggested Total *Additional* Research in Person Years** | Suggested Time Horizon for Additional Research, Years |
|---|---|---|---|
| EARTHQUAKE REDUCTION: | | | |
| Geophysical and Engineering Aspects | 3 | -- | 10 |
| Adoption Processes for New Techniques | 0 | 25 | 5 |
| EARTHQUAKE-RESISTANT CONSTRUCTION: | | | |
| Analysis, Design of Building Codes | 4+ | 200 | 10 |
| Code Implementation | 2 | 25 | 5 |
| Old Building Treatment | 0 | 100 | 10 |
| Adoption Processes | 0 | 30 | 5 |
| LAND USE MANAGEMENT: | | | |
| Seismic Risk Zoning Studies | 1 | 200 | 10 |
| Zone Adoption Processes | 0 | 40 | 5 |
| PREDICTION AND WARNING: | | | |
| Geophysical Aspects | 4+ | P | 10 |
| Warning System Implementation | 0 | 50 | 5 |
| INSURANCE: | | | |
| Adoption Processes | 1 | 10 | 5 |
| All-risk Insurance | 0 | 20 | 5 |
| COMMUNITY PREPAREDNESS, RELIEF AND REHABILITATION: | | | |
| Micro-Studies of Vulnerability | 1 | 30 | 5 |
| Preparedness Studies | 1 | 25 | 5 |
| Relief and Rehabilitation Processes and Socioeconomic Effects | 0 | 25 | 5 |

*Very crude estimates based on impressions of level of research activity. It would be very difficult to arrive at accurate estimates including unbudgeted as well as budgeted activity.

0 = zero to $10,000    3 = $1,000,001 to $2,000,000
1 = $10,001 to $100,000    4 = $2,000,001 to $4,000,000
2 = $100,001 to $1,000,000    P = In progress

**Person year is the amount needed to support one research worker, including staff and travel, for one year; currently $60,000.

TABLE III-2

RESEARCH OPPORTUNITIES

| Research Opportunity | National Aims: Economic Efficiency — Reduction of Net Losses, Benefits-Costs | | National Aims: Enhancement of Human Health — Reduction of Casualties | | National Aims: Avoidance of Social Disruption | | National Aims: Environment — Protection or Enhancement | National Aims: Equity — Distribution of Costs and Benefits | Research Findings: Expected Success of Research | Research Findings: Likelihood of Adoption |
|---|---|---|---|---|---|---|---|---|---|---|
| | Average | Cata-strophic | Average | Cata-strophic | Average | Cata-strophic | | | | |
| Earthquake Reduction<br>Geophysical and engineering<br>Adoption of techniques | Med | Low-Neg | Med | Low-Neg | Low | Low-Neg | NA | NA | Low | Low |
| Earthquake-Resistant Construction<br>Analysis, design of building codes<br>Code implementation and adoption<br>Old building treatment | High | High | High | High | High | High | NA | Low | High | Med |
| Forecast and Warning<br>Geophysical aspects<br>Detection, dissemination and response | Low | Med-High | High | High | Low-High | Low-High | NA | Neg-Low | Med | High |
| Land Use Management<br>Seismic risk zoning studies<br>Zoning adoption | Med-High | Med-High | Med | Med | Med | Med | Med | NA | Med | Low |
| Insurance<br>Adoption processes<br>All-risk insurance | Low-Med | Med-High | Low | Low | Med | Low | NA | Med | Med | Med |
| Relief and Rehabilitation<br>Micro-studies of vulnerability<br>Community preparedness studies<br>Relief processes and socioeconomic effects | Low | Low | Med | Med | Med | Low | NA | High | High | Med |

Med = Medium   Neg = Negative   ? = In doubt   NA = Not applicable

# PART II

# TSUNAMIS

# CHAPTER IV

# DIMENSIONS OF THE TSUNAMI HAZARD IN THE UNITED STATES

Large gravity waves in the sea, associated with some earthquakes and other impulsive disturbances, are referred to in international usage by the Japanese word, "tsunami." The term "seismic sea wave" is also used in some instances, and the inaccurate designation *tidal wave* still finds use. Cox (1963) defined tsunami as "a train of progressive long waves generated in the ocean or a small connected body of water by an impulsive disturbance." This definition does not include storm surges, astronomic tidal waves or seiches. Van Dorn (1966) has defined tsunami as "the gravity wave system formed in the sea following any large-scale short duration disturbance of the free surface." Though tsunamis occur comparatively infrequently, they can cause almost complete devastation when they strike.

## Physical Characteristics

### 1. Origin and Dynamics

Tsunamis may be generated by submarine volcanic explosions, by submarine landslides or subaerial landslides plunging into the water, or, most commonly, by tectonic displacements of the ocean floor associated with earthquakes. Great earthquakes frequently have their origins under the sea, particularly along the shorelines of the Pacific Ocean which is outlined by the circum-Pacific seismic belt. However, only a small percentage of these earthquakes is accompanied by tsunamis.

At present there is no way to determine with certainty if an earthquake is accompanied by a tsunami, except to note the occurrence and epicenter of the earthquake and to detect the arrival of the characteristic waves at a network of tide stations. It is commonly accepted that the earthquake must have a magnitude of 7 Richter or greater to be accompanied by a tsunami of significant magnitude. This does not mean, however, that earthquakes of lesser magnitude cannot generate local tsunamis which might be damaging in confined areas near the epicenter. Although the 1964 Alaska earthquake demonstrated that the epicenter need not be under the ocean, it is probable that there must be tectonic movement under the water in order to generate a tsunami.

Since it is known that the speed of tsunamis varies with water depth, the prediction of tsunami arrival times at coastal locations is possible once the epicenter has been determined. But it is not yet possible, due to the state of our knowledge about the ocean floor and the tsunami mechanism, to predict the wave height at any specific coastal location. The runup height of a tsunami wave, which is always greater than the height of the wave on open water, can vary greatly even in a single coastal region.

An area badly hit by one tsunami occurrence may not be touched by another. Crescent City, California, for example, was badly damaged as the result of a tsunami generated by an Alaskan earthquake (1964), but the probability of damage in that city from a tsunami generated by a Central or South American earthquake is not nearly as high. In the case of tsunamis generated in approximately the same source area, however, it has been observed that locations of unusually high runup for one tsunami tend to repeat in the tsunami sequence as points of unusual danger.

Other observations are that lee shores of islands normally receive less energy than unguarded coastlines on the direct line of approach from the tsunami source, and that there has been inter-island shadowing evident in the Hawaiian Islands. One continuing discussion has been that of the effect of narrow bays, inlets, and straits. Some of the greatest observed wave heights have been near the heads of long, funnel-shaped bays, but it has also been reported that waves are commonly less severe in bays and more severe on headlands, for the same reason that ordinary storm waves strike the headlands more violently.

Another indeterminable feature of a tsunami is how many successive waves there will be in the series, although there is rarely only one. Not only can the successive waves of a single tsunami follow either within minutes of one another or have a period of hours between waves, but there is no way to determine which wave in the series will be the greatest.

There may be observable changes in the water along the shore in the earliest part of the approach of a tsunami, but they do not, in general, provide information about the heights of the largest waves. Some tsunamis have been preceded by roaring sounds from the sea, but others are accompanied by no distinctive sound. In many instances the initial behavior of the water at a coast is a marked drop in level, exposing the ocean bottom for long distances out to sea; in other cases, the initial behavior is a rise in the water level. Occasionally unusual local water action or color has been reported as having preceded the arrival of the major waves.

A strong clue to a coastal community that a tsunami may be imminent is the perception of strong earthquake ground motion. This may indicate that the earthquake was of great enough magnitude to be accompanied by a tsunami, and close enough in origin to be followed very quickly by tsunami waves. Even though the tsunami will not reach more distant coastlines for a matter of hours, it can hit a nearby shore within a matter of minutes.

Tsunami waves travel outward in all directions from the generating source; however, depending on the geometry of the source, they may focus in a particular direction. The waves travel at a speed which depends on the depth of the water* and accelerate or decelerate in passing over an ocean bottom of varying depth. In deep water in the open ocean they travel at speeds of 350-500, or even 600 miles per hour. A tsunami can traverse the entire 12,000 to 14,000 miles of the Pacific in 20-25 hours and still be capable of causing great destruction.

The apparent period of tsunami waves ranges from five to sixty minutes or longer (time of passage from crest to crest), and the wave length (distance between crests) may be 50-100 or more miles. In the open ocean the height of the waves may be one foot or less; with many miles between crests, the waves are neither discernible to ocean vessels nor visible from the air. Detection becomes possible as the tsunami enters more shallow water, the wave speed and wave length decrease, and the wave height increases greatly. When the succession of waves reaches the shallow water of the coast, the speed slows to less than 40 miles per hour and a large tsunami may run up on land to heights of 50 feet or more, even on coasts remote from the origin.

The configuration of the coastline, shape of the ocean floor, and the character of the advancing waves all play an important role in the impact with which a tsunami hits a specific location. The amplitude

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*The speed is given approximately by $V = \sqrt{gd}$, where g is the acceleration of gravity and d is the depth of the water, in consistent units.

of the advancing wave is a complicated function of the characteristics of the generating source and the body of water in which the waves occur. It is not completely clear why waves in a particular tsunami event may be of negligible size at one point along a coast and the same waves may be much larger at a point just a few miles away; nor is it known why some tsunamis arrive with a powerful surge across the beach and others consist of a gradual rise of sea level, followed by a rapid draining back to the sea. Whatever the mechanisms, great destruction can be wrought by either an advancing turbulent wave front, or by the rapid outflow which sweeps earth and construction with it (OEP, Volume 3, 1972).

The duration of a tsunami event at an affected coast can be quite long. Oscillations of destructive proportions may continue for several hours; in some cases several days have elapsed before the sea has returned to its normal state.

A variety of procedures is used to report tsunami data. Four possible measures, used to describe the height of tsunamis as determined by instrumental data, are: (1) the absolute height of wave crests above current stage of the tide; (2) the absolute range of the wave (wave height) from trough; (3) the amplitude which is the absolute range divided by two; and (4) the relative height above a certain datum which require knowledge of the tide's stage at the time of reading. Most tide station reports use either (1) or (2) (U. S. Department of Commerce, 1970, pp. 20-21). However, a tsunami's amplitude also is frequently referred to in more general discussions. The term "runup height" is also commonly used, referring to the elevation above the tide level (at the time of the tsunami) reached by the waves as they inundate the land.

2. Types of Damage Typically Incurred in Tsunamis

Both movable property and fixed property can be submerged, broken or carried away, depending on the magnitude and dynamic action of the tsunami and the location, size, and construction of the property. Movable property refers to large ships as well as smaller vessels, railroad rolling stock, road vehicles, aircraft, and the contents of buildings. It is possible for such objects, from furniture to locomotives, to be washed further inland or out into the ocean. Fixed property includes docks, buildings, bridges, fuel storage tanks, hangars, runways, and so forth. Debris created or picked up by the tsunami action causes damage to other property also, and becomes part of the material to be cleared out of the affected area. A tsunami may also result in soil erosion and sedimentation.

Though electric and phone lines are the more vulnerable, it is possible that underground utilities such as sewer and water facilities could be affected. Waterfront fires may also erupt, especially where tank farms for the storage of fuel are located in the area of runup. If the fuel leaks out and spreads over the water, widespread fires may be caused.

Boats located in deep water outside a harbor will not usually be affected by the incoming waves, but boats which are docked are liable to suffer severe damage by pounding against each other or against the docks. They may become unmoored and be washed inland or capsized.

The economy of a coastal area which depends on water-supported activities, whether shipping, fishing, water transportation or recreation, may be greatly disrupted by a tsunami. This will be particularly true for towns which are virtually isolated except for access by water, as in some coastal areas of Alaska.

Tsunamis may disrupt the ecological balance along the shore and in coastal waters. To the extent that a local economy depends on the organisms that are destroyed or greatly affected, further hardship can be created for an area's commercial base or recreational appeal (Committee on the Alaska Earthquake, 1971; OEP, 1972, Volume 3).

## Incidence and Affected Population

### 1. Areas-at-Risk

Tsunamis are a relatively rare phenomenon, especially outside the Pacific area. Although there have been authenticated tsunamis in the Atlantic and Indian Oceans, these are rare and often only local disturbances. One of the most destructive tsunamis in history, however, was associated with the Lisbon earthquake of 1755. Others of great magnitude have occurred in the Bay of Bengal, the Caribbean Sea, and the Mediterranean. Disastrous tsunamis, the origins of which were associated with earthquakes, struck Puerto Rico in 1918 (earthquake in Mona Passage) and the eastern coast of Canada in 1929 (Grand Banks earthquake). In spite of these exceptions, it can be said that tsunamis are generally confined to the Pacific basin. They occur in most cases in connection with earthquakes along the Pacific littoral. One source, however, suggests that the Atlantic should not be ignored in the process of monitoring possible tsunamigenic seismic activity, pointing out that an unexpected tsunami hitting the Atlantic coast on a sunny summer day could result in enormous loss of life (Garb and Eng, 1969, p. 242).

Although no estimate has been made of the number of potentially endangered persons in each country bordering the Pacific, it can be noted that many thousands of miles of coastline in the United States, Canada, Mexico, Central and South American, Japan, Kamchatka, the Philippines, and scattered Pacific Islands, are exposed to the danger (OEP, 1972, Volume 3, p. 106). The map of epicenters of tsunami-generating earthquakes, 1900-1969, reflects this vulnerability (see Figure IV-1).

Early records of devastating tsunamis include descriptions of the tsunami caused by the Krakatoa volcano explosion in 1883, which drowned some 36,000 persons in Java and Sumatra, and the tsunami associated with the Sanriku earthquake of 1896, which contributed to the loss of 27,000 lives in Japan.

In Japan about 150 tsunamis resulting in damage are known to have occurred since the 7th century. There are also a recorded 27 tsunamis which occurred in remote areas of the Japanese coastline since the 16th century (Nakano, 1972). Especially strong tsunamis were recorded in what is now the USSR in 1737, 1780, 1898, 1918, 1923, 1953, and 1963 (Gerasimov and Zvonkova, 1972). Much of the area of Kamchatka that is tsunami-prone is not populated, however, reducing the amount of significant damage by tsunamis on the USSR Pacific coastline.

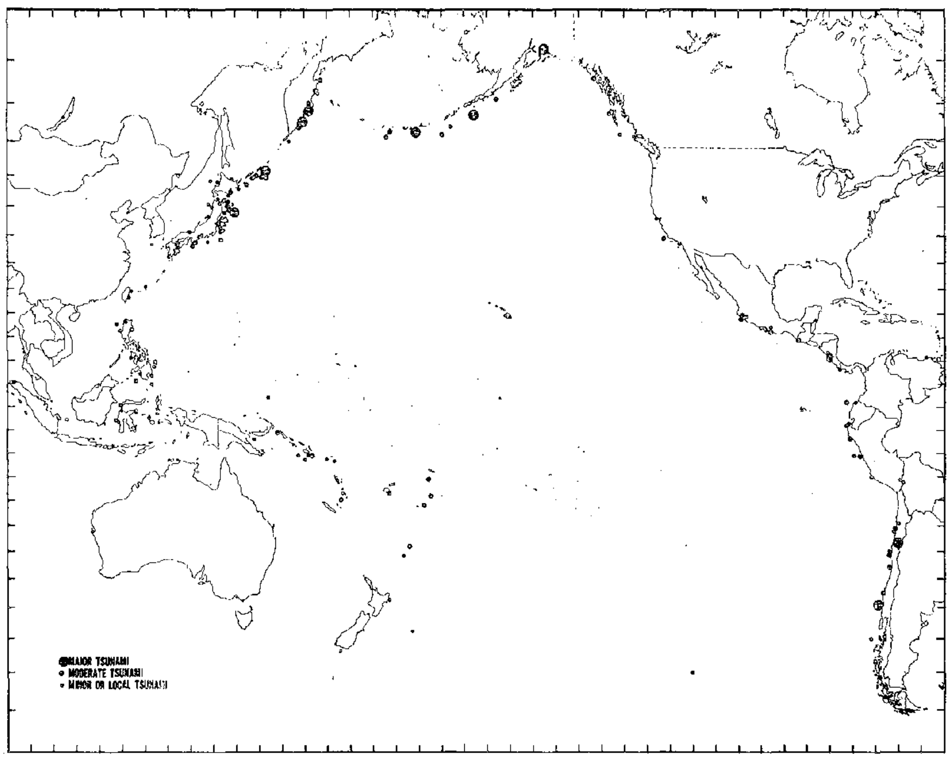
The figures (see Table IV-1) for principal tsunamis during historic times in Hawaii indicate that six tsunamis since 1819 have caused severe damage. Tsunamis of local origin in Hawaii are rare. According to one source, there have been two in the last 150 years; another source (Pararas-Carayannis, 1969, p. 2) indicates the number may have been at least four. Only one of these was significantly destructive.

Since 1900 in the Pacific area, at least 181 tsunamis have been recorded according to one source (OEP, 1972, Volume 3). Thirty-four of these were destructive only locally, and nine were destructive both locally and distantly.

The exact number is debatable. A second source (Iida, *et al.*, 1967) considers doubtful 6 of the minor tsunamis tabulated but adds 57 tsunamis in the period 1900 to 1967. Most of the additions are minor, but they include 4 local, separately generated, destructive tsunamis associated with the 1964 Alaskan

FIGURE IV-1

EPICENTERS OF TSUNAMI-GENERATING EARTHQUAKES, 1900-1969




(Office of Emergency Preparedness, 1972, Volume 3, p. 104)

TABLE IV-1

PRINCIPAL TSUNAMIS DURING HISTORIC TIME IN HAWAII:
CLASSIFIED BY SOURCE

| Source | Total Number | Number of Tsunamis Striking Hawaii: Damage Done in Hawaii — Unknown | None | Small | Moderate | Severe | Dates of Severe Damage |
|---|---|---|---|---|---|---|---|
| South America | 7[1] | | 1 | 1 | 1 | 4 | 1837, 1868, 1877, 1960 |
| Kamchatka | 6 | | 3 | 2 | 1 | | |
| Aleutian Islands | 3 | | 1 | 1 | | 1 | 1946 |
| Alaska | 2 [5] | | 2 | | | | |
| Japan | 4[1] | | 3 | 1 | | | |
| Hawaii | 2 | | | 1 | | 1 | 1868 |
| Mexico | 1 | | 1 | | | | |
| California | 1 | | 1 | | | | |
| East Indies | 1 | | | 1 | | | |
| Solomon Islands | 1 | | 1 | | | | |
| Unknown | 3 | 1 | 2 | | | | |
| Totals | 31 | 1 | 15 | 7 | 2 | 6 | |

[1]Source questionable in one case each. (Based on Macdonald & Abbott, 1970, p. 261)

earthquake that was responsible also for a major Pacific-wide tsunami (Cox, 1974).

Figure IV-1 is a map of the epicenters of the tsunami-associated earthquakes. The map should be interpreted with care; it shows the locations of local destruction by the tsunamis may be inferred, but the locations of distant destruction cannot.

If the 31 tsunamis striking Hawaii during historic time are grouped according to location of source, as in Table IV-1, one can draw tentative conclusions, within the limits of historic information, regarding the sources of tsunamis which reach Hawaii. Of the six tsunamis since 1819 which have resulted in severe damage, four had sources near South America, one in the Aleutians and one locally in the Hawaiian Islands. The two most recent tsunamis to result in severe damage in Hawaii had sources in the Aleutians (1946) and near South America (Chile, 1960). In terms of number of tsunamis, without regard to damage, seven had sources near South America, five in the Aleutians and Alaska, six in Kamchatka and four in Japan. The sample is small, but the results suggest source locations of particular interest to a tsunami warning system for Hawaii.

2. Population-at-Risk

Though history demonstrates that even a single tsunami potentially can affect tens of thousands of persons and billions of dollars worth of property, the United States has thus far been spared a disaster of such magnitude. In the past seventy years, as represented in Table IV-2, the United States and associated islands have experienced four tsunamis with major loss of life (nearly 400 deaths). Another three resulted in minimal loss of life, but over $1 million each in damages. This record does not mean that greater tsunami losses could not be sustained by the United States in the future. It is in the infrequency of occurrence that lies the greatest danger to human life, since evacuation is more difficult to accomplish if it is an unfamiliar procedure.

The information contained in Table IV-3 was developed by the National Oceanic and Atmospheric Administration. The purpose was to quantify the number of persons in the five states listed who might benefit from improved tsunami warning services in the long run. The probability is extremely small that a single tsunami event would endanger 600,000 to 1,100,000 persons. Tsunamis are not considered extremely hazardous to the population on San Francisco Bay, but they could cause considerable damage to shipping and shore facilities there.

Taking a more detailed look at the United States experience, it is seen that the tsunami associated with the major earthquake in the Aleutians in 1946 left 173 dead in Hawaii and resulted in about $25 million in damages (see Table IV-2). The most destructive tsunami of recent history was that generated on the coast of Chile in 1960. Although it killed some 2,000 persons and resulted in $550 million in damages* (U. S. Department of Commerce, 1969, p. I-6 & 7), only 61 of these deaths and $25 million of the damages were in the United States (see Table IV-2). The 1964 earthquake in Alaska was accompanied by the most costly tsunami, being responsible for over $100 million in damages in Alaska, California, Hawaii, Oregon, and Washington, and for the loss of 119 lives.

*It is not known what fractions of the losses in Chile were attributable directly to the accompanying earthquake.

TABLE IV-2

CASUALTIES AND DAMAGE IN THE UNITED STATES FROM TSUNAMIS, 1900-1971

| Year | Dead | Injured | Estimated Damage ($000) | Constant $ 1957-59=100 ($000) | Area |
|---|---|---|---|---|---|
| 1906 | — | — | 5 | 15 | Hawaii |
| 1917 | — | — | 3 | | American Samoa |
| 1918 | — | — | 100 | 140 | Hawaii |
| 1918 | 40 | — | 250 | 350 | Puerto Rico [1] |
| 1922 | — | — | 50 | 95 | Hawaii, California, American Samoa |
| 1923 | 1 | — | 4,000 | 72,860 | Hawaii |
| 1933 | — | — | 200 | 560 | Hawaii |
| 1946 | 173 | 163 | 25,000 | 38,000 | Hawaii, Alaska, West Coast |
| 1952 | — | — | 1,200 | 1,200 | Midway Island, Hawaii |
| 1957 | — | — | 4,000 | 4,000 | Hawaii, West Coast |
| 1960 | 61 | 282 | 25,500 | 25,000 | Hawaii, West Coast, American Samoa |
| 1964 | 122[2] | 200 | 104,000 | 103,000 | Alaska, West Coast, Hawaii |
| 1965 | — | — | 10 | 10 | Alaska |

[1]Another source shows 116 dead and $4,000,000 damage, but these larger figures may include deaths and damage directly attributable to the nearby accompanying earthquake.

[2]Later estimated to be 119 (see Table IV-4).

[3]Damage reported, but no estimates available.

TABLE IV-3

U.S. POPULATION POTENTIALLY ENDANGERED BY PACIFIC TSUNAMIS

| State | Total State Population[a] | Towns & Cities Susceptible to Tsunamis[b] | Total Population of Susceptible Cities[c] | Population Endangered[d] by a | |
|---|---|---|---|---|---|
| | | | | 50' Tsunami | 100' Tsunami |
| Washington | 3,352,892 | 102 | 1,040,000 | 66,200 | 139,600 |
| Oregon | 2,056,171 | 60 | 67,900 | 22,500 | 39,400 |
| California | 19,715,490 | 152[e] | 5,748,800 | 389,500 | 713,000 |
| Hawaii | 768,561 | 123 | 511,500 | 89,400 | 214,500 |
| Alaska | 294,607 | 52 | 82,400 | 22,700 | 35,200 |
| TOTALS | 26,187,721 | 489 | 8,050,600 | 590,300 | 1,141,700 |

[a]1970 Census.
[b]All or part of the city or town is within 100 feet above sea level and close to the shoreline.
[c]From estimates of the 1970 population.
[d]Population factored per study of topographic maps.
[e]Not including urban areas on San Francisco Bay, because they are not considered vulnerable.

(Office of Emergency Preparedness, 1972, Volume 3)

The coasts of California, Washington, and Oregon apparently have had very infrequent occurrences of damaging tsunamis, with Crescent City, California, in 1964, being the major exception. This does not imply, however, that the coast is not vulnerable. In 1964 the west coast of Canada experienced the effects of the tsunami generated in Alaska (White, 1966). Although no lives were lost, severe damage occurred, particularly in Alberni Inlet, British Columbia.

The definition of tsunami hazard areas is necessary for the estimation of future losses, and for the consideration of adjustments, including warning and evacuation plans, land use management, building codes and insurance. A standard for such definition should ideally be accurate, clear, simple and widely acceptable. Obvious difficulties in establishing such a standard are posed by the rare occurrence of tsunamis, the great variation in coastal topography, both offshore and onshore, and the problems associated with the prediction of wave height. For steeply sloping onshore topography it would appear reasonable to define hazard areas in terms of elevation, but for gently sloping topography a definition in terms of horizontal distance inland seems to be called for.

A standard widely used is as follows:

> Tentative standards for hazard areas on Pacific coasts define the potential danger areas as those within one mile of the coast that are lower than 50 feet above sea level for tsunamis of distant origin and lower than 100 feet above sea level for tsunamis of local origin (OEP, 1972, Volume 3, p. 103).

The referenced report refers to the above definition as an "internationally accepted standard." It points out that, "This approach is much too broad but must be used in the absence of more definitive knowledge" (OEP, 1972, Volume 3, p. 91). It is not clear whether the definition refers to a base of mean sea level or to some measure of high tide; one assumes that it should refer to high tide.

Historical evidence indicates that, at least in Hawaii, the hazard zones established in accordance with the above standard would include many areas in which there is quite negligible risk. A standard more realistically combining the potential runup height and potential distance of inland inundation of tsunamis of distant origin has been developed there for use in the warning system.

The population-at-risk depends on the density of the population in the tsunami hazard areas. Since the ocean is a major source of income for millions of people around the Pacific, and the basis of much trade and transportation, it can be expected that many areas along coastlines will be inhabited, frequently densely. Thus, a severe tsunami can endanger the lives of thousands of persons--many thousands, if it affects an extensive length of coastline--and can jeopardize the economy of a town, or even a state, as was the case with the Alaska earthquake of 1964. Table IV-3 shows the endangered population-at-risk within the hazard zones established by the simple standard below the 50- and 100-foot levels for the five Pacific states.

The actual runup height and inundation distance of any one tsunami at a particular location will depend not only on the characteristics of the tsunami (such as its mid-ocean height, period, and direction of approach) and on the coastal configuration, but also on the tide stage at the time of tsunami arrival and the height of storm waves at that time. The number of actually endangered persons in the hazard zone may depend significantly on such variables as the time of day, day of the week, and season of the year.

## Adjustments to the Hazard

The word "adjustment", as used here, is *not* meant to imply complete avoidance of risk. Some degree of risk must be acceptable, for economic reasons. Furthermore, because of the infrequent occurrence of tsunamis, information regarding their possible impact locations and runup heights is very scanty, and it must be assumed that no reasonable action can take into account all possible risk. For some locations the decision might be to make no preventive adjustment whatever.

The economic benefit gained by locating transport and commercial facilities on the shoreline, and the aesthetic pleasure of living by the sea will undoubtedly continue to contribute to the increase in the densities of population and structures in the tsunami hazard zone. Adjustments to reduce the hazard include engineering works, land use management, community preparedness, warning and evacuation systems, insurance, and relief and rehabilitation. These are discussed in the following pages in varying detail. Some of the adjustments are appropriate to other natural hazards and are treated in other reports of Assessment of Research on Natural Hazards (White, *et al.*, [1975]; Brinkmann, *et al.*, [1975] ). However, one of the adjustments, namely the warning system, has characteristics peculiar to the tsunami hazard and is discussed here in detail.

1. Engineering Works and Land Use Management

While many structures and roads and much human activity in a coastal community could be located and conducted in areas safe from tsunami threat, there are some business and recreational activities that simply cannot be conducted elsewhere. Other activities may not be economically feasible if conducted only in areas well out of the tsunami danger area. A quick visual survey of coastal communities, however, would reveal little concentrated effort in most to keep even unnecessary structures away from the waterfront.

Engineering and zoning solutions include some degree of avoidance of the potential high water, protection from it, or some degree of built-in resistance to the forces of the water. Examples of these solutions follow.

(1) Suitable structural design

(a) Construction of breakwaters and sea walls or the establishment of forests along the shores affording protection to areas lying inland

(b) Design of docks and shore facilities with an improved capability to withstand or divert the wave forces

(c) Design of buildings to allow for damage to lower floors without jeopardizing the entire structure

(d) The use of flood-proofing techniques

(e) Provision of emergency cut-offs in oil pipelines and other utilities to prevent widespread leakage of flammable materials and consequent spread of fire

(2) Selective zoning

(a) Location of storage tanks for combustible or contaminating materials out of the hazard area

(b) Location of land and air transportation terminals out of the hazard area

(c) Location of facilities where people usually gather in large numbers (schools, hospitals, public buildings, emergency control centers) outside the hazard area

(d) More general prohibition in the hazard area of residential and business construction not directly related to waterfront activities

Possible engineering adjustments have been discussed extensively by Wilson (Committee on the Alaska Earthquake, 1972). Zoning adjustments have apparently not been widely utilized. However, Hawaii County has included in its general plan a tsunami zone in which there are special restrictions on land use, and special engineering design standards (to be developed) will be applied. The Federal Coastal Zone Act may stimulate the extension of tsunami zoning.

There is apparently some variation in opinion regarding the effectiveness of engineering protection works. It has not been demonstrated that tsunamis, particularly large ones, can be modified in a realistic way. Breakwaters and other works justified on the basis of storm surge and normal wave action might be of value with small tsunamis, but it is doubtful that they can be made effective, or economically justifiable, in the case of major tsunamis.

2. Warning and Evacuation

The association of most tsunamis with earthquakes makes it possible to warn of the approach of a tsunami, and to evacuate persons and easily movable property from the hazard zone. Warning systems for locally generated tsunamis based on the felt motion of earthquakes were first instituted in Japan some centuries ago (Cox, 1964). The development of seismographs permitted the institution of warning systems for tsunamis of distant origin. Using seismological information alone, the Hawaiian Volcano Observatory engaged in issuing warnings of tsunamis in the 1920's, and did, on a few occasions, save some property from damage. However, the correlation between warnings and tsunamis of significance in Hawaii was very low and the system was discontinued in the 1940's.

Only a small fraction of even fairly strong submarine or coastal earthquakes are accompanied by tsunamis of significant magnitude. For example, Disaster Preparedness (OEP, 1972, Volume 1, p. 91) states, with respect to the Pacific Ocean basin, "Only one out of 15 earthquakes (7%) with the potential for tsunami generation actually produces the great waves." The same report lists 181 earthquakes which were accompanied by the generation of Pacific tsunamis in the period 1900-1970. Of these tsunamis, 43 (24%) were designated as having been destructive

The monograph Earthquake Engineering Research (National Academy of Sciences, 1969, p. 237) reports that "Earthquakes of (Richter) magnitude 6.5 or greater are sometimes accompanied by tsunamis." This estimate apparently was based on studies by K. Iida (1963). On the basis of the above bits of information, assuming their bases are compatible, one might propose the following tentative conclusion: About 7% of Pacific basin submarine earthquakes which have Richter magnitude 6.5 or greater may be accompanied by tsunamis of appreciable destructive power, and of these tsunamis about 25% may actually result in destruction. The combination of these percentages results in the very rough estimate of 2%.

Because so small a fraction of the earthquakes that might potentially be associated with tsunamis are actually associated with significant tsunamis, an effective warning system should at least discriminate against earthquakes with which no tsunami waves are associated. The present Pacific Tsunami Warning System* does this by requiring confirmation of wave generation before issuing warnings for use on coasts distant from areas of wave generation.

a. Pacific Tsunami Warning System

What was originally designated the Seismic Sea Wave Warning System was instituted in 1948 following the extensive damage and loss of life in Hawaii caused by the tsunami generated in the Aleutian Islands in 1946. Now called the Pacific Tsunami Warning System, it has linkages with Japan and the USSR, in which there are regional warning systems, as well as with certain other Pacific nations.

The system is headquartered at the Honolulu Observatory. Reporting seismographic and marigraphic stations are shown in Figure IV-2. When an earthquake has been recorded that, from information at the Honolulu Observatory or contributing stations, might be associated with tsunami generation, appropriate marigraphic stations are queried to determine whether tsunami waves are observed at times determined from the earthquake time and epicentral location and the travel times are calculated to each marigraphic station on the basis of ocean depths.

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*The U. S. Coast and Geodetic Survey started the tsunami warning service. It is now operated by the National Weather Service of the National Oceanic and Atmospheric Administration (NOAA).

Figure IV-2 shows, for example, tsunami travel times to Honolulu from various parts of the Pacific. If a tsunami is detected a warning is issued. Quantitative estimation of expected tsunami wave height is still not possible.

In this system a "tsunami watch" is a message from the Honolulu Observatory or Palmer Observatory in Alaska that an earthquake which *could cause* a tsunami has occurred in the Pacific Basin. A "tsunami warning" consists of information from the Honolulu Observatory that an earthquake has occurred and that a tsunami *is* spreading across the Pacific Ocean, together with the estimated times of arrival at various places. The Honolulu Observatory also issues the "cancellation" of the watch or warning when this is determined to be appropriate.

As already noted, the number of tsunamis in the Pacific that are actually destructive is a small fraction of those that are generated and detectable. The fraction of those that are destructive in any particular coastal area is still smaller. From the time of the establishment of the Seismic Sea Wave Warning System in 1948 through 1967, Cox (1968) found that out of 276 principal earthquakes, only 54 or possibly 60 were associated with detectable tsunamis. Only 18 of these tsunamis are reported to have been destructive (OEP, 1972, Volume 3) and, of these, only those of 1952 from Kamchatka, 1957 from the Aleutians, and 1960 from Chile resulted in any significant damage in Hawaii. (Eighteen tsunami warnings were issued during the period.) No tsunamis of significance at coasts distant from areas of generation were overlooked by the warning system, but three warnings were issued when it appeared later no tsunami had been generated and one when the tsunami is questionable.

The findings suggested efforts to reduce the number of false alarms and to analyze the risk from a particular tsunami, not for Pacific coasts in general, but region by region (Cox, 1968; Cox and Stewart, 1972). Experience since 1968 suggests that such regional evaluation is being made (Cox, 1974).

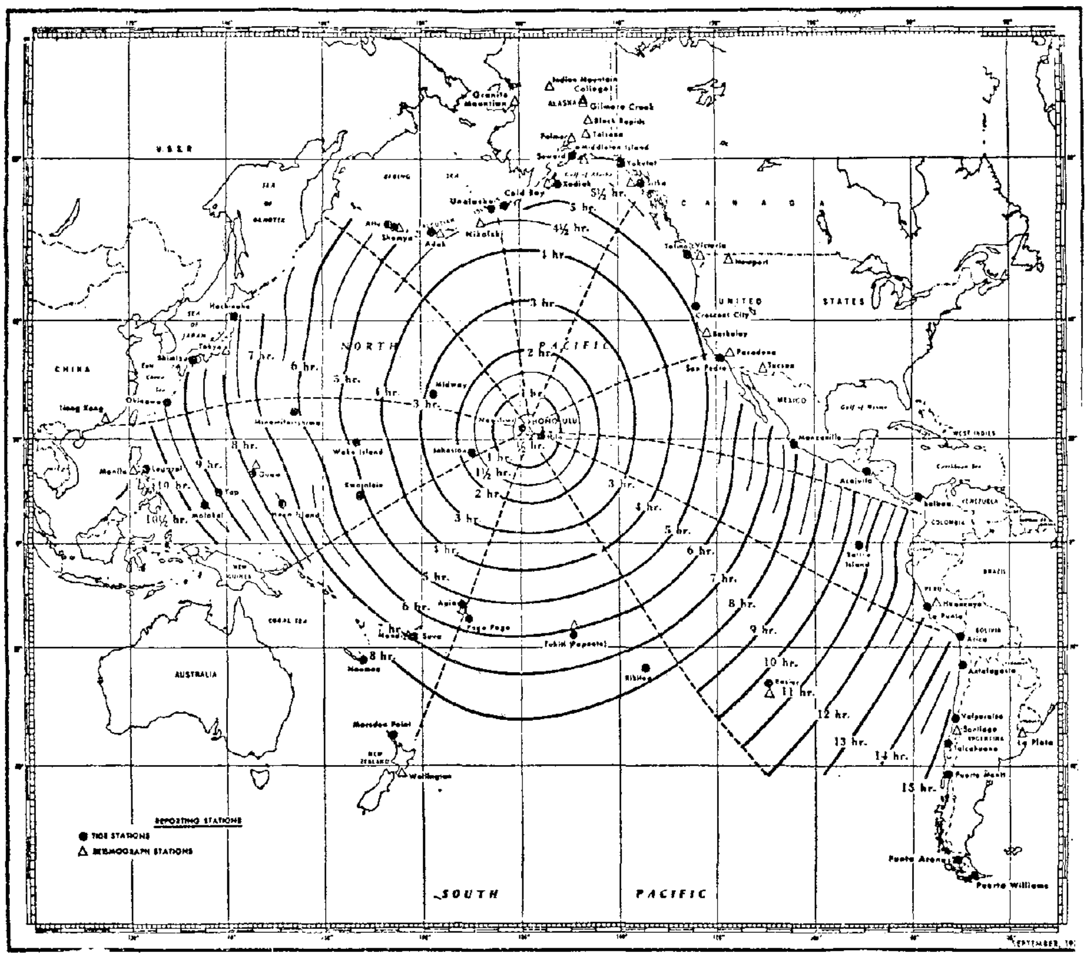
The development of the Pacific Tsunami Warning System can be cited as an example of effective action, involving international cooperation, in the field of hazard management.

b. Regional Warning Systems

For coasts in or close to the generating area of a tsunami, the rapidity with which the arrival of the waves follows the occurrence

FIGURE IV-2

TSUNAMI WARNING SYSTEM, SHOWING REPORTING STATIONS AND TSUNAMI TRAVEL TIMES TO HONOLULU




(Office of Emergency Preparedness, 1972, Volume 1, p. 92) of the earthquake precludes the confirmation of wave generation prior to the issuance of effective warnings. Warnings must be issued on the basis of earthquake magnitude and location alone. Japan has long had a national system of regional warning systems to cope with local and moderate distance tsunamis. A similar system has been established more recently in the USSR. It is through these systems that information is passed to and from the Pacific Tsunami Warning System.

The devastation caused by locally generated tsunamis accompanying the Alaska earthquake of 1964, as well as by the major tsunami associated with that earthquake, led to the institution of the Alaska Regional Tsunami Warning System in 1967. This system is intended to detect, locate, and calculate the magnitude of earthquakes in that region as quickly as possible, and to issue tsunami watch and warning messages through the use of initial seismic data. The time required to secure verifying marigraphic data is too great to permit timely warning of communities near the epicenter, so their warnings are based on seismic data only. As data from the tide gauges become available, the decision can be made on the need to alert towns and cities more distant from the epicenter. Determination of the need for watch and warning messages to Alaska for tsunamis of distant origin remains the responsibility of Honolulu Observatory (Haas and Trainer, 1973, pp. 1-2). A similar but less formalized regional warning system has recently been established in Hawaii.

c. Message Dissemination at the Local Level

For most tsunamis, a large part of the threatened population will be so distributed geographically that the travel time of the waves makes it possible for them to utilize a warning message if it is sent from the warning center promptly and received by the occupants of the hazard area. However, there are always problems in transmitting messages.

In the United States, tsunami watch and warning messages are transmitted by the Honolulu Observatory (now operated by the National Weather Service) to state Civil Defense agencies which forward them to local officials who disseminate the warnings to the population at risk. In Hawaii, for example, warnings are passed to the public directly by radio and television and indirectly through county Civil Defense agencies which utilize siren systems in coastal communities, wardens, and county police for dissemination to the public. Radio, television, telephone, siren signals, loudspeakers on automobiles and aircraft, and individual contacts are all utilized.

Certain stipulations apply to the effectiveness of any message from the warning center: (1) it must be relayed promptly at each relay point; (2) the essential information must not be altered and insertion of misleading information must not be permitted; (3) the message or signal must contain all information necessary, when coupled with information readily available to the recipients, to permit rapid, rational decisions; (4) the ultimate recipients must be motivated to take appropriate timely action; (5) there must be safe areas that the ultimate recipients can reach in time; and (6) the ultimate recipients must be motivated not to re-enter hazardous areas until the hazard is passed (modified from Haas and Trainer, 1973).

If any one or more of these conditions is absent, the intended objective of the warning system will not be achieved. There are many links in this effective warning chain, each link is of the same importance. The total or partial absence of any link precludes the successful completion of any effective warning. It is obvious from the above listing that a tsunami message alone cannot save lives and property. At a minimum, local officials must designate in advance safe areas and fail-safe arrangements for quick dissemination, by signal or message, of the critical information. The resident must know in advance what to do, when and where to go. A very large part of the responsibility rests at the local level. As a major type of adjustment possible in the case of tsunamis, even a superbly designed and functioning regional detection and warning system cannot insure against all casualties and unnecessary damage.

d. Utility and Limitations

The primary intent of the warning systems is to induce occupants of the area threatened by a tsunami to evacuate. They may be able incidentally to save some readily movable property, notably vehicles which they use to escape the threatened area. Attempts to remove much movable property that would unduly delay evacuation should be discouraged. Further, the warning systems are not intended to provide any protection to fixed property.

Some cautions concerning the effectiveness of warning systems in reducing the hazard to people deserve comment. The effects of over-warning in reducing public confidence in the systems has been noted in several investigations (Yutzy, 1964; Anderson, 1967; Cox, 1968; Cox and Stewart, 1972). The effects may be expected to be more serious where the occurrence of actually destructive tsunamis is rare than where disasters are common. Further, with long intervals between tsunamis, the retention of information on the significance of warnings and appropriate warning response may be decreased. Along the coasts of Japan where earthquakes are common and tsunamis not so infrequent, appropriate response to tsunami warnings is to be expected. Hawaii's experience with tsunamis of distant origin apparently leads to effective operation of the warning system. Where the occurrence of significant tsunamis is much less common, as along the coast of Alaska, less effective operation can be expected (Cox and Stewart, 1972).

A further limitation to the utility of warning systems lies in an inability to issue warnings sufficiently rapidly to be of value in the immediate areas of tsunami generation (local tsunamis) even if issuance of warnings is not deferred pending confirmation of wave generation.

With respect to the speed of tsunami onset following an earthquake, Haas and Trainer (1973) have developed the following event typology (p. 3).

TABLE IV-4

TSUNAMI SPEED OF ONSET, PHYSICAL CUES, EVACUATION TIME AND PREVENTIVE MEASURES

| Speed of Onset Types | Physical Cues | Approximate Time For Evacuation | Preventive Action |
|---|---|---|---|
| I | yes (?) | Less than minute | Be very quick or dead |
| II | yes | 5-10 minutes | Persons who are ambulatory can be evacuated plus a few valuables |
| III | yes | 15-30 minutes | A few persons can be evacuated |
| IV | no | 45 min.-12 hrs. | Most persons can be evacuated and up to 75% of all "movable" property |

Type I is illustrated by the events on March 27, 1964, in Valdez, Alaska. The water action and collapsing docks occurred almost simultaneously with the earthquake. No type of warning can assist in this situation.

In Type II the strong earthquake motion can be felt by local residents for perhaps 30 seconds to several minutes. This occurs when a large earthquake has a nearby epicenter. These physical cues are adequate as a warning device if properly interpreted. Infants, the elderly, those who cannot walk, and persons trying to assist them may not evacuate low-lying areas in time. Quick, decisive action by skilled local officials might add to prompt evacuation. The sounding of sirens and broadcast of specific warning messages might also assist, but these very seldom can be ordered in such a short time period. The level of death and injury in the community is dependent almost solely on the quick and appropriate response of individuals and the leaders of small groups, e.g., supervisor of a work crew. No regional detection and warning system can significantly alter the vulnerability of a community to a Type II tsunami event (Norton and Haas, 1970) because the tsunami waves, if generated, will arrive in five to ten minutes.

Type III refers to a community where clearly noticeable, but not large earth shocks are felt for up to a few minutes. The epicenter of the earthquake is sufficiently far away that the tsunami follows the felt earthquake by 15 to 30 minutes. Here the temblors may act as an *alert* to the populace to check with responsible officials on the possibility of tsunami action. Much time will be consumed by extra cautious individuals attempting confirmation of a probable tsunami. The temblors cannot, however, serve as a *warning* cue as is the situation in Type II because earth motion of this type is a common experience for local residents. Where the physical cues serve as an alert, and authoritative word is disseminated that evacuation should take place, there is a question whether there is enough time for most persons to be evacuated. Evidence suggests that the time constraints (15 to 30 minutes) are such that most persons *will not* be evacuated. Even under the best of circumstances it takes at least 20 to 25 minutes for the regional warning center to locate the earthquake epicenter and magnitude, send an appropriate message, and have it received and disseminated at the local level. This leaves very little time for even the most alert local officials to assure that evacuation takes place, or for alert residents to go to safe areas of their own volition.

A community faced with a Type III event is in almost as much peril as it is during a Type I event. There is relatively little that a regional detection and warning system can do to reduce the losses. Time is the critical factor; therefore, conscientious local officials and alert citizens can take only a few steps which can realistically reduce the level of loss a bit. A good rule of thumb is this: if earth temblors are felt for more than 30 seconds, immediate evacuation is in order. This covers both Type II and III.

In a Type IV event the community is almost totally dependent on some type of external tsunami detection and warning system. There are no natural cues from the earthquake itself because of the distance of its epicenter. Usually any cues such as unusual water movement come too late to be of much value. Thus, the functioning of the detection and warning center is crucial. In many instances, depending on the time limitations, the center can issue first a watch and then a warning message. Where onset time is short, e.g., where the time between the generation and arrival of the tsunami is between 30 and 60 minutes, any significant delay in the movement of messages from the warning center through intermediate points to the local community means that the community, in effect, has no warning. If the messages are timely, understood, and acted upon promptly most persons can move to safe areas, and for long onset occasions most valuables and up to 50 to 75% of readily movable property can be moved provided there is an adequate program of community preparedness.

It should be clear that variation in potential evacuation time, and the character of natural cues which may or may not be present means that almost every coastal community (in Alaska, if not the entire U. S. west coast and Hawaii) faces a complete range of possible tsunami events varying from Type I through Type IV. (The probability may in some cases, of course, be very low.) It should also be clear that if any community relies only on a regional detection and warning system, its citizens do not have adequate protection from the tsunami hazard. Citizen knowledge of how to interpret natural cues, where safe areas are located, how best to get there, and, above all, how fast to evacuate, are also critical. Local organization to assure that rapid evacuation takes place and that persons do not return until the danger is past is equally important.

For certain tsunami events, especially Types II and III, citizen knowledge of natural cues and safe areas is critical. Significant protection against Types I and III tsunami events is essentially unattainable (unless Type III is treated as Type II). Fortunately, most events fall into Type IV, where a well-planned warning and evacuation system at the local level can be effective if it can be kept operational over the long periods between tsunami warnings. The evidence suggests that intensive short-term public education efforts offer little hope for reducing the potential losses of life and property to tsunamis. Warnings and evacuation processes at the community level are exceedingly complex, as the literature on evacuation under any type of hazardous condition reveals. It may be that in the case of short evacuation periods associated with tsunamis which originate relatively near a community, rapid and complete movement of all persons to safe areas requires forced evacuation, but there are legal limitations to this procedure.

3. Community Preparedness

As already indicated, for a warning system to be effective, the warning messages or signals must contain all of the information necessary to permit rapid, rational decisions, and the recipients must be motivated to take appropriate action. Such signals as siren sounds cannot convey much information, and even radio broadcasts cannot contain all of the information needed to determine the range of rational actions throughout the region warned and pertinent for officials and the public alike. Much information must be in the hands of officials and the public, or be readily accessible to them.

In addition, the public needs to be informed as to the time limitations of warning systems and the need for prompt evacuation from areas of risk on the basis of earthquake intensity and duration alone.

There is, then, much that a community can do (1) to develop a perception of the tsunami hazard and its extent, (2) to prepare its members to take appropriate measures to protect themselves from a possible tsunami if a large earthquake is felt, (3) to prepare its officials and the general public to make intelligent use of warnings from regional and general systems, as well as (4) to discern the possibilities of property protection by engineering and zoning approaches and of property loss adjustment by insurance.

Experience itself is, of course, a valuable, though costly, teacher, but the lessons do not seem to carry far beyond those most immediately involved.

An indicator of the possible degree to which tsunami perception exists in a coastal community which has not had a noticeable tsunami in recorded history is the findings from Sitka, Alaska, which experienced a local earthquake of 7.3 Richter magnitude on July 30, 1972, with an epicenter 30 miles offshore. Sixty-one percent of the respondents reported that they immediately thought of the possibility of a tsunami upon feeling the earthquake; however, very few acted with sufficient alacrity. Using the time at which the respondent said he began evacuation, location at time of the earthquake, and topographic maps, it is estimated that about 85% of those in low-lying areas (below 15 feet above mean sea level) would have been killed or injured (Haas and Trainer, 1973, p. 15) had a tsunami been associated with the earthquake.

Frequent mass education efforts to remind the populace, and to introduce new inhabitants, to the potential hazard and the clues to its impending occurrence, may save lives. Incorporating into the school curriculum information on the hazard and measures to be taken to protect life and property, is likely to be more effective.

A pilot study conducted in Alaska makes one less than optimistic as to the effectiveness of mass education programs. The study was conducted in 1969-71 in four Alaska towns to determine to what extent residents did perceive the tsunami hazard, and to ascertain what kind of public education program would produce the desired level of knowledge about what to do among the residents of an endangered town. Residents of four towns were interviewed to indicate the level of knowledge about tsunamis among the population. A different type of public education program was then conducted in each of three of the towns, with the fourth town being used as a control community. The residents were again interviewed some 18 weeks after the education efforts had been completed. None of the programs appeared to have resulted in any significant change in what residents know about tsunamis or the warning system, in how reliable they felt the warning system was, nor in their expressed intended behavior in response to a tsunami warning. The personal contact approach and the mass media approach were found to be associated with significant increases in the respondent's perceptions of the severity of the local tsunami threat, however. The evidence, somewhat discouraging in nature, is that short-term public education efforts, even intense ones dealing with matters of high salience, do not have a measurable lasting effect (Haas and Trainer, 1973).

A similar study in Hawaii where continuing efforts in the schools are stimulated by the general awareness of the hazard of tsunamis engendered by the history of Hawaiian tsunami disasters might lead to more optimistic conclusions.

Rapid warning of the people is very critical. Procedures for providing early warning can be incorporated into local agencies responsible for community safety and welfare. This entails detailing such things as:

(1) A specific person responsible for making the decision to put a local warning and evacuation procedure into effect, and specified replacement for that person;

(2) Specific procedures for notifying the endangered populace of the need to keep track of the possible danger, or of the need to evacuate, including removal of vessels to open water and of other movable property to safe areas;

(3) Procedures for door-to-door contact to assure evacuation when that is indicated; and

(4) Specified and equipped places outside the danger zone to which evacuated persons can go.

The Office of Emergency Preparedness reports that Hawaii, California, and Alaska have tsunami communications plans or procedures which are based on the Federal plan (NOAA, 1971). Such items as evacuation procedures, traffic control, assembly points, mass care, and other emergency operations are left to local governments to detail. However, the Federal plan indicates message formats, and state officials are instructed on procedures, and on whom to contact for information. Local-level plans have not been developed in many tsunami-vulnerable communities. OEP cites Ventura County and parts of Orange County, California, as having excellent plans. Several communities in Hawaii, either from previous experience, or from a combination of theoretical calculations and an experience factor have defined the likely vulnerable areas and established safety zones. In the case of Hawaii, maps indicating inhabited areas of major islands that should be evacuated on receipt of tsunami warnings are printed in the telephone books for each county, together with the meaning of siren warning signals. Reference is made to these maps in the course of warning messages broadcast to the public (OEP, 1972, Volume 1, p. 98).

Lack of interest or information on the part of local officials, especially in smaller communities, may inhibit the prompt and well-specified type of plan which is desirable, as well as the regular up-dating and drills which add to its effectiveness in the actual crisis situation. Furthermore, the relative infrequency of actual damaging tsunamis creates the dilemma of keeping a populace aware of the danger and practiced in risk-reducing behavior, yet at the same time not making them cynical by too frequent false warnings and evacuation procedures.

4. Tsunami Insurance

No tsunami insurance coverage was routinely available in such places as Crescent City, California, in 1960 or 1964; in Hilo, Hawaii, in 1960; or in the tsunami-destroyed Alaskan towns in 1964. However, the National Flood Insurance Act (as amended in 1973) extends Federal flood insurance subsidy provisions to cover tsunami risks (U. S. Congress, 1973; U. S. Department of Housing and Urban Development, 1973). Experience is still inadequate to indicate the utilization that will be made of these revised provisions.

5. Relief and Rehabilitation

The undertaking of immediate post-impact relief measures for tsunamis appears to be similar to that in the case of other disaster situations, for example, flash floods, with an affected local government reacting to the limits of its resources, and then turning to the next level of government for assistance. The Federal government apparently played its usual important relief role in the case of the major tsunami disasters in the United States in 1960 and 1964.

A special point to be taken into account by public officials and medical personnel in the immediate aftermath of a wave, is that there are always several waves associated with one tsunami and they may be many minutes or even hours apart. Furthermore, the largest waves may arrive late in the series. Strong efforts, therefore, should be made to keep residents, curiosity seekers, and relief personnel from entering low-lying areas until assurance of an all-clear situation is received.

All levels of the government may also be involved in the longer-term rehabilitation programs. In Hawaii, for example, state financial assistance was provided to those who suffered heavy property losses from the 1960 tsunami. The Federal role in rehabilitation was especially heavy in Alaska following the 1964 disaster.

It is especially reasonable and timely to institute feasible protective measures for the future at a time when major rehabilitation is needed by a community due to the damaging impact of a tsunami. At the time of the 1960 tsunami, planning for an urban renewal project in

Hilo, Hawaii had nearly been completed. As a result of the disastrous effects of the waves in that city, the plans were revised so as to set aside as permanent open space much of the waterfront area in which buildings had been destroyed. Though adequate documentation is not available, it appears doubtful that the long-term adjustment would have been accomplished except for the temporal coincidence of the disaster and the urban renewal planning process.

An example of the increasing concern for protective measures to reduce future cost of rehabilitation is found in Hawaii's Plan for Emergency Preparedness. In the section, "Disaster Protective Measures," the concept is mentioned that,

> Indirect responsibilities would include such actions as introducing legislation or promulgating rules and regulations designed to establish flood plain zones and shoreline setback, building codes relating to earthquakes, tsunami and hurricane resistant structures, and stability of building sites. . . . (Hawaii Department of Defense, 1971, p. A-1).

6. Combinations of Adjustments*

Because the adjustments discussed may be combined, the interactions among the various adjustments need examination. For example, because warning systems are effective primarily in reducing the hazard to people rather than property, engineering adjustments affording protection to property may effectively be combined with them. Seawalls may effectively protect both people and property if they are not overtopped and do not fail. However, the risk of failure cannot be overlooked, and a seawall overtopped might conceivably result in higher runup than would have occurred if the wall did not exist.

Breakwaters also may reduce the height of waves in the areas behind them, but by resonance they may increase wave height, and the estimation of the particular effects is difficult and somewhat uncertain.

Multi-story buildings so designed as to resist the force of the waves may provide safety not only for those who occupy the upper stories but those who move to them on the basis of warnings. Hence the presence of such buildings offers clear advantages in the evacuation of persons from the ground level particularly in densely populated areas.

Such engineering adjustments as breakwaters and seawalls might

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*This section based on Cox (1974).

logically affect tsunami hazard insurance premiums in affected areas, with the same qualifications as in the case of the engineering adjustment interactions with warning systems. We doubt that there is any provision for premium discrimination based on protective works because, so far as we know, there are no breakwaters or seawalls in the United States built specifically for tsunami protection.

Tsunami warning systems are, in general, ineffective in providing protection to property. Hence, there is no reason for the adjustment of property insurance premiums for insurance of property against tsunamis on the basis of tsunami warning system effectiveness.

Tsunami hazards are so small compared with all the other hazards to which people are exposed, and people move so readily in and out of tsunami hazard areas, that adjustment of life and medical insurance premiums for the degree of exposure to tsunami risk does not seem practical.

Restrictive land use zoning would reduce the need for tsunami insurance more surely than would engineering protective measures, such as breakwaters and seawalls. Zoning, however, could not rationally result in the reduction of premiums for insurance for such structures as might be present in the hazard zone. However, flood-proofing and tsunami-resistant design might logically be appropriate bases for premium reduction.

Zoning is clearly advantageous in setting the limits to areas in which special engineering design is desirable or should be required. And zoning of a sort is an essential in the warning system to indicate what areas merit evacuation and in an insurance system to indicate where there is a tsunami hazard, and would be further advantageous in indicating the degree of risk and hence the appropriate premium rate.

The availability of an insurance system may tend to encourage resistance to the development of restrictive land use zoning. It is too early to determine the extent to which this will be true.

The need for relief and reconstruction measures will be reduced by effective engineering, land use zoning, warning, and insurance adjustments. However, the expectation that the government will provide relief and rehabilitation assistance may tend to reduce the adoption of engineering, land use zoning, and insurance adjustments, but there are no data available that could be used to check whether this tendency is significant.

## Role of the Federal Government

Besides its extensive involvement in relief and rehabilitation following tsunami disasters, the Federal government provides the major portion of the instrumentation and personnel utilized in the Pacific Tsunami Warning System and in the Alaska Regional Tsunami Warning System. It has also offered guidelines for community preparedness.

It is likely that the major portion of research to be carried on in the future with respect to acquiring precision in predicting a tsunami, and speeding up the warning process, will be funded by Federal agencies.

## Costs and Benefits of the Hazard

Data on how much dollar damage has resulted from past major tsunamis in the United States is available (see Table IV-2). The extent to which double counting is a problem is not clear. It appears that there is a greater problem with respect to costs of earthquakes, where the figures do not appear to include or exclude consistently tsunami damages in cases where both types of damage occurred in the United States for a particular earthquake-tsunami event.

Communities could feasibly benefit from deciding, after a tsunami devastation, to utilize the majority of the beach area as open space, and keep as much of the commercial facilities as possible further back, or concentrated in one area. This would have to be weighed against the extra costs incurred by the commercial facilities. Likewise, there are such unquantifiable dimensions as the benefits--including aesthetic benefits--of living by the sea, weighed against possible loss of property, and maybe loss of life, but with the latter possibly having a very low probability. It is necessary, furthermore, to consider the costs of special structural adjustments for commercial structures (docks, transfer sheds, etc.) which must be located in vulnerable, exposed areas. In connection with any of these considerations it is desirable to estimate the probabilities of occurrence of tsunamis of various runup heights. Such estimates for various areas have been made by Wiegel (1969).

Another point that is sometimes made is that the earthquake-tsunami disaster in Alaska may have resulted in certain long-term benefits to specific industries and facilities (Committee on the Alaska Earthquake, 1970, pp. 58-76). Furthermore, a city that has a significant part of it rebuilt after a disaster is likely to be a better planned city and therefore could be a safer, more usable city.

# CHAPTER V

## FUTURES: SIMULATION AND SCENARIO

### Simulation of Tsunami Loss Management

1. Selection of the Natural Event or Sequence of Events

   a. Statistical Selection

We have not attempted a simulation of tsunami loss management. It would not appear to be fundamentally different in principle from the simulation of loss management for earthquakes or for hurricane storm surge. It could involve considerations from each of those hazards, but it would be different in detail.

Since most destructive tsunamis are generated in connection with earthquakes, some of the considerations in the statistical selection of the generation of the tsunami (magnitude, time of occurrence, location of source), or sequence of separately generated tsunamis would be similar to those in the statistical selection of an earthquake, or sequence of earthquakes. Tsunamis, however, are even more rare than earthquakes; only a small percentage of the generators of earthquakes also result in tsunamis. Furthermore, tsunamis involve the characteristics of speed, travel distance and directionality of the tsunami waves in the open ocean, and the response of the waves to offshore and onshore topography. The number of physical variables is great--whether greater than the number associated with earthquake is debatable.

Whether the statistical selection of the tsunami, or sequence of tsunamis, should start with the generators and proceed from there to the resulting locations of coastal impact, or start with known locations of coastal impact, is a question for consideration. It would seem to be simpler to start with known locations of coastal impact and develop probabilities for magnitude and occurrence based on the past histories of those locations. In either case the history is short and the events are rare.

b. Arbitrary Selection of Historical or Maximum Expected Events

Three relatively simple approaches to the simulation of tsunami impacts at a particular coastal location would be (1) the repetition of the sequence of known impacts at that location, (2) the repetition of the tsunami of greatest magnitude known at the location, and (3) the application of a tsunami of the greatest expected magnitude based on a study of all known tsunami impacts at all coastal locations having topography similar to that of the location being studied.

2. Population and Facilities-at-Risk

The simulation of distribution of population, buildings and other facilities would involve the same general sorts of considerations as for simulating any other hazard, but special considerations in designing the computational model might be similar to those for simulation of the effects of hurricane storm surge.

3. Selection of the Study Area or Areas

a. Macro- and Micro-Studies

Within the limits of the United States the obvious area types for simulation of tsunami loss management for macro-studies are:

(1) the entire coastline, both Atlantic and Pacific;
(2) the entire Pacific coastline;
(3) the coastline of California, Oregon and Washington;
(4) the Pacific coastline of Alaska, including the Aleutian Islands; and
(5) the coastline of the state of Hawaii.

For micro-studies, they are:

(6) limited regions of especially exposed coastline; and
(7) particular locations of great vulnerability based on evaluations of hazard exposure and population-at-risk.

b. Local Topography

Area types (6) and (7) would involve sub-selections regarding topography, for example, on-shore topography which is steeply rising and would result in wave runup to great elevations, or is gently sloping and would lead to runup to considerable distances inland. The physical damage, structural adjustments, land-use zoning, and location of emergency refuge areas would be different in these cases of extreme topography.

4. Warning Time; Locally versus Distantly-Generated Tsunamis

Another consideration in designing the simulatior model is the distance from the tsunami source to the point of impact, which is the most important variable in determining the length of the possible warning time, and consequently has great influence on the type of action possible in warning and evacuation (see Table IV-4). Examples of locally-generated tsunamis which have led to disaster are: Hawaii 1868; Puerto Rico 1918; and Alaska 1964. Examples of distantly-generated tsunamis having severe consequences include: Aleutian Islands (source) to Hawaii (impact) 1946; South America to Hawaii 1837, 1868, 1877 and 1960; and Alaska to Crescent City, California 1964. In order to explore the adjustment of forecast and warning it would be desirable to investigate all four types of situations shown in Table IV-4, or at least Types I, II and IV.

5. Selection of Data-Base Grid Cell Size

The standard latitude-longitude coordinate system is probably the best grid system to use. However, it does not result in an efficient coverage of the narrow, strip-like area of concern along the coastline, because to obtain complete coverage of a given width of strip, substantial parts of a large proportion of the cells will be outside the strip. The overall increase in computational efficiency created by using the latitude-longitude system, however, probably outweighs its disadvantages in this case.

For tsunami loss simulation a maximum unit cell size of one-minute longitude by one-minute latitude (approximately 1.15 miles square at the equator) may be a satisfactory compromise, although for micro-studies a smaller cell size may be justifiable in some cases.

6. Simulating the Adjustments

a. Modification of the Natural Event

There is no known way to modify a tsunami source.

b. Modification of the Human-Use System

The presence or absence of breakwaters and other energy dissipating or diverting devices, wave-resistant construction, the use of flood-proofing techniques, and selective zoning of land use can be entered in the simulation flow network in much the same way as the engineering and land use adjustments are treated in Chapter II of this report, and in the flood (White, *et al.*, 1975) and hurricane reports (Brinkmann, *et al.*, 1975).

Forecasting is available through international and regional tsunami warning networks. The effectiveness with which the warning is received and implemented by the community depends on various characteristics of the warning, the community and the natural event. This should provide one of the most important subjects of investigation in the simulation of the tsunami hazard.

c. Modification of the Loss Distribution

The simulation of the effects of a disaster insurance program, community preparedness, and relief and rehabilitation is difficult for some of the same reasons that simulation of the effectiveness of a warning system is difficult. All of them involve human response and complicated interrelationships with other adjustments.

## Alternative Futures

Should the scenario technique be pursued for tsunamis, there are three pieces of writing which provide examples of (1) narratives of people's responses, (2) dramatic writing for persuasive purposes, and (3) comparative information on separate tsunami events in the same city and in different cities. These examples are not scenarios, but they may prove useful in scenario preparation.

1. Narratives

The introduction to the section on "The Human Response in Selected Communities" for the study of the Alaska earthquake of 1964 describes the various ways in which the information was gathered to provide the narrative account of this widespread disaster. The study committee felt that such an account could "present an overview of the entire complex of events and provide a background for the understanding of the many technical papers in the several volumes of the Committee report", as well as provide a record of at least some of the significant social science data (Committee on the Alaska Earthquake, 1970, pp. 245-399).

The major functions that a community provides its residents are outlined: (1) preservation of life and health; (2) provision of food, clothing, and shelter; (3) socialization; (4) economic activity and legal activity that assists the economic reconstruction; (5) leisure, recreation, and other social activities; (6) utility services; (7) power and authority; and (8) maintenance or restoration of public order (Committee on the Alaska Earthquake, 1970, p. 246). Attempts were made to collect information on events relevant to each function. Information on the economy, demography, ecology, and physical aspects of the communities was also collected for time periods before and after the disaster.

The narrative accounts for the affected communities begin by describing the way each town looked and went about its business. Accompanying the description of the specific physical events of the earthquake and tsunami there is a description of thoughts and actions of specific individuals as they responded to the tremors and waves. Following that is a description of how specific officials and organizations went to work at the business of relief and then rehabilitation.

2. Dramatic Writing

With respect to the example of dramatic writing, the intent of the government publication entitled, Tsunami! (U.S. Department of Commerce, 1965), is to present in an interesting and understandable way the inception and working of the Seismic Sea Wave Warning System (now called the Tsunami Warning System). The booklet incorporates drawings to depict such things as the causal agents of tsunamis, the shoaling effect as the tsunami approaches the shore, buildings and instrumentation associated with the warning system, tsunami travel-time charts for various points around the Pacific, and characteristic scenes from the countries affected, accompanied by factual explanatory text. There are also photographs of destruction caused by tsunamis. The dramatized fictional section of the text attempts to carry the reader through the steps of warning, mobilization, evacuation, and the experience of watching (presumably safely) the impact of the tsunami waves.

3. Comparative Material

For comparative material on real events, the article, "Tsunami Warning in Crescent City, California, and Hilo, Hawaii"

(Anderson, 1970), provides a comparison of these two cities with respect to utilization of information from the warning system, and instrumentation of local plans during successive tsunami alerts.

Both cities received warnings in 1964. Only mild wave action materialized at Hilo, but Crescent City experienced a tsunami in which the fourth wave killed 11 people and damaged 29 blocks.

Hilo officials acted quickly and purposefully in accordance with a written and well-routinized warning and evacuation plan, produced as an aftermath of the destructive tsunami experienced in Hilo in 1960. Crescent City officials, whose experience of the past years had been of a series of false alarms, hesitated. Even though evacuation procedures were soon instrumented, loss of life and unnecessary property damage resulted. Anderson notes, "the evidence indicates that even if Hilo had been subjected to the violent wave action which hit Crescent City there still would have been little or no injury or loss of life due largely to the implementation of warning techniques and procedures which had been conceived beforehand."

The article also describes the receipt of another tsunami warning in 1965 in Crescent City, the response of city officials to it, and of community residents to the officials' actions, and the degree to which protective action was accomplished that time. No wave action occurred, but Anderson concludes that the actions taken would have contributed to lower property losses to waterfront businessmen had the 1964 event been repeated.

The comparisons made between the way in which Hilo established and carried out its local warning and evacuation procedures over successive events, and the similar process for Crescent City indicate specific improvements and changes in organizational behavior, and the relative degree to which further effectiveness is felt by Anderson to have been gained by each city.

# CHAPTER VI

## RESEARCH RECOMMENDATIONS

### Comparison of Losses Due to Earthquakes and Tsunamis

A study of data on historical dollar damage and lives lost due to earthquakes and tsunami disasters in the United States and its possessions, since 1900, results in the following approximate ratios:

$$\frac{\text{earthquake damage}}{\text{tsunami damage}} = 10$$

$$\frac{\text{earthquake deaths}}{\text{tsunami deaths}} = 2.5$$

If the damage ratio were computed using current dollars, the ratio would be larger because of the very great loss which occurred in San Francisco in 1906, and the considerable inflation since that time. About 80% of the damage at San Francisco has been estimated to have been caused by fire, making that a very singular event; nevertheless, the fires were started by the earthquake. The data were arranged as far as possible to avoid including tsunami damage and deaths in the earthquake loss data since some publications do include both in one table.

The ratios above, for the United States, appear to be in the right direction if one considers the lesser frequency of occurrence and the smaller area of vulnerability for tsunamis than for earthquakes.

Research opportunities on adjustments to earthquakes have already been discussed in this report at considerable length; such discussions with respect to flash floods and storm surge, both of which may result in water damage similar in some respects to tsunami wave damage, will be found in the related reports on floods (White, *et al.*, 1975) and hurricanes (Brinkmann, *et al.*, 1975). The general findings of such a study for tsunamis can be expected to show similarities to those for the other hazards mentioned, except in physical and social details, and in suggested extent of funding.

## Research Opportunities

In attempting to assess research opportunities, the effort has been to canvass the full range of possible adjustments, the dynamic factors affecting them, the total benefits and costs to society of the current mix of adjustments, and the likely consequences for society of introducing new information and techniques through research. It is difficult to arrive at a statement which does justice to the very great potential for devastation which a tsunami striking a vulnerable, densely populated coastline can have, and which at the same time places the tsunami hazard in proper perspective with other natural hazards as they affect the United States as a whole. We need to know more about tsunamis and the effects, but their relatively low frequency of occurrence and the relatively low population-at-risk make it difficult to justify large absolute expenditures for research.

### 1. Warning Systems

The tsunami detection and warning dissemination system must be continued. Since the United States taxpayer supports the system, it must be made to pay off in the saving of lives on those rare occasions when it is needed.

It is not now known what incentives are required to insure that vulnerable communities maintain adequate local warning response capability. Information on that question could be gathered by a research effort on the order of ten person years over a five-year period. Ideally such an effort would be part of a more comprehensive study of warning response, as described in the monograph on warning systems in this series (Mileti, 1975a).

### 2. Hazard Mapping

It would be desirable to do some research on mapping tsunami risk zones. Techniques for accomplishing the mapping need to be determined, as do means for disseminating the information on risk at the local level in order for it to be included in land use management and building code decisions. It is estimated that a total of 10-15 person years would be required for such research.

### 3. Tsunami-Resistant Construction

Some research could be justified on tsunami-resistant construction techniques. Additional research of seven person years would contribute to knowledge in this field.

## 4. Summary

It should be recalled that the judgments made here are on research related to tsunamis as a hazard to life and property, they do not attempt to encompass all geophysical research on the hazard.

The recurrence interval for damaging tsunamis in the United States is long and the available history is short and sparse. It therefore seems desirable to make additional historical studies in an effort to fill out a more complete history of tsunami impact. It is suggested that this be done under a study of insurance.

The results of our evaluation are presented in Tables VI-1 and VI-2. Table VI-1 presents estimates for research which are in addition to currently ongoing and planned research.

Since, with one exception, the proposals made are for relatively low levels of activity (equivalent to one or two person years per year or less), it is suggested that the proposals should be grouped in three or four categories. In many cases the research could be combined with research on other hazards.

TABLE VI-1

FUNDING LEVELS FOR RESEARCH OPPORTUNITY SETS

| Research Opportunities | Estimated Current Annual Level[1] | Suggested Total *Additional* Research in Person Years[2] | Suggested Time Horizon for Additional Research, Years |
|---|---|---|---|
| BREAKWATERS AND OTHER PROTECTIVE WORKS: | | | |
| Engineering | 0 | -- | -- |
| Socioeconomic Effects | 0 | -- | -- |
| TSUNAMI-RESISTANT CONSTRUCTION: | | | |
| Analysis, Design and Building Codes | 0 | 5 | 5 |
| Adoption Processes | 0 | 2 | 5 |
| LAND USE MANAGEMENT: | | | |
| Risk Zone Studies | 0 | 10 | 10 |
| Zone Adoption Processes | 0 | 2 | 5 |
| WARNING SYSTEMS: | | | |
| Geophysical and Engineering Aspects | 2 | 10 | 5 |
| Warning Implementation; Socioeconomic Effects | 0 | 10 | 5 |
| INSURANCE: | | | |
| Including Adoption Processes and History of Tsunami Occurrence | 1 | 5 | 5 |
| COMMUNITY PREPAREDNESS, RELIEF AND REHABILITATION: | | | |
| Vulnerability Studies | 0 | 3 | 5 |
| Adoption Processes | 0 | -- | -- |

[1]Very crude estimates based on impressions of level of research activity. It would be difficult to arrive at accurate estimates including unbudgeted as well as budgeted activity.

0 = zero to $10,000
1 = $10,001 to $100,000
2 = $100,001 to $1,000,000
3 = $1,000,001 to $2,000,000
4 = $2,000,001 to $4,000,000

[2]Person year is amount necessary to support one research worker, including staff and travel, for one year; currently $60,000.

TABLE VI-2
RESEARCH OPPORTUNITIES

| Research Opportunity | National Aims | | | | | | | | Research Findings | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Economic Efficiency — Reduction of Net Losses Benefits-Costs | | Enhancement of Human Health — Reduction of Casualties | | Avoidance of Social Disruption | | Environment — Protection or Enhancement | Equity — Distribution of Costs and Benefits | Expected Success of Research | Likelihood of Adoption |
| | Average | Cata-strophic | Average | Cata-strophic | Average | Cata-strophic | | | | |
| Protection Works<br>Engineering<br>Socioeconomic effects | Low-Neg | Low-Neg | Low | Low-Neg | Low | Low-Neg | Low-Neg | NA | Low-Med | Low |
| Tsunami-Resistant Construction<br>Analysis, design, building codes<br>Adoption processes | Low-Neg | Med | Med | Med | Med | Med | NA | NA | High | Low |
| Forecast and Warning<br>Geophysical aspects<br>Detection, dissemination and response | Low | Low | High | High | High | High | NA | Low | Med | Med |
| Land Use Management<br>Risk zoning studies<br>Zoning adoption | Low | Med | Med | Med | Med | Med | High | Low | High | Low |
| Insurance<br>Socioeconomic effects<br>Adoption processes | Med | Low | Low | Low | Med | Med | NA | Med | Med | Low |
| Relief and Rehabilitation<br>Community preparedness<br>Vulnerability studies | Low | Low | Low | Low | Med | Med | NA | High | High | Med |

Med = Medium   Neg = Negative   ? = In doubt   NA = Not applicable

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