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A WORKSHOP ON "EARTHQUAKE HAZARDS IN THE PUGET SOUND, WASHINGTON AREA"

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EDITORS
Walter W. Hays and Paula L. Gori
U.S. Geological Survey
Reston, Virginia 22092

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Carla Kitzmiller

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BACKGROUND AND SUMMARY OF THE WORKSHOP ON EARTHQUAKE HAZARDS IN THE PUGET SOUND, WASHINGTON AREA

by

Walter W. Hays and Paula L. Gori
U.S. Geological Survey
Reston, Virginia 22092

INTRODUCTION

One hundred and two geologists, seismologists, engineers, social scientists, emergency planners, and public officials participated in a 3-day workshop on "Earthquake Hazards in the Puget Sound, Washington Area," held in Seattle, Washington, October 29-31, 1985. The workshop was scheduled to coincide with the establishment of a special task force appointed by the Governor of Washington to consider the formation of a Washington State Seismic Safety Council. The first two days, attended by 85 people, followed an interactive problem-solving format and had a comprehensive scope. This part of the 3-day meeting was cosponsored by the U.S. Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), the Washington State Department of Natural Resources, and the Washington State Department of Emergency Management. The third day of the meeting, attended by 27 people, was a special extension of the workshop which was organized as a meeting of a "working group" of experts on subduction zone earthquakes and earthquake preparedness. Ten of these participants also attended the first two days of the workshop. The meeting of the "working group" was cosponsored by the USGS and the U.S. Nuclear Regulatory Commission (NRC). The goal of the "working group" was to discuss the potential for a great subduction-zone earthquake in the Puget Sound area and to define a research agenda that would resolve two questions in the next 3 to 5 years:

1. Does geologic evidence exist in the Puget Sound area for large prehistoric subduction-zone earthquakes?

2. How can the current pattern of convergence, deformation, and the configuration of the plates be determined?

The Puget Sound workshop was the thirty-third in a series of workshops and conferences that USGS has sponsored since 1977 under the auspices of the National Earthquake Hazards Reduction Program, usually in cooperation with FEMA and one or more other Federal or State agencies and institutions. Each workshop and conference has a general goal of improving mitigation of earthquake hazards by bringing together producers and users of earthquake hazards knowledge to discuss: a) technical issues, b) mitigation issues, and c) ways to resolve them. In addition, each workshop has a specific goal of strengthening the current research and earthquake-hazards-mitigation activities in the State or region. In this workshop, the specific goals were to:

1. Review the results of current research studies in the Puget Sound area.

2. Review the lessons learned from past earthquakes in the Puget Sound area and in other parts of the world that are transferable to the Puget Sound area.

3. Review the body of knowledge accumulated for other subduction zones of the world and discuss the similarities and dissimilarities of the Puget Sound area, in terms of earthquake potential and the nature and extent of earthquake hazards with other subduction zones.

4. Review the status of ongoing earthquake preparedness, education, and planning programs in the Puget Sound area.

5. Recommend a range of achievable actions that are needed in the Puget Sound area to reduce potential losses from earthquake hazards and to accelerate progress in research and implementation of loss-reduction measures in the next 3 to 5 years.

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HISTORICAL SEISMICITY OF THE WASHINGTON AND OREGON REGION

The Washington and Oregon region as a whole is characterized by a low-to-moderate level of seismicity in spite of the active volcanism of the Cascade Range. Table 1 lists the most important earthquakes that have occurred in the region. The three most recent damaging earthquakes were:

1. 1965 Seattle earthquake--This magnitude (M_s) 6.5 earthquake occurred between Tacoma and Seattle on April 29, 1965, with a focal depth of about 59 km (35 mi). It was felt over 337,000 km^2. It caused damage of $12.5 million (actual dollars). Seven people were killed.

2. 1949 Olympia earthquake--This magnitude (M_s) 7.1 earthquake occurred between Olympia and Tacoma on April 13, 1949, with a focal depth of about 70 km (42 mi). It was felt over some 390,000 km^2 and caused damage of $25 million (actual dollars). Nearly all tall buildings in Olympia were damaged. Eight people were killed.

3. 1872 Pacific Northwest earthquake--This December 14, 1872, Pacific Northwest earthquake was felt over a wide region extending from the Pacific Coast to Montana and from British Columbia to central Oregon. Although this earthquake predated instrumental seismology, the available data suggest that it had a shallow depth of focus and an epicentral intensity of about IX on the Modified Mercalli Intensity scale. The precise location of the epicenter is still somewhat controversial.

SEISMICITY IN THE PUGET SOUND, WASHINGTON AREA[1]

Since 1840 nearly 1,000 earthquakes large enough to be felt by residents have occurred in the State of Washington. Many of these caused localized property damage. Some past earthquakes were felt throughout Washington, northern

[1] This section is reprinted with minor editorial changes from Noson, Linda, 1984 "Seismic Summary," Washington Geologic Newsletter, v. 12, no. 2, pp. 2-4.

Oregon, and southern British Columbia. Two of these events, a magnitude 7.1 in Olympia (1949) and a magnitude 6.5 between Tacoma and Seattle (1965), caused damage totaling well in excess of $200 million (1983 dollars), many injuries, and 15 deaths. Seismologists agree that earthquakes comparable to those in 1965 and 1949 will recur in Washington State.

TABLE 1. HISTORICAL SEISMICITY OF THE WASHINGTON AND OREGON REGION

(From Algermissen, S. T., 1983, An introduction to the seismicity of the United States, Earthquake Engineering Research Institute Monograph, El Cerrito, California, 148 p.)

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Dec. 14, 1872	Near Lake Chelan, WA (Probably shallow depth of focus)	IX	(7.0)
Oct. 12, 1877	Cascade Mountains, OR	VIII	
Mar. 7, 1893	Umatilla, OR	VII	
Mar. 17, 1904	About 60 km NW of Seattle	VII	
Jan. 11, 1909	North of Seattle, near Washington/British Columbia	VII	
Dec. 6, 1918	Vancouver Island, B.C.	(VIII)	7.0
Jan. 24, 1920	Straits of Georgia	(VII)	
July 16, 1936	Northern Oregon, near Freewater	VII	(5.7)
Nov. 13, 1939	NW of Olympia (Depth of focus about 40 km)	VII	(5.8)
April 29, 1945	About 50 km SE of Seattle	VII	
Feb. 15, 1946	About 35 km NNE of Tacoma (Depth of focus 40-60 km)	VII	6.3
June 23, 1946	Vancouver Island	(VIII)	7.2
April 13, 1949	Between Olympia and Tacoma (Depth of focus about 70 km)	VIII	7.1
April 29, 1966	Between Tacoma and Seattle (Depth of focus about 59 km)	VIII	6.5

Note: Numbers in parentheses are best estimates.

Recent studies (Heaton and Kanamori, in press; Savage, Lisowski, and Prescott, 1981; Weaver and Smith, 1983) suggest that many more damaging earthquakes than those that have already occurred in the State in historic times are possible. Weaver and Smith discuss recent seismic data from southwestern Washington that outline a 90 km (54 miles) nearly north-south striking crustal earthquake zone. They have interpreted this as a fault capable of generating a moderate- to large-magnitude shallow earthquake. The general tectonic model proposed by Weaver and Smith to explain recent earthquake observations in Puget Sound makes it necessary to consider the possibility of an earthquake comparable to the devastating magnitude (M_s) 8.5 Prince William Sound, Alaska earthquake in 1964. The Alaska earthquake has been assigned a moment magnitude (M_w) of 9.2, the second largest event in this century. Neither a sizable shallow earthquake in southwestern Washington nor a large Alaska-type event have been considered in the current assessment of the earthquake hazards and risk for Washington. The 1964 Alaskan earthquake was a subduction zone earthquake (Figure 1).

On the basis of past earthquake activity, the Applied Technology Council (1978) assigned most of the Olympics, Puget Sound, and the north Cascades a seismic hazard index of 4 on a scale of 1 (lowest) to 4 (highest) in regard to expected levels of ground accelerations and ground velocities. The seismic hazard index is used in the development of seismic regulations for the design of buildings. Even without considering the interpretation of recent seismic data, which suggests the possibility of even larger ground accelerations and ground velocities, most of Washington has been classified as an area of high earthquake risk.

When the possibility of a large damaging earthquake is discussed, most people assume one is talking about California, Alaska, or perhaps Turkey. Those three areas do have a higher recurrence rate for damaging earthquakes than the Puget Sound area. Public awareness of an indigenous earthquake hazard is likewise greater in those areas than in areas such as the Puget Sound where such earthquakes occur less frequently. Consequently, more effort and funding have been devoted to finding ways to reduce the personal and economic effects of future earthquakes in those locations. Unfortunately, in places like Washington State where such earthquakes occur less often, public awareness of the potential dangers and losses from earthquakes is disturbingly low.

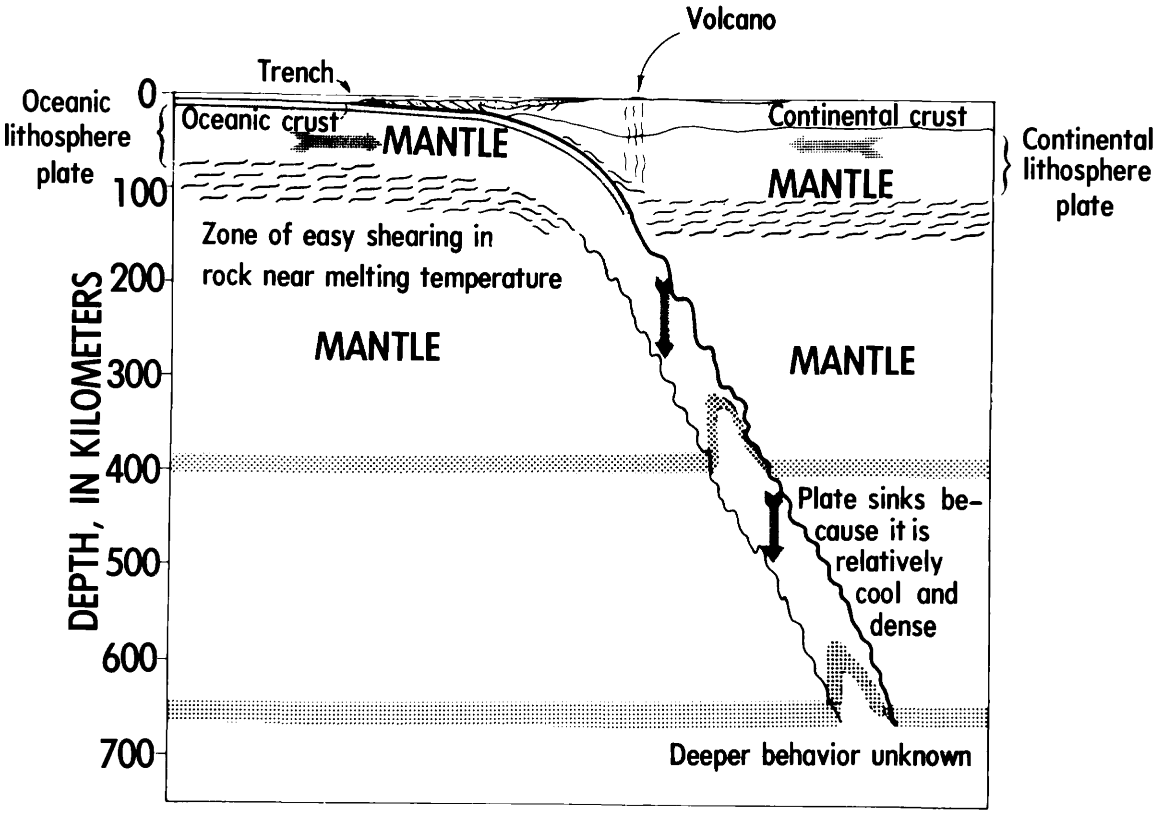

Figure 1.--Schematic illustration of the physical processes taking place in a subduction zone where one tectonic plate is slowly being thrust over another tectonic plate. In the Puget Sound area, the North American plate is being thrust over the Juan de Fuca plate at a rate of approximately 3 cm/yr. Many aspects of this process are still controversial in the Puget Sound area and many technical issues are unresolved, including: 1) the present day rate of convergence, 2) the physical features and seismic coupling of the Juan de Fura and North American plates, 3) the capability of the subduction zone to rupture and produce large to great earthquakes, and 4) the range of magnitudes, recurrence intervals, and physical effects of future potential earthquakes.

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Without awareness, the motivation to act effectively to develop and implement earthquake hazards reduction measures is absent.

The earthquake risk in the State of Washington cannot be restricted to one jurisdiction. Past large earthquakes located deep beneath southern Puget Sound were felt strongly in the State and caused significant damage throughout western Washington. More catastrophic events would similarly affect large areas. The economic impact of severe damage to the major metropolitan areas of the State would adversely affect all State resources. Eastern Washington has had moderate, very shallow earthquakes historically. The shallow depth of eastern Washington earthquakes limits the area somewhat over which damages are high, but increases the degree of damage near the epicenter. Therefore, earthquakes must be seen as a statewide concern.

GROUND-SHAKING HAZARD IN THE PUGET SOUND, WASHINGTON AREA

An earthquake in the Puget Sound area can cause the hazards of ground shaking, ground failure, surface fault rupture, regional tectonic deformation, seiches, and (depending on the hypocentral location) tsunamis (Figure 2). Each of these physical phenomena (hazards) can cause damage, economic losses, loss of life, injuries, loss of function, and loss of confidence.

The ground-shaking hazard usually causes the greatest percentage of damage and losses, although ground failures and tsunamis can also be very devastating. Representations of the ground shaking hazard can be either deterministic or probabilistic (for example, see publications by Ihnen and Hadley, 1984; Algermissen and others, 1982). Each type of representation has its particular value in applications. The probabilistic mode of representation (Figures 3-6) are becoming more common and are now being applied in the development of zoning maps in building codes (for example, the 1978 Applied Technology Council model building code) and in the formulation of design criteria for critical facilities that require large margins of safety.

The most important ground-motion parameters are : 1) amplitude, 2) spectral composition, and 3) duration of shaking. Although some controversy still exists over procedures for defining the ground-shaking hazard in terms of these three

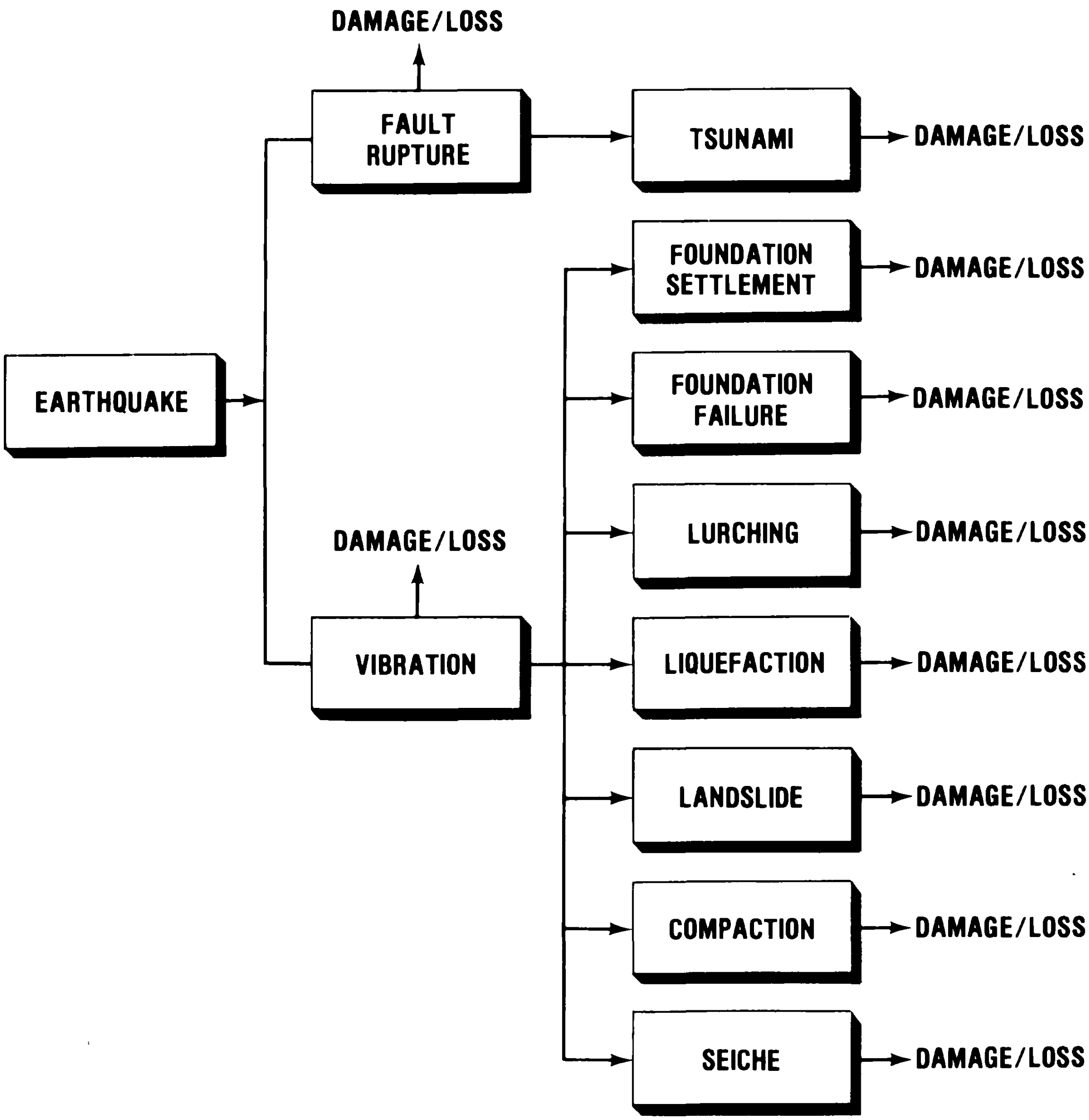

Figure 2.--Schematic illustration of the types of physical phenomena (hazards) that an earthquake in the Puget Sound area can cause. Each phenomenon (hazard) can cause significant damage and losses unless mitigation strategies have been implemented in each urban area.

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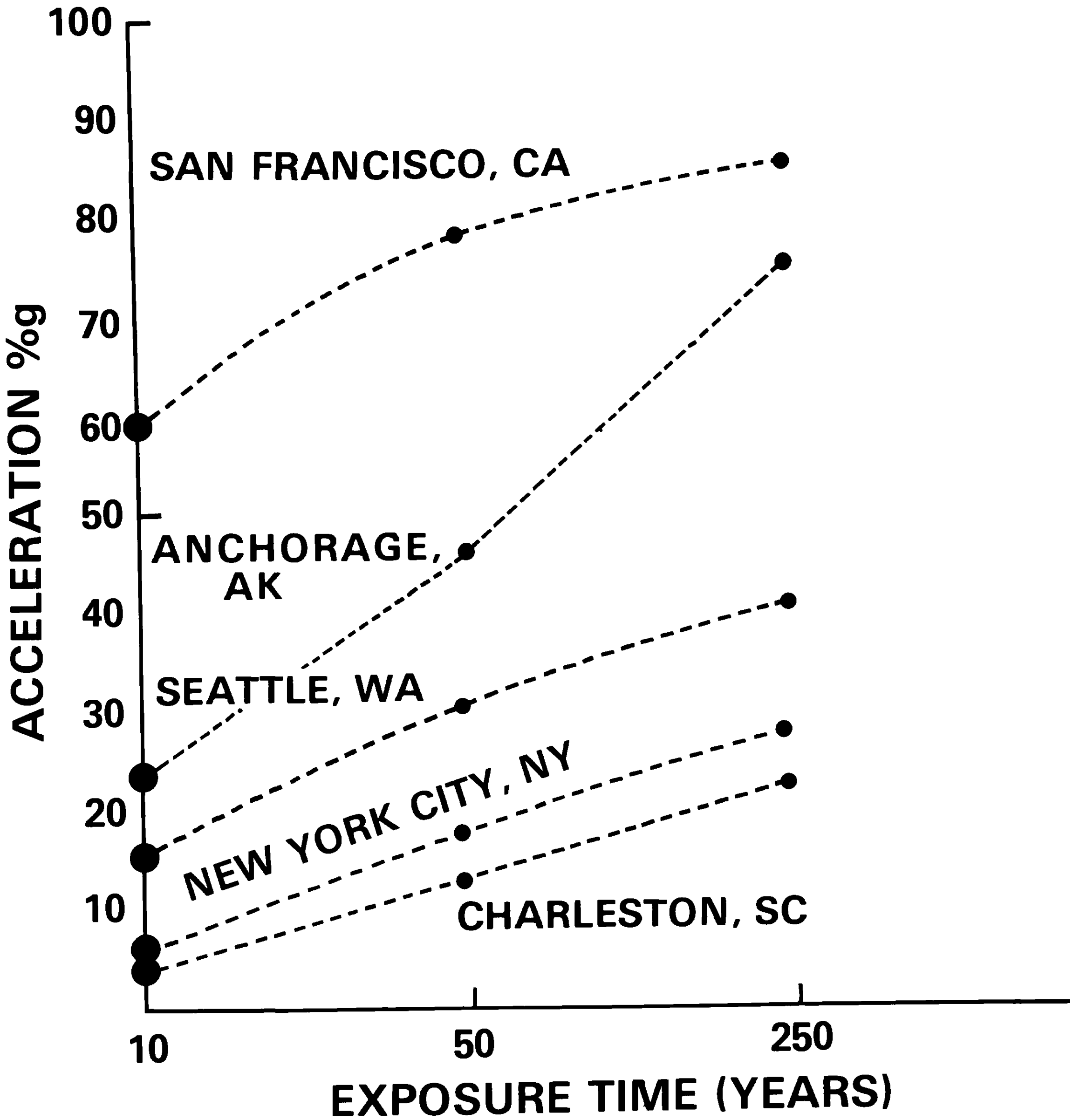

Figure 3.--Comparison of the ground-shaking hazard in terms of peak horizontal bedrock acceleration and exposure time for the Seattle area and several other parts of the United States. The potential amplifying effects of soil must be considered separately. Although some controversy exists over absolute values of peak rock acceleration at a location, the relative values for a given exposure time are stable between locations. (From Algermissen and others, 1982).

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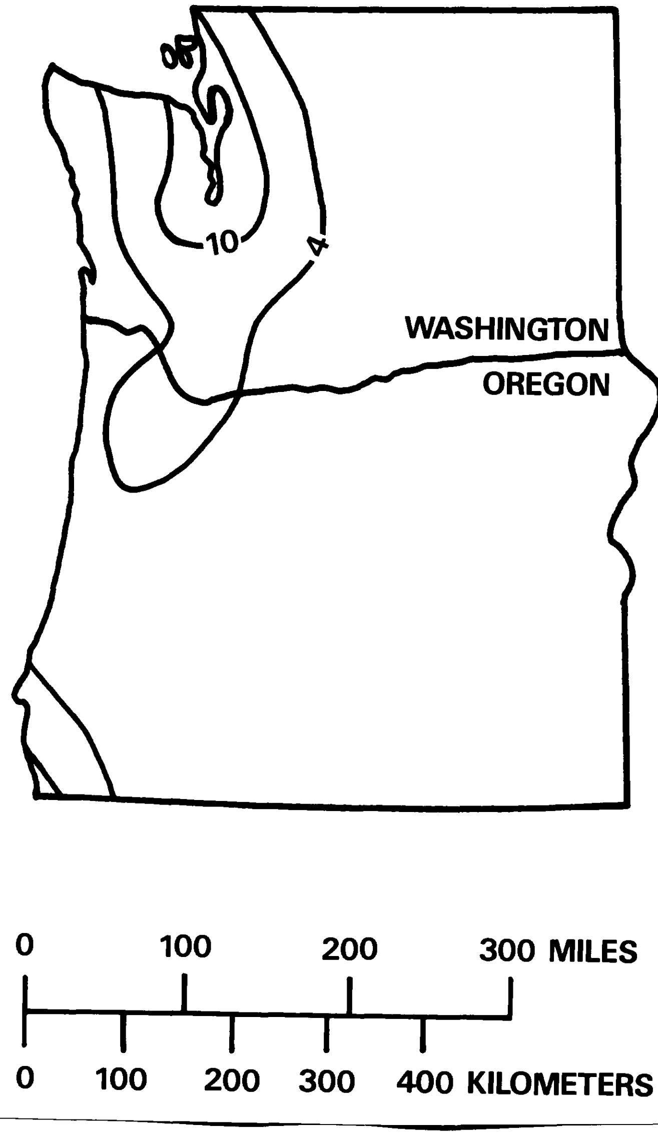

Figure 4.--Map showing the ground-shaking hazard in Washington and Oregon in terms of peak horizontal bedrock acceleration and a 10 year exposure time. The effects of soil must be considered separately. The values of acceleration have a 90 percent probability of nonexceedance (From Algermissen and others, 1982).

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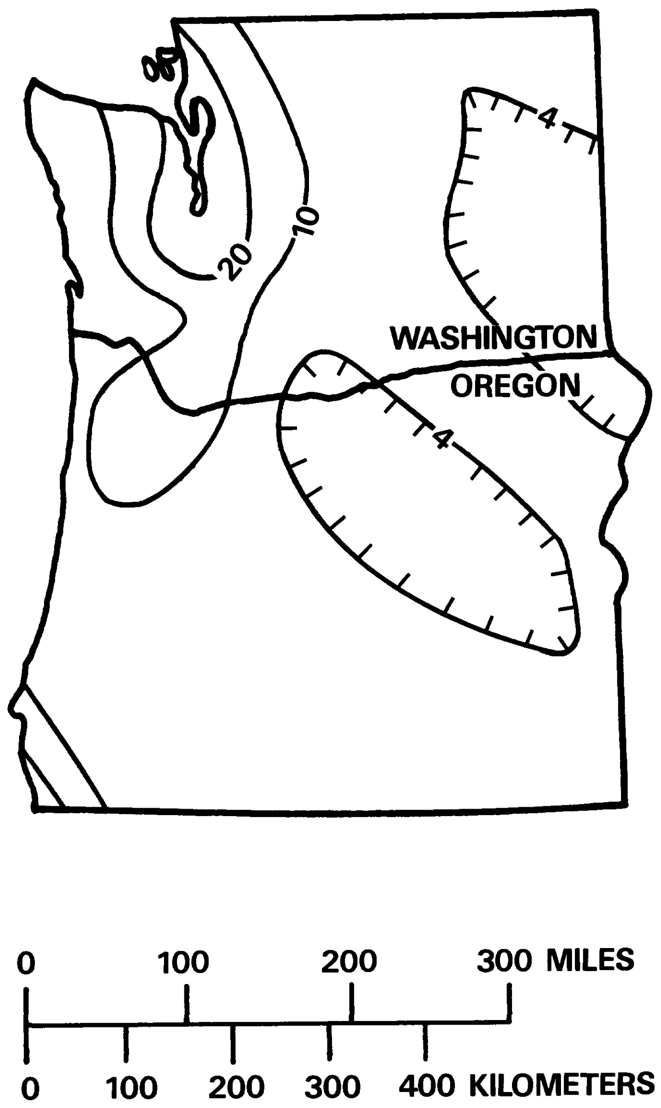

Figure 5.--Map showing the ground-shaking hazard in Washington and Oregon in terms of peak horizontal bedrock acceleration and a 50 year exposure time. The values of acceleration have a 90 percent probability of non-exceedance (From Algermissen and others, 1982). Such a map is typically used in building codes. An ordinary building has a useful life of about 50 years.

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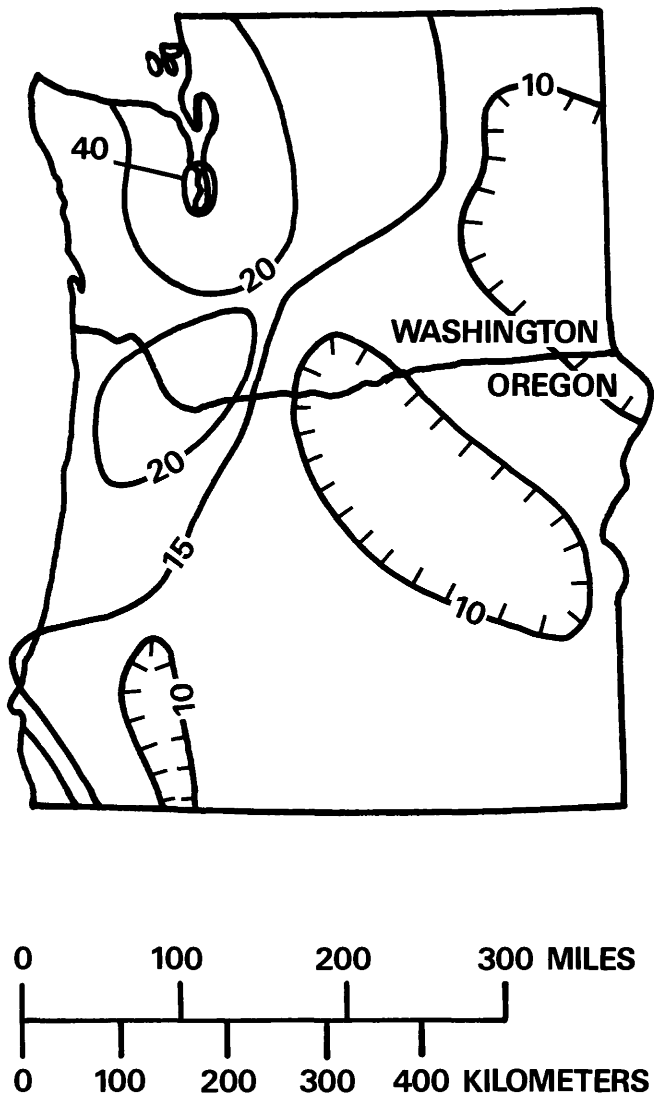

Figure 6.--Map showing ground-shaking hazard in Washington and Oregon in terms of peak horizontal bedrock acceleration and a 250 year exposure time. The values of acceleration have a 90 percent probability of non-exceedance (From Algermissen and others, 1982).

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parameters, the data and the state-of-knowledge has advanced to the point that realistic representations can now be made. The process requires: a) considerable research, b) synthesis of existing data, and c) utilization of new data and understanding gained from damaging earthquakes in areas having analogous tectonic settings. It is illustrated schematically in Figure 7.

THE REGIONAL EARTHQUAKE HAZARDS ASSESSMENTS PROGRAM ELEMENT OF THE NEHRP

Beginning October 1, 1983, the USGS initiated the program element, "Regional Earthquake Hazards Assessments." This element, a part of the National Earthquake Hazards Research Program (NEHRP), was created to develop the basic information and the partnerships needed for evaluating earthquake hazards and assessing the risk in broad geographic regions containing important urban areas and to provide a technical and political basis for devising loss-reduction measures that can be implemented by local governments. The goal is to provide an integrated program having comprehensive research goals and producing generic information that can be used to reduce potential earthquake losses in urban areas. The scientific emphasis is on developing a fundamental physical understanding of the cause, frequency of occurrence, and the physical effects of earthquake ground shaking, surface faulting, ground failure, and tectonic deformation in various geographic regions. This program element requires a high degree of team work, utilizing technical and nontechnical skills, to accomplish the goals of each task. Users of the information produced by this program (for example: agencies of Federal, State, and local governments involved in emergency response, building safety, and planning) cannot find such an integrated synthesis and evaluation of earthquake hazards in the scientific literature. Also, loss estimates have not been updated in most urban areas for many years and the risk may be seriously underestimated due to the sharp increase in building wealth and construction.

The interrelated tasks of the program element are described below:

Task 1: Information Systems - Because each research project produces basic data and information, the goal is to produce a comprehensive information system, available to both internal and external users, designed to give a data base that is as uniform in quality and as complete on a regional and

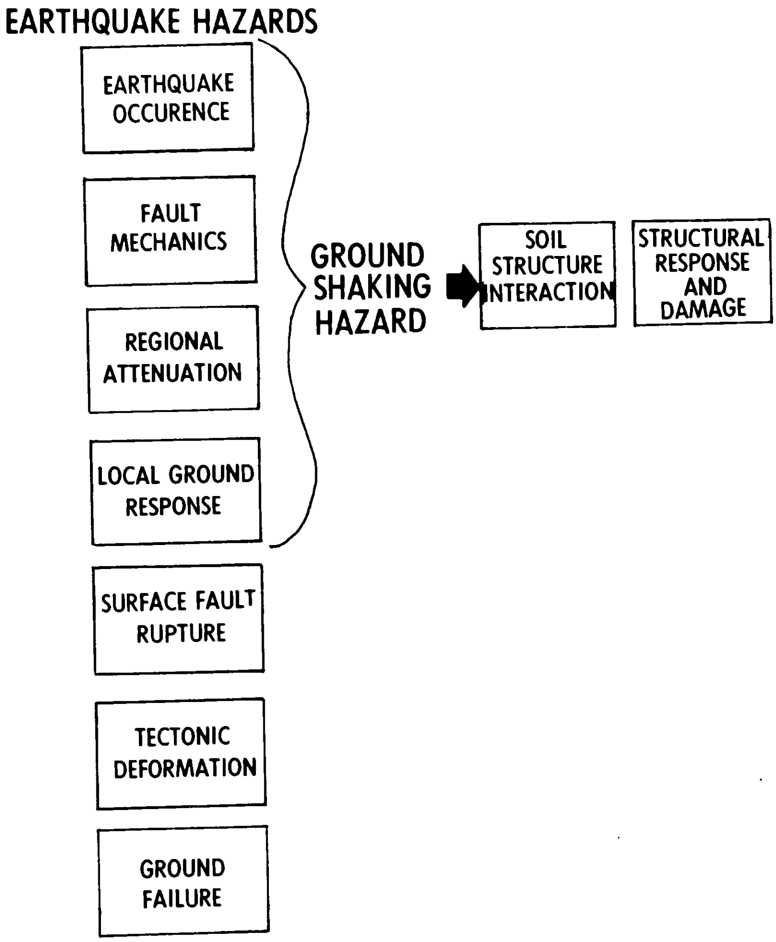

Figure 7.--Schematic illustration of the wide range of topical studies that must be performed to define the ground-shaking hazard in an urban area. The most important physical parameter controlling the amplitude, spectral composition, and duration of the free-field ground shaking at a site include: 1) earthquake occurrence (seismicity, recurrence rates), 2) fault mechanics (seismogenic sources, hypocenter, fault type, fault rupture length), 3) regional attenuation (epicentral distance between the source and recording site, Q), and 4) local ground response (thickness and physical properties of the soil-rock column). Soil-structure interaction, which occurred in the 1985 Mexico earthquake, is an important consideration in earthquake-resistant design.

urban scale as possible. Several categories of data can be identifed, including: seismicity, gravity and magnetics, well logs, seismotectonic data, fault trenching data, stress measurements, seismic reflection profiles, ground failure data, soils data, ground motion data, inventory of structures, damage assessments, bibliographic references, publications, and maps. Because of the potentially large scope of the task, care must be exercised to create a system that is both practical and economical. An initial task is to create a "directory of researchers" for the Puget Sound area.

Task 2: Evaluation and Synthesis of Hazards Information - The goal is to use new and existing data to produce synthesis reports and maps describing the state-of-knowledge about earthquake hazards (ground shaking, surface faulting, earthquake-induced ground failures, and tectonic deformation) in the region and to recommend future research to increase the state-of-knowledge required for the development and implementation of loss-reduction measures. The research will provide a fundamental understanding of the cause, nature, and physical effects of each earthquake hazard. Development of models (hypotheses) and analysis of data are important aspects of this task.

Task 3: Ground Motion Modeling - The goal is to develop deterministic and probabilistic ground motion models and maps. Commentaries will be provided so that others can use the models for generating ground-shaking hazard maps and for evaluating the sensitivity of uncertainty in median values of important physical parameters.

Task 4: Loss Estimation Models - The goal is to devise economical methods of acquiring inventories of structures and developing a standard model for loss estimation. Commentaries on the use of such a model and its limitations will be provided so that others can use it. Loss estimates will be produced for several specific planning scenarios.

Task 5: Implementation - The goal is to foster implementation of loss-reduction measures in urban areas. In an urban area, the severity of an earthquake disaster depends upon three factors: a) the magnitude of the earthquake--the larger the magnitude the greater the potential for damaging levels of ground shaking and other earthquake hazards, b) the location of the earthquake source relative to an urban area--except in special cases such as the 1985 Mexico earthquake, the closer the source of energy release to an urban area, the greater the potential for damage, and c) the degree of earthquake preparedness within the urban area--the smaller the number of loss reduction measures adopted by the local community and the lower the level of preparedness, the greater the potential for a disaster having great loss of life and economic loss.

To increase the state-of-preparedness in an urban area, conferences and workshops will be convened to bring together producers and users of earthquake hazards information. Participants representing business and industry, the private sector, Federal, State, and local government will be involved in the conferences and workshops. Proceedings of the conferences and workshops will be communicated to a wide audience, promulgating the research results and recommending specific actions, based on these research results, that will increase the overall state-of-preparedness.

The external scientific and engineering community are participating in this program element through the USGS' program of grants and contracts. In 1986, the Puget Sound, Washington area was assigned 3rd priority in terms of allocation of external USGS resources, following the Wasatch Front, Utah area (first), and California.

THE 1985 CHILE EARTHQUAKE

Information on the large earthquake (M_s = 7.8) that occurred near Valparaiso, Chile, on March 3, 1985, is included in this report because the experience and information provided by the 1985 Chile earthquake are considered to be very relevant to three regions of the United States: the Puget Sound area, Southern Alaska, Washington, and Puerto Rico. Similar effects as those in the Chile earthquake could happen in each of these three regions. All four regions have a similar tectonic setting, namely a subduction zone where one tectonic plate is sliding at the rate of several inches per year beneath

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another tectonic plate (see Figure 1). The world's greatest earthquakes (e.g., 1960 Chile earthquake (Mw = 9.5) and 1964 Prince William Sound, Alaska, earthquake (Mw = 9.2)) have occurred in subduction zones. The 1960 and 1985 Chile earthquakes were caused by subduction of the Nazca tectonic plate beneath the South American plate. The 1985 Chile earthquake caused 176 deaths, 2500 injuries, and economic losses from architectural and structural damage to buildings and lifelines of about $2 billion. Unreinforced masonry and adobe buildings sustained the greatest damage from ground shaking. Although, well-engineered buildings generally performed well, a hospital suffered extensive damage, indicating the need for stringent earthquake-resistant design criteria for critical facilities and tough inspection standards and enforcement procedures.

THE 1985 MEXICO EARTHQUAKE

A month before the workshop, a great earthquake occurred in Mexico on September 19, 1985. This earthquake was the most devastating earthquake of the past decade in North America. It severely damaged parts of Mexico City, the world's most populated metropolitan area. Because it was also a subduction zone earthquake having potential relevance for Puget Sound, Alaska, and Puerto Rico, its effects are summarized below for completeness.

The great 1985 Mexico earthquake, initially rated as M_s = 7.8 but later upgraded to M_s = 8.1, occurred at a depth of 18 km (11 mi) in the Mexico trench subduction zone where the Cocos tectonic plate is being subducted beneath the North American plate at the rate of about 3 cm/year. The existence of a possible seismic gap in this portion of the Cocos plate and a general forecast of a large earthquake having an average recurrence interval of about 35 years had been made in 1981 by McNally. The exact time of the earthquake had not been specified, however. This earthquake was noteworthy because about 300, 5 to 20 story buildings located in part of Mexico City, (about 250 miles from the epicenter) collapsed partially or totally, causing an estimated 10,000 deaths, numerous injuries, and economic losses of possibly $5 to 10 billion. A quarter million people lost their homes.

Because of prior planning by American and Mexican scientists and engineers, a number of strong motion accelerographs were in place in the epicentral area at the time of the earthquake and recorded ground motions in the order of 0.18 g, a low value for a great earthquake. Both the epicentral region and a part of Mexico City were assigned an intensity of IX on the Modified Mercalli Intensity scale. The extraordinarily high degree of damage at this large epicentral distance according to Rosenbleuth (1986) was mainly due to a double resonance phenomenon (called soil-structure interaction) involving the ground response and the building response. The long period (2 second) ground motion was amplified by the 50-meter thick, water-saturated, ancient lake bed underlying part of Mexico City. The amplified ground motion was amplified again by the 5 to 20 story buildings because the resonant period of the ground was very close to the resonant period of the buildings, especially as damage caused some of the building periods to lengthen. The ground motion had a duration of more than 3 minutes (see Figure 8). The lake beds were recognized in 1964 by Zeevaert as having a characteristic site period of about 2 seconds, the natural period of vibration of a typical 20-story building. Past distant earthquakes (e.g., 1957 and 1962 Mexico earthquakes) had also caused damage in Mexico City that was attributed to site amplification by the lake bed.

A building code including a factor for soil conditions has been adopted and implemented in Mexico City since 1976, but it was not appropriate for the most severe effects of this great earthquake in the lake bed zone. However, buildings built after 1976 performed better than those built before 1976. In the 1985 earthquake, six buildings collapsed at the Mexico General Hospital; about 400 doctors, nurses, and patients were trapped in the ruins of the Juarez hospital, just 8 blocks from the Presidential Palace. Government buildings, as a group, sustained considerable damage. Long distance telecommunications with the rest of the world were interrupted for several days after the earthquake due to the destruction of the main microwave transmitter and the lack of a redundant, backup system.

The strong motion data, from the Mexico earthquake, together with the data acquired in the March 3, 1985, Chile earthquake, provide an unprecedented strong-ground motion data sample for subduction zone earthquakes recorded near the source.

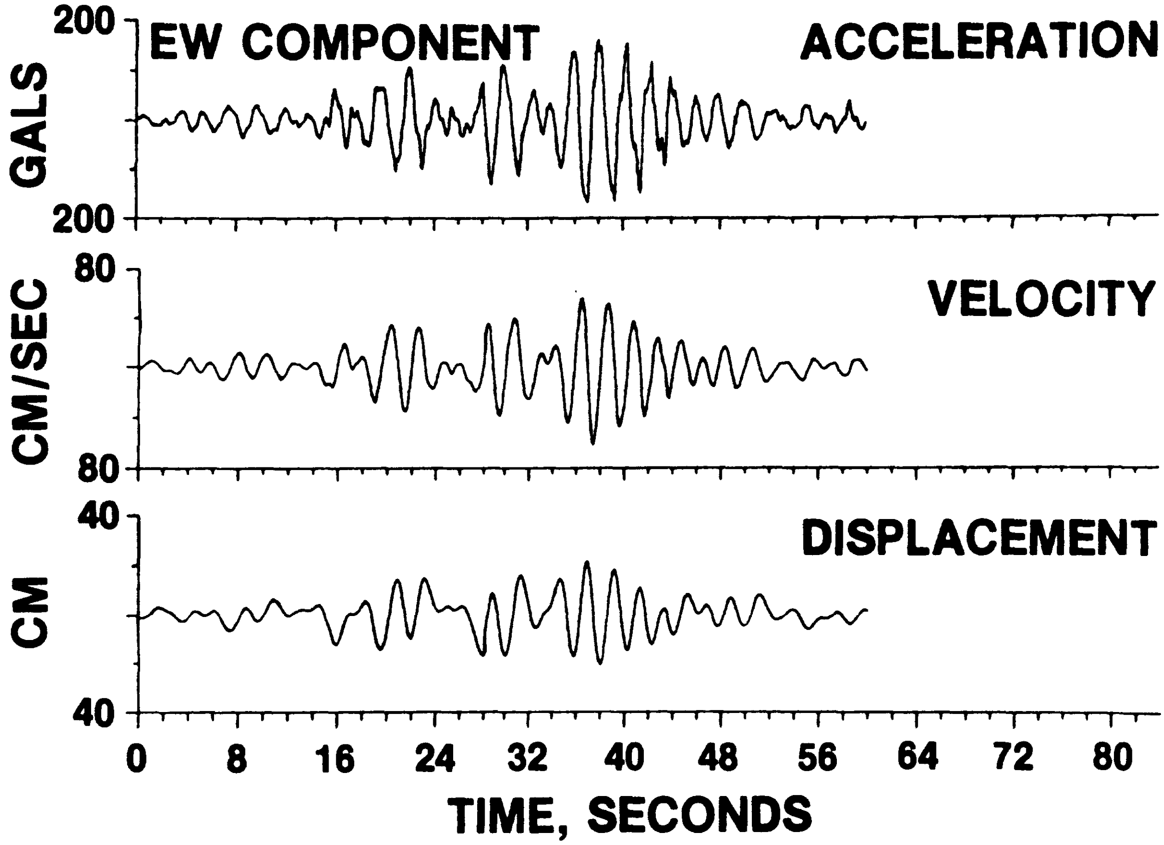

Figure 8.--Accelerogram (top) recorded in a free field location on the surface of the 50-meter-thick lake bed forming the foundation in parts of Mexico City. The epicenter of the September 19, 1985 Mexico earthquake was located some 250 miles to the west. The strong 2 second period energy in the acceleration, velocity (middle) and displacement (bottom) time histories are a consequence of the filtering effects of the lake bed which has a resonant period of about 2 seconds. The ground motion was amplified about a factor of five relative to adjacent sites underlain by firmer rock-like materials. The approximate coincidence of the dominant period of ground shaking with the fundamental period of vibration of the 5-20 story buildings located in the lake bed zone contributed to their partial and total collapse. These records were provided by the Universidad Nacional Autonoma de Mexico.

ASSESSMENT OF EARTHQUAKE HAZARDS AND POTENTIAL RISK

A schematic illustration of the total range of the subject that must be considered in order to assess potential risk and to foster implementation of loss-reduction measures is shown in Figure 9. The assessment of the potential risk (chance of loss) in an urban area from earthquake hazards is a complex task requiring three models: 1) an earthquake hazards model, 2) an exposure model (inventory), and 3) a vulnerability model. Each model is described briefly below with additional detail being provided by the papers contained in this report.

Earthquake Hazards Model (See papers by Crossen, Heaton, Schwartz, Ihnen, Grant, Preuss, and Bernard.) Assessment of risk in Puget Sound is closely related to the capability to model the earthquake hazards of ground shaking, surface fault rupture, earthquake induced ground failure, tectonic deformation, and tsunamis. Most of the spectacular damage and losses in an earthquake are caused by partial or total collapse of buildings as a consequence of the severity of the horizontal ground shaking. However, ground failures triggered by earthquake ground shaking can also cause substantial damage and losses. For example, during the 1964 Prince William Sound, Alaska, earthquake, ground failures accounted for about 60% of the estimated $500 million total loss with landslides, lateral spread failures, flow failures, and liquefaction causing damage to highways, railway grades, bridges, docks, ports, warehouses, and single family dwellings. Surface faulting, which generally affects a long narrow area, has not occurred in the Puget Sound area. Surface faulting, which generally occurs in earthquakes of magnitude 5.5 or greater in California and Nevada, has damaged lifeline systems and single family dwellings, but has not directly caused deaths and injuries. Tsunamis have occurred in Puget Sound, Alaska, Hawaii, Puerto Rico, and the Virgin Islands, and have caused substantial loss of life and damage.

The earthquake hazards model seeks to characterize the nature and extent of each hazard by finding explicit answers to the following questions:

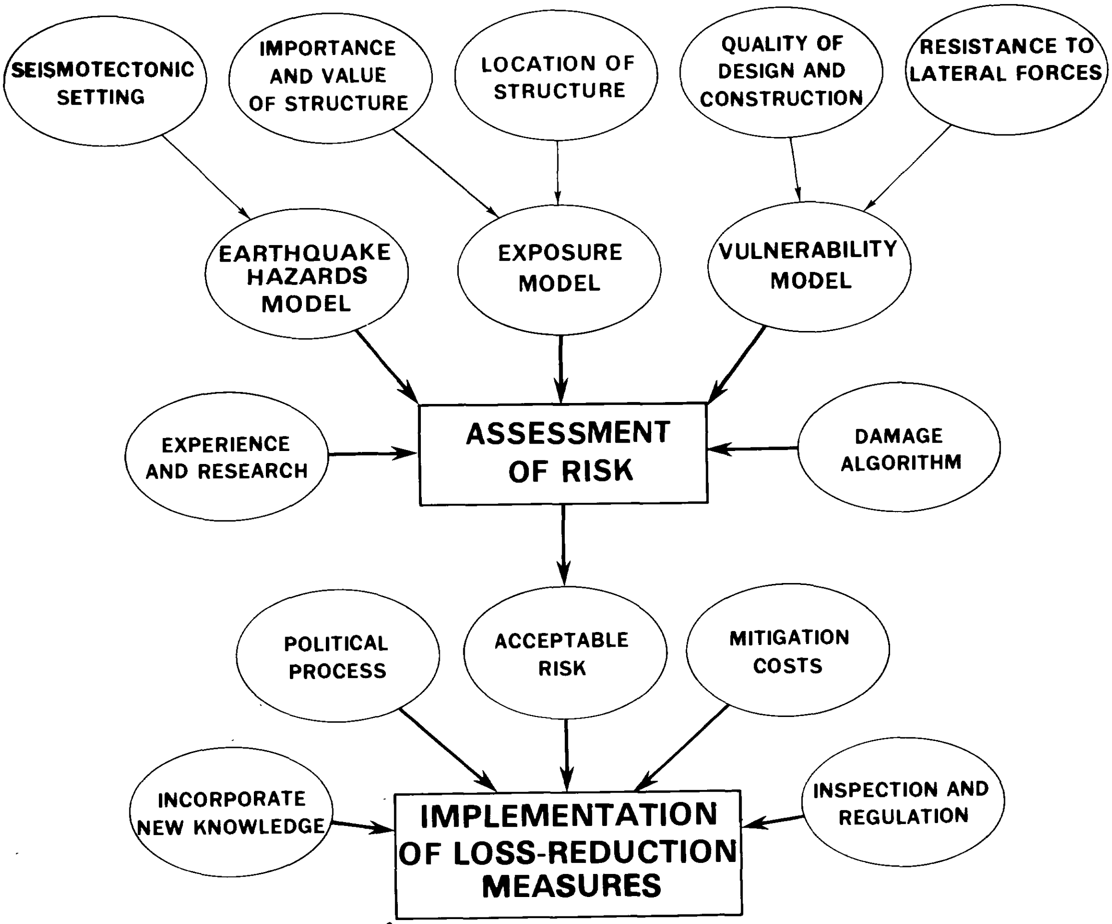

Figure 9.--Schematic illustration of the wide range of subjects that must be considered in the assessment of regional earthquake hazards and risk of the Puget Sound area. Three models: a) earthquake hazards, b) exposure, and c) vulnerability are needed. Incorporation of new knowledge from damaging earthquakes is an important part of the process that fosters implementation of effective loss-reduction measures.

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1. Where have past earthquakes occurred? Where are they occurring now?

2. Why are they occurring?

3. How often do earthquakes of a certain size (magnitude) occur?

4. How bad (severe) have the physical effects (hazards) been in the past? How bad can they be in the future?

5. How do the physical effects (hazards) vary spatially and temporally?

The answers to these questions are used to define the critical, controlling physical parameters for each hazard. For example, the amplitude, frequency composition, and duration of horizontal ground shaking are the three parameters of ground shaking that correlate best with damage.

Exposure Model (See paper by Olsen). The spatial distribution of things and people exposed to earthquake hazards is called inventory. The inventory is one of the most difficult models to characterize.

For risk assessments, the term structure is used to refer to any object of value that can be damaged by the earthquake hazards of ground shaking, surface faulting, ground failure, tectonic deformation, and tsunami wave run up. The various categories of structures include:

1. Buildings (residential, agricultural, commercial, institutional, industrial, and special use).

2. Utility and transportation structures (electrical power structures, communications, roads, railroads, bridges, tunnels, air navigational facilities, airfields, and waterfront structures).

3. Hydraulic structures (earth, rock, or concrete dams, reservoirs, lakes, ponds, surge tanks, elevated and surface storage tanks, distribution systems, offshore platforms, and petroleum systems).

4. Earth structures (earth and rock slopes, major existing landslides, snow, ice, or avalanche areas, subsidence areas, and natural or altered sites having scientific, historical, or cultural significance).

5. Special structures (conveyor systems, sky lifts, ventilation systems, stacks, mobile equipment, tower, poles, signs, frames, antennas, tailing piles, gravel plants, agricultural equipment, furnishings, and shelf items in the home).

A structure consists of many elements. To predict losses, the contribution of each individual element to the total response of a structure responding to the dynamic forces induced by ground motion (or another hazard) must be modeled.

Vulnerability Model (See paper by Olsen). Vulnerability is a term describing the susceptibility of a structure or a class of structures to damage. The prediction of the actual damage that a structure will experience when subjected to a particular hazard (such as ground shaking) is very difficult as a consequence of:

1. Irregularities in the quality of the design and construction (for example, some building are designed and built according to a building code; some are not).

2. Variability in material properties.

3. Uncertainty in the level of ground shaking induced in the structure as a function of magnitude, epicentral distance, and local site geology.

4. Uncertainty in the response of the structure to earthquake ground shaking, especially in the nonlinear range after failure occurs.

A fragility curve can be used to represent failure of a specific type of structure (or a structural system) when it is exposed to the dynamic forces induced by ground shaking. For most structures, damage occurs as a function of the amplitude, frequency composition, and duration of horizontal ground shaking and manifests itself in various states ranging from "no damage" to "collapse." Specification of the damage states of a structure is very difficult because each state of damage is a function of the lateral-force-resisting system of the structure and the severity of the hazard.

OPTIONS FOR RESEARCH AND MITIGATION (See papers by Hays, Nosen, Bolton). In conjunction with an assessment of the potential risk from earthquake hazards, answers are needed for the following questions:

1. What are the viable options for mitigating potential losses from earthquake hazards? Which options are best?

2. What research is needed to provide sound technical and societal bases for devising loss-reduction measures (that is, development of a technology or methodology).

3. How is technology transferred?

The answers to these questions encompass a wide range of possibilities and provide mitigation options such as the following:

1. Personal and institutional preparedness (See paper by Linda Noson)--prepare on an individual and institutional basis for the wide range of impacts that are expected to occur, taking advantage of efficiencies provided by preparation for other natural hazards such as floods.

2. Avoidance (See papers by Preuss and Buck)--when the spatial characteristics of the hazard are known, select the least hazardous areas for construction sites.

3. Land-use regulation (See papers by Preuss and Buck)--reduce the density of certain types of buildings and facilities or prohibit their construction within parts of the area characterized by a relatively high frequency of occurrence or severity of damage.

4. Engineering design criteria and building codes (see papers by Hays and Olsen)--require buildings to have a lateral-force-resisting system that is appropriate in terms of the frequency of occurrence and the severity of the hazard expected in a given exposure time (for example, an exposure time of 50 years which corresponds with the useful life of ordinary buildings). Incorporation of lessons learned from past damaging earthquake is needed to improve earthquake-resistant design.

5. Distribution of losses--use insurance and other financial methods to distribute the potential losses expected in a given exposure time.

6. Response and recovery (See papers by Buck, McCallum)--plan response and recovery measures that will address all of the needs identified in realistic earthquake disaster planning scenarios.

7. A seismic safety organization (see paper by Steinbrugge)--devise public policy and plans to achieve seismic safety. (Note: such organizations now exist in California, Kentucky, South Carolina, Massachusetts, and New York).

8. Technology transfer--initiate a specific program of technology transfer to augment local resources by taking advantage of advances in knowledge and mitigation made in other parts of the United States (Figure 10).

WORKSHOP PROCEDURES

The procedures used in the workshop and meeting of the "Workshop Group" were designed to enhance the interaction between all participants and to facilitate achievement of the general and specific objectives. The first four procedures described below were used in the first 2-days of the workshop; the fifth was used on the third day in the meeting of the "Working Group:"

PROCEDURE 1: Scientists, social scientists, engineers, planners, and emergency management specialists gave oral presentations in four plenary sessions to provide basic information on the themes of the workshop.

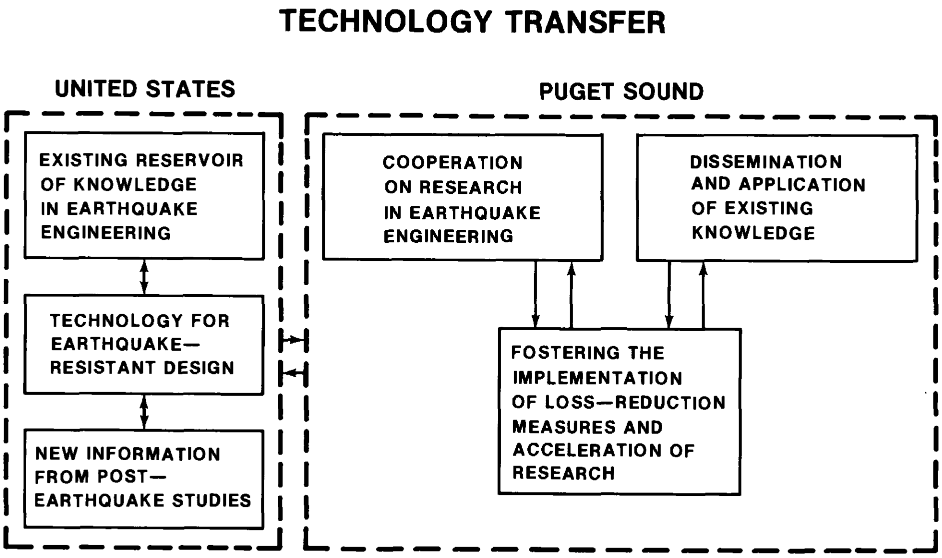

Figure 10.--Schematic illustration of the basic components of a program of technology transfer for the Puget Sound area. Each part of the United States has faced the problem of earthquake hazards and has developed technical data bases and specific strategies for implementing loss-reduction measures. Some elements of the data bases and experiences are transferrable at low cost and effort to the Puget Sound. With cooperation over a 3-5 year period, much can be accomplished.

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PROCEDURE 2: Research reports and preliminary technical papers prepared in advance by the speakers were distributed at the workshop and used as basic references. The technical papers prepared by the speakers were finalized after the workshop and are contained in this publication.

PROCEDURE 3: Three discussion groups met simultaneously to work and discuss a set of problems prepared: a) to illustrate methodology, b) to define the nature and extent of potential earthquake hazards in the Puget Sound area, and c) to provide a framework for answering the question:

> If the 1949 and 1965 Puget Sound earthquakes recurred today, what types of physical effects are likely to occur and how severe could the losses be?

PROCEDURE 4: The participants were assigned randomly to a second set of three discussion groups. The goal was to identify the priority actions that are needed in the next 3 to 5 years to reduce potential losses from future earthquake hazards in the Puget Sound area. Each group addressed the questions:

1. What do we know now?

2. What do we still need to know in order to accomplish our goals?

3. What achievable activities should receive the highest priority in the next 3 to 5 years?

Group 1: Concentrated on regional geologic and seismological studies needed to assess the earthquake potential of the Puget Sound area and to define the ground-shaking hazard. The Moderator was Walter Hays, USGS.

Group 2: Concentrated on scientific and engineering studies needed to assess the ground failure hazards in the Puget Sound area. The Moderator was Darrell Herd, USGS.

Group 3: Concentrated on actions needed to foster implementation of loss reduction measures in the Puget Sound area. The Moderator was Paula Gori, USGS.

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PROCEDURE 5: Twenty-seven experts on various topics related to subduction zone earthquakes and earthquake preparedness were invited to participate in a special session on the third day of the workshop. The goal was to clarify, to the extent possible, how the Puget Sound area fits the worldwide body of knowledge on subduction zones that has been accumulated and to define specific research tasks that might be undertaken to resolve technical issues that are causing controversy. The meeting was scheduled so that specific information could be provided to potential proposers in the annual Program Announcement of the USGS' research program that was scheduled for December 1985.

PLENARY SESSIONS

Following an introduction of the workshop objectives and agenda by Walter Hays, USGS, the highlights of the September 19, 1985, Mexico earthquake were presented by E. V. Leyendecker of the National Bureau of Standards. The workshop processes were developed in 4 plenary sessions and 2 sets of group discussions involving all the participants. The themes, objectives, and speakers for each plenary session are described below.

PLENARY SESSION I: Review of current studies and the state-of-the-art in identifying and assessing earthquake hazards in the Puget Sound area.

Objective: An integrated series of overview presentations answering the questions: WHERE? WHY? HOW BIG? HOW OFTEN? WHAT ARE THE PHYSICAL EFFECTS OF GROUND SHAKING, EARTHQUAKE-INDUCED GROUND FAILURE, SURFACE FAULTING, REGIONAL TECTONIC DEFORMATION, AND TSUNAMIS? WHAT ARE THE POTENTIAL LOSSES FROM THESE PHYSICAL EFFECTS? and WHAT ARE THE OPTIONS FOR MITIGATING THESE LOSSES?

Speakers: Geological and seismological setting of the Puget Sound area
--Robert Crosson, University of Washington
--Darrell Cowes, University of Washington
--Craig Weaver, U.S. Geological Survey

The potential for a major earthquake in the Puget Sound area and a preliminary assessment of some of its possible effects
--Tom Heaton, U.S. Geological Survey

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Tsunami potential in the Puget Sound area
--Jane Preuss, Urban Regional Research

The potential for ground failures in the Puget Sound area
--Paul Grant, Shannon and Wilson, Inc.

Evaluation of potential losses in the Puget Sound area--
Extrapolation from 1949, 1965, and 1976 to the present
--Bruce Olsen, Consulting Engineer

PLENARY SESSION II: Review of lessons learned from past earthquakes that are applicable to the Puget Sound area

Objective: Presentations describing the scientific, engineering, and societal lessons gained from past worldwide earthquakes that can be transferred to the Puget Sound area

Speakers: Societal lessons
--Patricia Bolton, Batelle Human Affairs Research Center

Technical lessons
--Walter Hays, U.S. Geological Survey

PLENARY SESSION III: Review of earthquake preparedness and planning programs in the Puget Sound area

Objective: Presentations giving the status of important programs in the Puget Sound area that provide answers to the question, "Is the Puget Sound area prepared for a major earthquake?"

Speakers: Earthquake education
--Linda Noson, University of Washington (State Seismologist)

Status of earthquake preparedness planning
--Bill Mayer, Federal Emergency Management Agency, Region X
--Larry McCallum, Washington Department of Emergency Management

Comments on mitigation activities of the Federal Emergency Management Agency
--Gary Johnson, Federal Emergency Management Agency, National Office

Building codes, current practices, and possible changes that would affect the potential performance of buildings in the Puget Sound area in a major earthquake
--Bruce Olsen, Consulting Engineer

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PLENARY SESSION IV: RECOMMENDATIONS FOR NEXT STEPS

Speakers: Functions of a Seismic Safety Organization
--Karl Steinbrugge, Consulting Engineer

Technical, societal, and political issues that need to be resolved in the Puget Sound area and actions for recommended research, mitigation actions, and response and recovery planning needed in the next 3 to 5 years
--Walter Hays, U.S. Geological Survey
--Gary Johnson, Federal Emergency Management Agency, National Office
--Jerry Thorsen, Washington State Department of Natural Resources
--Bill Mayer, Federal Emergency Management Agency, Region X
--Larry McCallum, Washington State Department of Emergency Management

DISCUSSION GROUPS AMD QUESTIONNAIRES

Two discussion periods were scheduled. The first period was used to discuss typical problems. In the second period three groups were formed to identify priority actions that are needed to reduce potential losses from future earthquake hazards in the Puget Sound area. Each group used at least one of the following four questionnaires to focus the discussion on: What do we know now? What do we still need to know in order to accomplish our goals? What achievable activities should receive the highest priority in the next 3-5 years?

The moderators of the three discussion groups were: Group 1--Walter Hays, USGS; Group 2--Darrell Herd, USGS; and Group 3--Paula Gori, USGS

Each participant was given the following instructions with the four questionnaires:

On the basis of your knowledge and perceptions select the status that you believe to be appropriate for each research study and research product, where:

Number 1 means that we know very little and lack empirical and theoretical knowledge. Implementation is not yet feasible.

Number 2 means that we have limited empirical and theoretical knowledge. Implementation is not yet credible.

Number 3 means that we have adequate empirical and theoretical knowledge to solve the problem in a general way. Implementation is feasible and has an acceptable technical basis, but controversy exists.

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Number 4 means that we have sufficient empirical and theoretical knowledge to solve the first order problem reasonably accurately. Implementation is credible and can be fostered with minimal controversy.

Number 5 means that we have the required empirical and theoretical knowledge to solve the first order problem completely. Implementation of loss reduction measures can be achieved and the appropriate partnerships exist to produce the required legislation and to enforce it.

Select the appropriate priority, where priority 1 means that this research activity or product development should receive first priority, etc.

QUESTIONNAIRE I: STATUS OF RESEARCH ON EARTHQUAKE AND TSUNAMIGENIC POTENTIAL IN THE PUGET SOUND, WASHINGTON AREA

Research topic	Status	Recommended Priority for next 3 to 5 years
RESEARCH		
1. Historic seismicity	1 2 3 4 5	1 2 3
2. Current seismicity	1 2 3 4 5	1 2 3
3. Activity of specific faults	1 2 3 4 5	1 2 3
4. Tectonic setting	1 2 3 4 5	1 2 3
5. Seismic gaps	1 2 3 4 5	1 2 3
6. Seismogenic sources (subduction zone)	1 2 3 4 5	1 2 3
7. Earthquake recurrence	1 2 3 4 5	1 2 3
8. Tsunamigenic sources	1 2 3 4 5	1 2 3
PRODUCTS		
1. Seismicity maps	1 2 3 4 5	1 2 3
2. Map of seismogenic zones	1 2 3 4 5	1 2 3
3. Map of tsunamigenic zones	1 2 3 4 5	1 2 3
4. Fault activity map	1 2 3 4 5	1 2 3
5. Seismotectonic maps	1 2 3 4 5	1 2 3

QUESTIONNAIRE II: STATUS OF RESEARCH ON THE GROUND SHAKING HAZARD IN THE PUGET SOUND, WASHINGTON AREA

Research topic	Status	Recommended Priority for next 3 to 5 years
RESEARCH		
1. Seismogenic zones	1 2 3 4 5	1 2 3
2. Attenuation laws for acceleration	1 2 3 4 5	
3. Attenuation laws for velocity	1 2 3 4 5	1 2 3
4. Attenuation laws for spectral velocity ordinates	1 2 3 4 5	1 2 3
5. Duration	1 2 3 4 5	1 2 3
6. Engineering properties of soil and rock	1 2 3 4 5	1 2 3
7. Local ground response	1 2 3 4 5	1 2 3
PRODUCTS		
1. Map of seismogenic zones	1 2 3 4 5	1 2 3
2. Probabilistic maps of ground shaking hazard	1 2 3 4 5	1 2 3
3. Maps of ground shaking hazard for specific scenarios	1 2 3 4 5	1 2 3
4. Maps of seismic risk zones	1 2 3 4 5	1 2 3
5. Engineering properties of surficial deposits	1 2 3 4 5	1 2 3

QUESTIONNAIRE III: STATUS OF RESEARCH ON THE GROUND-FAILURE HAZARD IN THE PUGET SOUND, WASHINGTON AREA

Research topic	Status	Recommended Priority for next 3 to 5 years
RESEARCH		
1. Liquefaction potential	1 2 3 4 5	1 2 3
2. Landslide susceptibility	1 2 3 4 5	1 2 3
3. Reactivation of old landslides		
4. Characterization of sensitive clay behavior	1 2 3 4 5	1 2 3
5. Characterization of foundation materials	1 2 3 4 5	1 2 3
PRODUCTS		
1. Regional liquefaction maps	1 2 3 4 5	1 2 3
2. Regional landslide susceptibility maps	1 2 3 4 5	1 2 3
3. Maps of sensitive clay formations	1 2 3 4 5	1 2 3
4. Dam inundation maps	1 2 3 4 5	1 2 3

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QUESTIONNAIRE IV: IMPLEMENTATION OF SPECIFIC ACTIONS TO REDUCE POTENTIAL LOSSES FROM EARTHQUAKE HAZARDS IN THE PUGET SOUND, WASHINGTON AREA

Topic	Status	Recommended Priority for next 3 to 5 years
RESEARCH		
1. Siting considerations for new construction.	1 2 3 4 5	1 2 3
2. Delineation of the hazard for emergency response purposes.	1 2 3 4 5	1 2 3
3. Local planning tools (comprehensive planning, zoning, and building codes).	1 2 3 4 5	1 2 3
4. Education programs for decisionmakers.	1 2 3 4 5	1 2 3
5. Education programs for the general public including school children.	1 2 3 4 5	1 2 3
6. Research on hazard laws which are hazard specific (lateral spreading, fault rupture, tsunami, etc.).	1 2 3 4 5	1 2 3
7. Warning system hazard awareness and personal preparedness.	1 2 3 4 5	1 2 3
8. Liability and insurance products.	1 2 3 4 5	1 2 3
9. Studies pertaining to level of exposure and definition of "reasonable" level of risk.	1 2 3 4 5	1 2 3
PRODUCTS		
1. Improved model warning procedures.	1 2 3 4 5	1 2 3
2. Preparation of model codes and plans (comprehensive planning and zoning).	1 2 3 4 5	1 2 3
3. Educational (curriculum packages pertaining to earth sciences).	1 2 3 4 5	1 2 3

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SUMMARY OF RECOMMENDATIONS OF DISCUSSION GROUPS

Using the 4 questionnaires presented above as a frame of reference to focus discussion, the discussion groups arrived at a number of consensus-type conclusions. They are summarized below in the context of each questionnaire.

I. Earthquakes and tsunamigenic Potential	Status	Priority
A. Research		
Historical Seismicity	3	1
Current Seismicity	3	2
Activity of Specific Faults	2	3
Tectonic Setting	2	3
Seismic Gaps	2	3
Seismogenic Sources	2	1
Earthquake Recurrence	2	1
Tsunamigenic Sources	2	1
B. Products		
Seismicity Maps	3	2
Map of Seismogenic Zones	2	1
Map of Tsunamigenic Zones	2	2
Fault Activity Map	2	3
Seismotectonic Maps	2	2

II. Ground-Shaking Hazard	Status	Priority
A. Research		
Seismogenic Zones	3	1
Attenuation law, acceleration	2	3
Attenuation law, velocity	2	3
Attenuation law, spectral velocity	1	1
Duration	2	3
Engineering Properties of Soil/Rock	3	2
Local Ground Response	2	1
B. Products		
Map of Seismogenic Zones	2	1
Probabilistic Maps of Ground Shaking	3	3
Ground Shaking for Specific Scenarios	2	1
Map of Seismic Risk Zones for Building Code	3	2
Reports, Engineering Properties of Soil/Rock	2	1

III. Ground-Failure Hazard	Status	Priority
A. Research		
Liquefaction Potential	4	2
Landslide Susceptibility	3	1
Reactivation of Old Landslides	3	2
Characterization of Sensitive Clay Behavior	3	3
Characterization of the Foundation	4	3

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	Status	priority
B. Products		
Regional Liquefaction Maps	2	1
Regional Landslide Susceptibility Maps	3	2
Maps of Sensitive Clay Formations	2	2
Dam Inundation Maps	4	3
Maps of Fill Areas	2	1

IV. Implementation A. Research	Status	Priority
Siting considerations	4	2 Knowledge is available for siting new construction. Maps of surface geology are available. There is sufficient information to require site specific information for entire Puget Sound area. Site specific studies can be required through Uniform Building Code/Environmental Impact Statements. Although building officials may require site specific studies, they may not be aware of need or availability of information.
Delineation of the hazard for emergency response purposes	3	2 Varies with jurisdiction. Insufficient information about vulnerability of transportation systems, freeways, etc. Need to decide on design event. Design event may need updating as new information accumulates. Accessibility of information may be a problem.
Local planning tools	3	2 Are available but not integrated. Implementation and enforcement varies. May have conflict of purpose.
Education programs for decisionmaker	3	1 Programs are available. There is a lack of on-going, programs. Professional curriculum is weak.

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	Status	Priority
Education programs for the general public including school children	3	1 Red Cross provides training on first aid and safety and survival. There are limited programs on earthquakes. All materials to design a program are available. The Seattle Earthquake Safety and Education Project rates an "A".
Research on hazard laws which are hazard specific (lateral spreading, fault rupture, tsunami, etc.)	1	3
Warning system hazard awareness and personal preparedness	2	2
Liability and insurance products	1	2
Studies pertaining to level of exposure and definition of "reasonable" level of risk	2	3

B. Products

	Status	Priority
Improved model warning procedures	2	3
Preparation of model codes and plans (comprehensive planning and zoning)	2	1
Educational (curriculum packages pertaining to earth sciences)	3	2
Hazard Maps: Ground shaking, liquefaction potential, landslide susceptibility, etc.	3	2

THE "WORKING GROUP" MEETING

The following individuals were a part of the "Working Group" that met on the third day of the workshop:

John Adams, Earth Physics Branch, Canada
Ted Algermissen, U.S. Geological Survey
Leon Beratan, Nuclear Regulatory Commission
John Booker, University of Washington
Jane Bullock, Federal Emergency Management Agency
Don Caldwell, Golder Associates
Bob Crossen, University of Washington
Walter Hays, U.S. Geological Survey
Tom Heaton, U.S. Geological Survey
Darrell Herd, U.S. Geological Survey
Steven Ihnen, Sierra Geophysics, Inc.
Gary Johnson, Federal Emergency Management Agency
Hiroo Kanamori, California Institute of Technology
Ken Lajoie, U.S. Geological Survey
Brian Lewis, University of Washington
Stephen Malone, University of Washington
Caryl Michaelson, U.S. Geological Survey
Jane Preuss, Urban Regional Research
Anthony Qamar, University of Washington
Al Rogers, U.S. Geological Survey
Gary Rogers, Pacific Geosciences Center, Canada
Bob Rothman, Nuclear Regulatory Commissio
Jim Savage, U.S. Geological Survey
David Schwartz, U.S. Geological Survey
Stewart Smith, Incorporated Research Institution for Seismology
Bill Spence, U.S. Geological Survey
Jerry Thorsen, Department of Natural Resources
Craig Weaver, U.S. Geological Survey
Jim Zollwig, U.S. Geological Survey

Following a comprehensive overview presentation by David Schwartz, USGS, the working group discussed a wide range of technical issues concerning the potential for a great earthquake in the Puget Sound area. The following generalizing principles were suggested to guide research in the next 3 to 5 years:

Give highest priority to research in the Puget Sound area that:

1. Ascertains if a great prehistoric subduction zone earthquake has occurred in the Puget Sound.

2. Determines the nature of the interface of the subducting plates and their capability to produce large to great earthquakes.

3. Defines the pattern of current deformation and the configurations of the plates.

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4. Quantifies the maximum magnitudes, recurrence intervals, and physical effects of potential large to great earthquakes.

5. Adds new knowledge on the entire boundary of the Pacific-North American plates, especially in the Pacific Northwest.

6. Enables comparisons on a global scale with other subduction zones.

CONCLUSIONS AND RECOMMENDATIONS OF THE WORKSHOP

The following conclusions emerged from the workshop:

1. Although a reasonable body of knowledge on earthquake hazards in the Puget Sound area has been accumulated, additional knowledge is needed to resolve important technical issues and to eliminate or reduce controversy.

2. In general, a high priority should be given to proving that the Puget Sound area is facing a new threat--that a high probability exists for the occurrence of a great subduction zone earthquake. However, the recurrence of damaging shallow earthquakes like the 1872 Pacific Northwest earthquake should not be minimized because of its potential for causing damage.

3. As specific goals in the ongoing research program sponsored under the auspices of the NEHRP, highest priority should generally be given to studies of:

   a) historical seismicity (for example, restudy important historic earthquakes) such as the 1872 and the 1949 earthquakes).
   b) seismogenic sources (including the potential subduction zone model).
   c) earthquake recurrence rates.
   d) tsunamigenic sources.
   e) attenuation law for spectral velocity.
   f) local ground response (and potential soil-structure interaction).
   g) engineering properties of soil and rock.

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h) regional liquefaction susceptibility.

i) regional landslide susceptibility.

4. As specific goals to continue fostering the implementation of loss-reduction measures, high priority should be given to producing:
   a) maps of seismogenic zones.
   b) maps of ground shaking for specific planning scenarios.
   c) reports on engineering properties of soil and rock.
   d) maps of regional liquefaction susceptibility.
   e) maps showing fill areas.
   f) education programs for the decisionmaker and the public.
   g) preparation of model codes and urban land-use plans.

5. The participants of the "Working Group" urged that another meeting of the same type be planned in the near future to communicate and to accelerate progress in both research and implementation of research results in the Puget Sound area.

6. High priority should be given to the planning for a possible Seismic Safety Council in Washington. All available resources should be marshalled to complete the September 1986 report to the Governor of Washington.

ACKNOWLEDGMENTS

The valuable contributions of the Steering Committee: Gary Johnson, FEMA; Dick Buck, FEMA; Jane Bullock, FEMA; Bob Crossen, University of Washington; Susan Tubbesing, University of Colorado; Ray Lasmanis, Department of Natural Resources; and Jane Preuss, Urban Regional Research, are gratefully acknowledged. David Schwartz, USGS, provided valuable technical assistance for the meeting of the "Working Group." His support made this part of the meeting a rich learning experience for everyone. Leon Beratan, NRC, provided encouragement and financial support for the meeting of the "Working Group".

Carla Kitzmiller, Lynn Downer, Wanda Fuller, and Shirley Carrico provided excellent administrative support which is sincerely acknowledged.

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APPENDICES

Three appendices are included in the report. Appendix A contains a list of the participants. Appendix B contains a glossary of technical terms, including terminology on subduction zones. Appendix C lists the 96 strong motion stations in Oregon and Washington.

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EVALUATION OF THE WORKSHOP ON "EARTHQUAKE HAZARDS IN THE PUGET SOUND, WASHINGTON, AREA"

by

Sallie A. Marston
University of Colorado
Boulder, Colorado 80309

On October 29 and 30, 1985, a workshop on the earthquake hazard in the Puget Sound Area of Washington State was held in Seattle. The workshop was designed to define the nature of the earthquake threat as well as to assess the adequacy of planning and preparedness programs in the area. At the close of the two-day event, participants were asked to evaluate the success of the workshop based on a number of criteria.

Responses were elicited on a five-point scale: 1 and 2 representing the lowest level of agreement, or a "no" response, 3, moderate agreement, and 4 and 5 highest agreement, or a "yes" response (see Figure 1). Since not all respondents answered all questions, percentages reflect only those questions completed. Also, percentages discussed in the text are a combined total of a positive response of 3, 4 and 5.

The questionnaire asked workshop participants to rate 1) the usefulness of the information and activities provided; 2) the usefulness of the various session formats; 3) the level of earthquake awareness and concern before and after the workshop. Finally, participants were asked to list one or two "positive" and "less than positive" aspects of the workshop and to identify possible future actions they might undertake to carry out some of the specific recommendations made in the workshop.

Evaluations returned by 36 participants indicate that the workshop was successful in meeting its objectives (see Figure 2 for percentages). Ninety-two percent of the participants found the workshop useful for increasing their knowledge of the potential risk. Eighty-eight percent found that the workshop increased their knowlege of the social and technical issues that face the Puget Sound area before, after, and during an earthquake. Seventy-eight percent felt that the workshop had improved their awareness of educational, preparedness, and building code and construction practices in the area. Finally, over 97% felt that the workshop added to their understanding of what actions could be taken to reduce potential earthquake losses in the Puget Sound area.

In another area the participants indicated that the workshop was successful in providing new sources of information and expertise (92%) and establishing a better understanding of the problems faced by researchers and decision makers (97%).

In evaluating the effectiveness of various session formats, 97% found the formal presentations to be useful, with virtually all of the participants giving a high rating to discussions about the 1985 Chile and Mexico earthquakes. Participants rated the discussions following the presentations as useful (89%). In examining the rating of the problem solving/discussion group it is useful to break the responses into the three categories of low, moderate and high. As the percentages show, the percentage of low (28%) and moderate (30%) ratings is significant. The ratings for questionnaire/discussion groups are similar with a low rating of 20% and a moderate rating of 33%. It would appear that these activities are regarded as less than useful or, at least, in need of improvement. Participants also found the preprints of abstracts (87%) and the informal discussions (94%) to be of value.

Nearly all of the participants would welcome the opportunity to repeat the workshop experience. In addition, the participants indicated unanimous support for future workshops on the earthquake hazard in the Puget Sound Area.

Responses related to pre-workshop awareness and concern of the earthquake threat indicated that four out of five participants considered themselves already knowledgeable and concerned. Still, after the workshop <u>all</u> respondents indicated that the experience increased both awareness (92%) and concern (100%).

Because this workshop is meant not only to increase awareness and concern but also to affect future behavior, the questionnaire elicited open ended responses about future mitigative action. One of the most common responses to this question was related to improving public awareness of the hazard through education. Other possible future actions included: update community disaster plans, attend more meetings, keep up with code requirements, become involved in community earthquake planning, hire an environmental geologist and produce hazard zonation maps.

Comments regarding "positive" and "less than positive" aspects were numerous. Among the latter, and most often noted, were that the scientific presentations were too technical and the technical speakers need to improve their communication skills. Other comments on aspects of the workshop that need improvement include: more interaction between researchers and planners; more emphasis on state-federal interaction; follow up information (names, addresses, session summaries); discussion formats need improvement, and, a discussion of the financial/insurance impact of the hazard would be helpful.

The positive comments which had wide support among the workshop participants were also numerous. The positive comment most often indicated was the opportunity to interact with a wide variety of experts on the various aspects of the earthquake hazard. Other comments included: the accessibility and usefulness of the information presented; the opportunity to interact with others in the Puget Sound Area who are involved in earthquake research or mitigation; and, the increased awareness of the hazard the workshop promoted.

Figure 1

EVALUATION OF WORKSHOP BY INDIVIDUAL PARTICIPANTS

	Low 1 & 2	3	High 4 & 5
1. Did you find the workshop to be useful to you or your organization by increasing your knowledge of:			
a. earthquake hazards in the Puget Sound area?...........	3	11	22
b. the potential risk from earthquake hazards in the Puget Sound area?...................................	6	12	18
c. societal and technical issues that face the Puget Sound area before, during, and after an earthquake?...	4	16	16
d. status of educational and preparedness programs and building codes and construction practices in the Puget Sound area?................................	8	10	18
e. achieveable actions that can be taken to reduce potential losses from earthquake hazards in the Puget Sound area?...................................	6	13	17
2. Did the workshop benefit you or your organization by:			
a. providing new sources of information and expertise you might want to utilize in the future?.................	1	5	30
b. establishing better understanding of the problems faced by researchers and decisionmakers?..............	3	8	25
3. Did you find the following activities useful:			
a. formal presentations?................................	1	8	25
b. information about the 1985 Chile and Mexico earthquakes?..	-0-	12	24
c. discussions following the formal presentations?.......	4	10	22
d. problem solving/discussion groups?....................	10	11	15
e. questionnaires/discussion groups?.....................	7	12	17
f. preprints of papers, expanded abstracts?..............	4	7	21
g. informal discussions during breaks and after hours?...	2	7	26
4. If the clock were turned back and the decision to attend the workshop were given to you again, would you want to attend?..	1	-0-	33
5. Should future workshops be planned to continue the work initiated at this meeting?................................	-0-	4	30
6. Prior to attending this workshop, I would rate my awareness of the earthquake threat in Puget Sound as................	7	8	21
7. Prior to attending this workshop, I would rate my concern about the state-of-earthquake preparedness in Puget Sound as..	3	10	23
8. I now rate my awareness as..................................			
9. I now rate my concern as....................................			

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Figure 2

EVALUATION OF WORKSHOP BY PERCENTAGES OF PARTICIPANTS

	Low 1 & 2	3	High 4 & 5
1. Did you find the workshop to be useful to you or your organization by increasing your knowledge of:			
a. earthquake hazards in the Puget Sound area?...........	8%	31%	61%
b. the potential risk from earthquake hazards in the Puget Sound area?..	17%	33%	50%
c. societal and technical issues that face the Puget Sound area before, during, and after an earthquake?...	11%	44%	45%
d. status of educational and preparedness programs and building codes and construction practices in the Puget Sound area?................................	22%	28%	50%
e. achieveable actions that can be taken to reduce potential losses from earthquake hazards in the Puget Sound area?..................................	17%	36%	47%
2. Did the workshop benefit you or your organization by:			
a. providing new sources of information and expertise you might want to utilize in the future?.................	3%	14%	83%
b. establishing better understanding of the problems faced by researchers and decisionmakers?.............	8%	22%	70%
3. Did you find the following activities useful:			
a. formal presentations?.................................	3%	23%	74%
b. information about the 1985 Chile and Mexico earthquakes?...	-0-	33%	67%
c. discussions following the formal presentations?.......	11%	28%	61%
d. problem solving/discussion groups?....................	28%	30%	42%
e. questionnaires/discussion groups?.....................	20%	33%	47%
f. preprints of papers, expanded abstracts?.............	12%	22%	66%
g. informal discussions during breaks and after hours?...	6%	20%	74%
4. If the clock were turned back and the decision to attend the workshop were given to you again, would you want to attend?...	3%	-0-	97%
5. Should future workshops be planned to continue the work initiated at this meeting?..............................	-0-	12%	88%
6. Prior to attending this workshop, I would rate my awareness of the earthquake threat in Puget Sound as................	20%	22%	58%
7. Prior to attending this workshop, I would rate my concern about the state-of-earthquake preparedness in Puget Sound as..	8%	28%	64%
8. I now rate my awareness as.................................	-0-	3%	97%
9. I now rate my concern as...................................	-0-	6%	94%

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SEISMOLOGICAL SETTING OF THE PUGET SOUND REGION

by

Robert S. Crosson

Geophysics Program

University of Washington

Seattle, Washington 98195

INTRODUCTION

Recent investigations [e.g.,Heaton and Kanamori] as well as others have made it clear that the implications of a large subduction earthquake along the Juan de Fuca plate margin must be carefully studied. A subduction earthquake, possibly of magnitude greater than 8, would determine the seismic hazard evaluation along the coastal regions of Washington and Oregon, and possibly drastically change the current view of hazards in much of western Washington, western Oregon, and British Columbia. Evidence for the earthquake potential along this margin comes from a variety of sources, including correlation of plate age with rate of convergence, geodetic strain data, leveling data, and plate morphology comparisons. Arguments have been made both for and against seismic subduction along this zone, and clearly much additional work remains to be done to resolve this critically important question. Although instrumental seismological data may not directly resolve the issue of seismic vs. aseismic subduction, critical auxiliary evidence and structural data are obtained from seismic network operation and other seismic experiments. Here we review some of the current findings of network seismology in western Washington.

TECTONIC SETTING

The Juan de Fuca plate is a remnant of the once larger Farallon plate that covered much of the northeast Pacific. The JDF plate varies in age from zero along the ridge crest to about 8 My where it descends eastward along the Cascadia subduction zone beneath the North American (NA) plate. Current estimates place the rate of convergence of these two plates at 3 to 4 cm/yr in a direction about N50°E. Such estimates are based on analysis of magnetic anomaly patterns and past plate reconstructions.

New material is being accreted to the NA plate by the subduction process and deformation of sediments on the continental shelf and slope provides evidence of the continuing convergence. On a scale the size of the JDF plate, the actively spreading JDF ridge is seismically quiet, the Blanco transform fault zone at the south end of the plate is seismically active, the Gorda plate shows scattered and diffuse seismicity, and the Cascadia subduction zone is quiet with scattered but lower level earthquake activity in western Washington and northwest Oregon. No large subduction earthquakes are known to have occurred in historic time, however the record only extends for not much more than 150 years. On the other hand, there are a many intraplate earthquakes up to magnitude 7, within either the NA or JDF plates. At even the lowest levels of seismicity, subduction earthquakes are not detected, making the nearly 1000 km long Cascadia subduction zone truly unusual in worldwide perspective.

The concept of plate coupling advanced by Ruff and Kanamori is usefully applied to the Cascadia zone. If the zone is strongly coupled (welded together by friction and other processes), then strain is probably accumulating at a moderate rate and eventual release in a large magnitude earthquake

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on the subduction zone is likely. If the zone is weakly coupled, then all or most of the deformation may be occurring as plastic or inelastic flow. Evidence such as the geodetic strain accumulation and subduction zone morphology may be used to infer the degree of coupling,however considerable uncertainty remains.

SEISMICITY

The modern instrumental network was started at the University of Washington for the Puget Sound region in 1970. By the mid 1970's, broad regional coverage for western Washington was established and the network has grown in density and coverage since that time. The University currently operates more than 100 stations statewide, providing detection capability for most of Washington to approximately magnitude 2 or better. The highest level of regional earthquake activity on a continuing basis is in the greater Puget Sound region, with localized intense activity found at Mt. St. Helens, and in eastern Washington. A zone of seismicity trending NNW passes through the Mt. St. Helens region and has been interpreted by Weaver and Smith as a shallow crustal fault zone, perhaps the only one clearly identified as being active seismically along this continental margin.

In the Puget Sound region, crustal earthquakes are found above a depth of 30 km, occurring in distributed clusters over most of the basin to the Cascade margin on the east. Subcrustal earthquakes are found at a depth of 35 km or greater, concentrated in a narrow depth range of 40 km to approximately 60 km, and displaced somewhat to the west of the shallow earthquakes. Subcrustal earthquake sparsely cover an area roughly 3500 km^2. An unusual feature of the seismicity is the quiet zone separating the deep from shallow earthquakes. This zone has been conventionally interpreted as the projection of the megathrust or boundary that separates the NA and JDF plates. The deep zone has some structure with a more or less horizontal planar zone in the southern basin, and a shallow dip to the east near the northern end of the Olympic Peninsula. North of the Olympic Peninsula, the deep zone becomes less coherent and almost disappears beneath the Strait of Georgia. Recurrence statistics show that the b value of the deep suite of earthquakes is nearer to .7 compared with a value closer to 1.0 for the shallow suite. It appears that most, if not all, of the large earthquakes in the Puget Sound basin (greater than magnitude 6) occur in the deep suite. However the magnitude 5.5 Elk Lake earthquake in 1981, north of Mt. St. Helens, was at a depth of about 10 km, and shallow earthquakes near magnitude 5 may be common in the Mt. Rainier region based on the historical catalog and network seismicity. The capability for magnitude 6 or greater earthquakes to occur in crust of the Puget Sound basin is now unknown.

STRESS

The arrival polarities from network observations provide a basis for studying focal mechanisms, inferred slip directions, and inferred principal stress directions. With the current network configuration in Washington, many earthquakes provide well constrained focal mechanisms. A study of shallow (less than 35 km) earthquake focal mechanisms in the Puget Sound region shows that most events are thrust or strike slip with P axes oriented predominantly northward. Insofar as these reflect the directions of maximum principal compressive stress, we may infer that the dominant tectonic stress in the shallow lithosphere of the North American plate is approximately N-S. The focal mechanisms of deep earthquakes in the same region show a much more complex pattern with no clear dominant direction of either maximum or minimum compression. Subcrustal earthquakes are responding to different tectonic processes than the shallow earthquakes, and that stress is largely decoupled between these two groups. The quiet zone of separation is probably a region of stress decoupling. Surface strain measurements [Savage et al.] suggest maximum relative compression in a direction N70°E in the Puget Sound region, a direction significantly different from that suggested by the focal mechanism data. One possibility for reconciling these observations is that the strain measurements are sensitive to small changes in the ambient stress, whereas the earthquake focal mechanisms are likely to respond to the magnitude of ambient stress. These two quantities may be different in a complex tectonic environment. Additional strain and earthquake measurements are necessary to clarify this problem.

STRUCTURE

In spite of an increase in both effort and data in recent years, the deep structure of the continental margin region is still not well known. Taber (1983) used seismic refraction data to establish the overall geometry beneath the continental shelf and slope, but the structure inland is largely inferred. Many studies have been made using teleseismic data, local and regional earthquake data, and seismic refraction measurements, with varying results. A recently completed Pn study shows that the Moho transition is flat and readily detectable beneath western Washington. No evidence of a shallowly dipping (10°) subducted slab was detected from this study, suggesting that the slab may lie at some depth below the 40 km Moho transition in the Puget Sound region. This evidence, coupled with a reexamination of the coastal refraction data and a teleseismic receiver function analysis near the Washington coast, suggests that the slab may dip as steeply as 25° beneath the margin. Although tentative, this hypothesis may have implications for

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seismic hazard modeling from subduction earthquakes as well as for the origin of the deep earthquakes beneath Puget Sound. Further work is needed to adequately test this hypothesis.

DISCUSSION

Many basic seismological problems associated with the Cascadia subduction zone require further investigation. The modern seismograph network provide us with vastly more data with which to solve fundamental problems. Although the seismological studies have not provided us with the direct evidence needed to assess the capability of the subduction zone to produce great earthquakes, much valuable auxiliary evidence is accumulating. Continued network measurements are important to detect possible changes in earthquake activity related to the subduction process. It can be expected that detection of small subduction earthquakes might signal buildup of stress precursory to a major subduction event. For this reason, monitoring in western Oregon should be established, even though present day seismicity is low. Efforts should be increased to obtain paleoseismic evidence of prehistoric large earthquakes (or their lack), and geodetic strain and leveling measurements must be expanded. If great earthquake potential for the Cascadia subduction zone is firmly established, then the information on structure, stress, and regional tectonics that we are getting from current seismological research will provide the necessary basis for hazard analysis.

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Earthquakes Potential Associated with
the Cascadia Subduction Zone

by

Thomas H. Heaton and Stephen H. Hartzell
U.S. Geological Survey
525 S. Wilson Ave.
Pasadena, CA 91106

Cascadia Subduction Zone

The Cascadia subduction zone extends 1200 km along the western Coast of North America from Cape Mendocino, Calif. to Vancouver Island, B.C. This zone comprises the boundary along which the North America plate overrides three relatively small oceanic plates (Gorda, Juan de Fuca, and Explorer plates) at a rate of between 2 1/2 to 4 1/2 cm/yr. However, subduction along this boundary has presented earth scientists with a dilemma. Despite compelling evidence of active plate convergence, subduction on the Cascadia zone has often been viewed as a relatively benign tectonic process. There is no deep oceanic trench off the coast; there is no extensive Benioff-Wadati seismicity zone; and most puzzling of all, there have not been any historic low-angle thrust earthquakes between the continental and subducted plates. The two simplest interpretations of these observations are: 1) the Cascadia subduction zone is completely decoupled and subduction is occurring aseismically, or 2) the Cascadia subduction zone is uniformly locked and storing elastic energy to be released in future great earthquakes. Lacking direct geologic or historic (less than 200 years) evidence of great subduction earthquakes, a full resolution of this issue may prove elusive.

Are there any other subduction zones that appear to be similar to the Cascadia subduction zone? It appears that one of the most diagnostic characteristics of the Cascadia subduction zone is the very young age of the subducted oceanic lithosphere (approximately 10 m.y.). Other subduction zones where comparably young crust is subducting are found in southern Chile,

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southwestern Japan, Colombia, and Mexico. These zones share many physical characteristics (including noteable periods of seismic quiescence) with the Cascadia subduction zone. However, they have also been the source regions for some of the largest historic subduction earthquakes (southern Chile , 1960 M_w 9 1/2 ; southern Japan, 1707 M_w 8 1/2 , 1944 M_w 8.1, 1946 M_w 8.1; Colombia, 1906 M_w 8.8; Mexico, 1932 M_w 8.2, 1985 M_s 8.1). A comparison of tectonic features of the Cascadia subduction zone with those along the rupture zone of the 1960 M_w 9 1/2 Chilean earthquake is shown in Figure 1. A more complete summary of the results of this comparison study is given in Table I. If the Cascadia subduction zone is in fact similar to these other subduction zones, then the possibility of an earthquake of very large size must be considered.

Estimating Ground Motions for Large Subduction Earthquakes

There is currently a fairly large inventory of strong motion records from shallow subduction earthquakes of $M_w < 8\,1/4$ (most of these are Japanese). Unfortunately relatively few records are available from subduction zones where young oceanic crust is subducted, or from very large subduction earthquakes ($M_w > 8\,1/4$). In order to understand how these earthquakes may differ from earthquakes for which we do have strong motion data, we have systematically characterized the time history of energy release for 63 of the largest subduction earthquakes in the last 50 years by studying broad-band teleseismic body-waves from those events as recorded in Pasadena, California. Comparison of the teleseismic time functions with strong motion records from 13 of these earthquakes often (but not always) shows a good correspondance between the source duration and complexity as deduced from near and distant observations. A comparison of the teleseismic time functions with the age of the subducted plate does not yield obvious trends. Thus, we feel that the strong motion recordings from Japan can be used to make meaningful estimates of potential ground motions in the northwestern U.S.

We have collected over 50 strong ground motion recordings from more than 20 shallow subduction earthquakes having magnitudes of 7 or greater and have prepared a set of figures summarizing the gound motions as well as the spatial geometry of the stations relative to the aftershock zones. Response spectra

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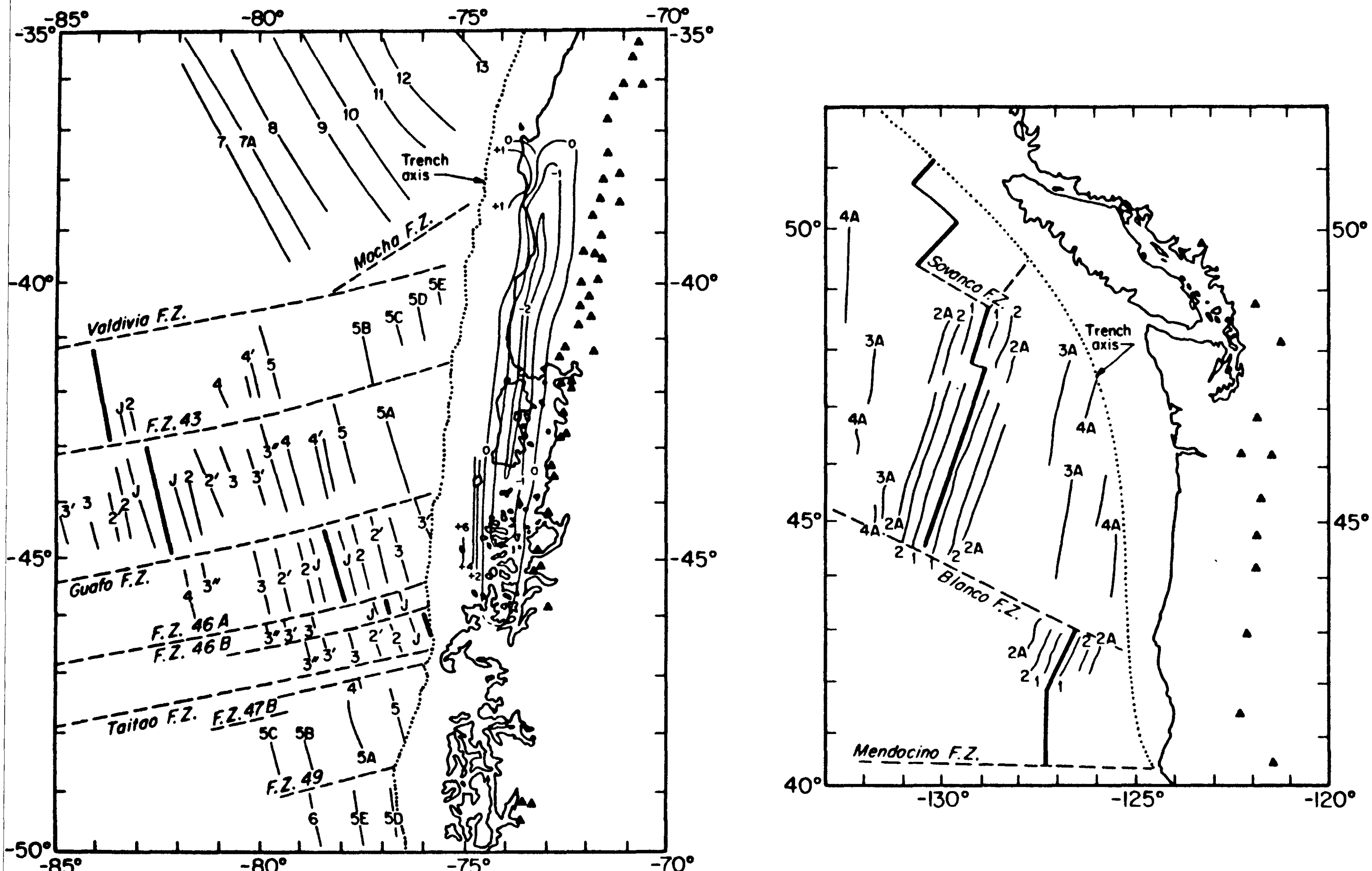

Figure 1. Comparison of the geometry of subduction in the northwestern United States with that in southern Chile. Maps are on the same scale. Sea-floor magnetic lineations and Quaternary volcanoes are shown. Coseismic vertical deformation from the 1960 M_W 9.5 earthquake is also shown.

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TABLE I.

	Cascadia	Southern Chile	Nankai Trough	Alaska	Colombia	Mexico (Rivera Plate)
Age (m.y.) of subducted plate	10	5 to 30	18 to 24	40 to 50	10 to 15	10?
Convergence rate (cm/yr)	3.3 to 4.3	9	3.3 to 4.3	5.7	8	2.3
Character of trench	shallow sediment filled	shallow sediment filled	shallow sediment filled	shallow sediment filled	shallow sediment filled	shallow few sediments
Free-air gravity anomaly	small 50 mgal	small 50 mgal	moderate 100 mgal	moderate 100 mgal	small 50 mgal	moderate 100 mgal
Background seismicity	very low	very low	low	moderate	low	?moderate?
Heat flow	high 1-2 HFU	high 1-2 HFU	high 1-2 HFU			
Quaternary volcanism	yes	yes	no	varies along the trench	yes	yes
Inland sea or valley	yes	yes	yes	yes	?no?	no
Width of continental margin	30-120 km	100 km	110 km	180 km	130 km	80 km
Largest historic earthquakes M_w	none in 150 yr.	9.5 (1960)	8.1 (1944,1946) ?8.5? (1707)	9.2 (1964)	8.8 (1906)	8.2 (1932)
Average repeat time	?400 yr.?	128 yr.	180 yr.	?800 yr.?	unknown	?50 yr.?

have been calculated for all components of acceleration. These spectra have been sorted by magnitude and horizontal distance to the rupture surface. An example of this procedure is shown in Figure 2. Comparison of spectra at similar distances and earthquake magnitudes shows a very large scatter (about one order of magnitude). This illustrates, that when considering questions of design ground motions, the way in which this scatter is treated may be of greater significance than deciding design earthquake size and magnitude.

There are no strong motions records available for earthquakes of $M_w > 8\frac{1}{4}$. In order to estimate motions from such earthquakes, we sum records from smaller earthquakes using a model of the rupture characteristics of giant earthquakes. The rupture characteristics are chosen in such a way that the summation process will be compatible with observed teleseismic records of giant earthquakes.

Many of the items mentioned in this abstract are discussed in more detail in the following papers.

Hartzell, S.H., and T.H. Heaton (1985). Teleseismic time functions for large, shallow subduction zone earthquakes, Bull. Seism. Soc. of Am., v. 75, pp. 965-1004.

Heaton, T.H., and H. Kanamori (1984). Seismic potential associated with subduction in the northwestern United States, Bull. Seism. Soc. of Am., v. 74, pp. 933-941.

Heaton, T.H., and H. Kanamori (1985). Reply to Hemendra Acharya on his comments on "Seismic potential associated with subduction in the northwestern United States", Bull. Seism. Soc. of Am., v. 75, pp. 891-892.

Heaton, T.H., and P.D. Snavely, Jr. (1985). Possible Tsunami along the northwestern coast of the United States inferred from Indian Traditions, Bull. Seism. Soc. of Am., v. 75, pp. 1455-1460.

Heaton, T.H., and S.H. Hartzell (1985). Source characteristics of hypothetical subduction earthquakes in the northwestern United States, submitted to Bull. Seism. Soc. of Am., 67 p.

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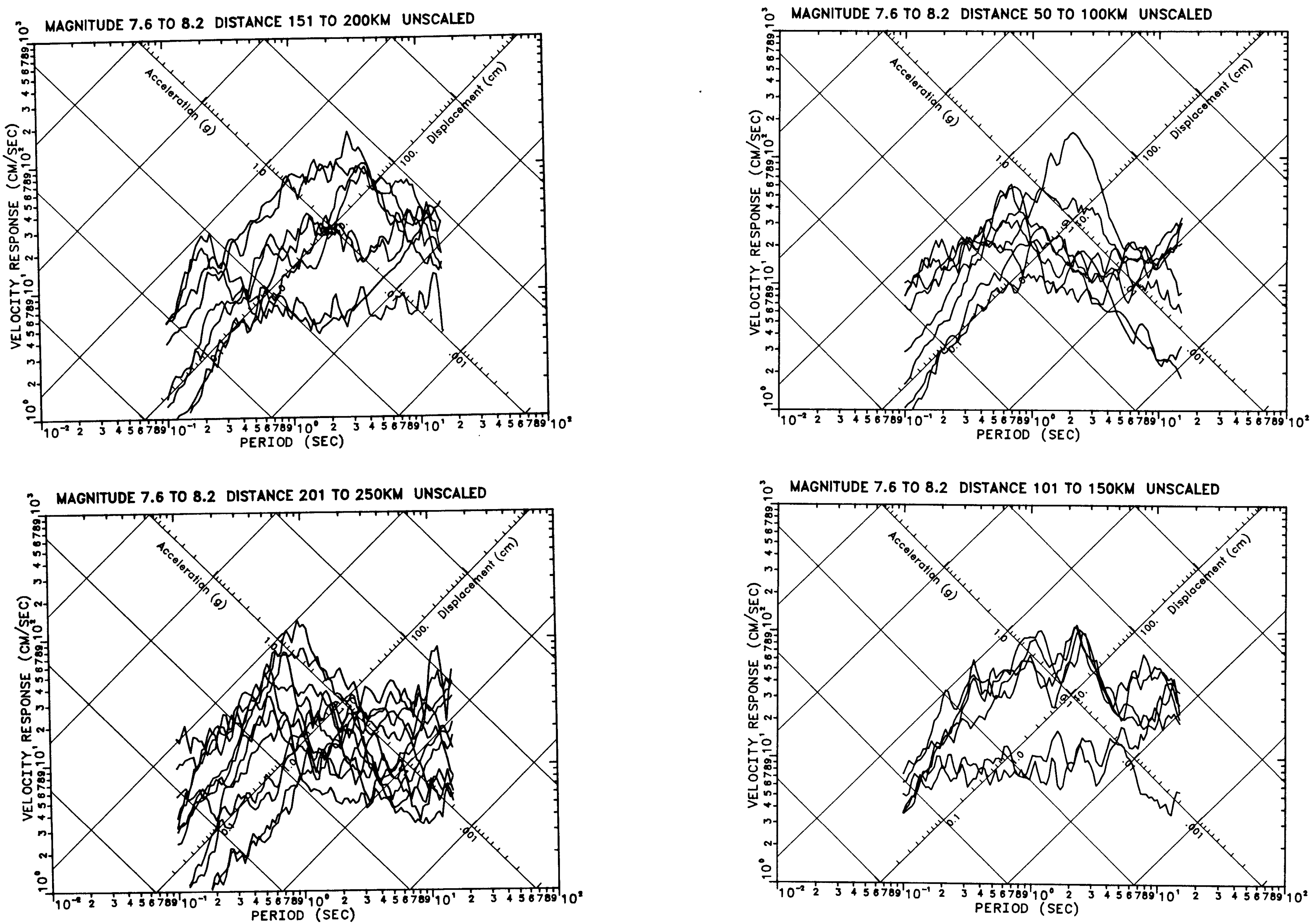

Fig. 2 Response spectra (5% damping) from large shallow subduction earthquakes.

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SUBDUCTION ZONE EARTHQUAKES IN THE PACIFIC NORTHWEST:
EVALUATING THE POTENTIAL--THOUGHTS FOR DISCUSSION AT THE SEATTLE WORKSHOP

David P. Schwartz

U.S. Geological Survey

Menlo Park, CA 94025

INTRODUCTION

There are three potential sources of damaging earthquakes in the Pacific Northwest. These are shallow crustal faults of Quaternary age, faults within the subducted slab of the Juan de Fuca plate that produce earthquakes at depths of 50 to 70 km, and the shallow interface between the Juan de Fuca and North American plates. Shallow crustal faults have not produced any documented historical surface-faulting earthquakes in the region; however, the historical seismic record, the distribution of shallow instrumentally-recorded seismicity, and the occurrence of events such as the 1983 M_L=5.5 Elks Lake, Washington earthquake clearly indicate their potential. Extensional faults within the subducted slab below Puget Sound have produced damaging earthquakes with magnitudes of M=6.3 (1946), M=7.1 (1949), and M=6.5 (1965). The recurrence interval, maximum magnitude, and potential areal distribution of earthquakes from this source are not known.

The shallow interface between the Juan de Fuca and North American plates is perhaps the most enigmatic of the potential sources. Presently available geologic, seismologic, and geodetic data permit a variety of interpretations regarding the nature of plate interaction along this shallow interface. These include: present-day accumulation of strain on the plate interface using trilateration data (Savage and others, 1981); a strongly coupled plate boundary with the potential for large thrust earthquakes based on comparison with other

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subduction zones (Heaton and Kanamori, 1984); a locked plate interface interpreted from the orientation of P-axes along the Mt. St. Helens seismic zone (Weaver and Smith, 1983); aseismic subduction based on leveling surveys and tide gauge measurements (Ando and Balazs, 1979); and an unlocked subduction zone with aseismic subduction based on the lack of interplate earthquakes, the north-south orientation of P-axes of earthquake fault plane solutions, and the amount of seismicity observed since 1900 (Rogers, 1983). There is clearly, at the present time, a high degree of uncertainty regarding the seismic potential of the interface. As used in the present discussion, seismic potential refers to 1) the ability of the interface to rupture and produce large thrust earthquakes, and 2) the range of magnitudes, recurrence intervals, and the spatial distribution of potential subduction events.

Given these uncertainties, a major question is what new experiments or studies can be undertaken to better define and quantify the seismic potential of the Juan de Fuca-North American plate interface? Also important is a consideration of methods to translate our understanding of the hazard into estimates of ground motion for the region. One approach to evaluating the seismic potential that has been used and that has focused attention on the region is comparison between characteristics of the Juan de Fuca plate and other subduction zones. This comparative approach forms an important framework for evaluating observations from the Pacific Northwest. It can also provide a focal point for discussion at the workshop. I have reviewed aspects of subduction zone comparisons below and I have also listed a series of questions that might serve to focus discussion at the meeting.

SUBDUCTION ZONE COMPARISONS AND QUANTIFICATION OF PACIFIC NORTHWEST SEISMIC HAZARDS

For most subduction zones the seismicity during this century appears to form an adequate basis for evaluating the seismic potential of the zone (Ruff and Kanamori, 1980). However, the Juan de Fuca subduction zone is not known to have produced any interplate earthquakes during the historical record of approximately 150 years. This lack of interplate seismicity, which is the most unique characteristic of the zone, can be variously interpreted to mean that subduction is not occurring, that it is occurring aseismically, or that the zone is in the quiescent phase of a seismic cycle that is significantly longer than the historical record. Because the seismicity data alone cannot be used to unequivocally evaluate the seismic potential of the zone, and because the present geodetic and geologic data are subject to alternative interpretations, other approaches need to be developed and used. One is to compare seismological, geological, geophysical, and kinematic characteristics of Juan de Fuca subduction with characteristics of other subduction zones.

Several authors have correlated subduction zone characteristics with seismic potential. Some correlations are qualitative (Kanamori, 1977; Uyeda and Kanamori, 1979; Lay and others, 1982) and group subduction zones into broad categories such as "strongly coupled" or "weakly coupled". Strong coupling means that slip and energy release across the plate interface are accomodated mainly by large earthquakes, whereas weak coupling means that the relative plate motion across the interface occurs mainly through aseismic slip and small earthquakes. Other correlations are more quantitative (Ruff and Kanamori, 1980; Heaton and Kanamori, 1984; Peterson and Seno, 1984) and use physical characteristics as a basis for estimating the size of earthquakes on a subduction zone.

Kanamori (1977) noted a variation in rupture length and magnitude of the largest interplate earthquakes among the various subduction zones of the northwest Pacific. To explain this, he proposed a model in which a youthful, strongly coupled subduction style gradually evolves into a mature, weakly coupled subduction style that is characterized by back-arc spreading and the formation of marginal seas. Uyeda and Kanamori (1979) further examined the relationship between seismic potential and back-arc spreading. They concluded that great interplate earthquakes occur along subduction zones whose back-arc regions are not actively spreading, but do not occur along zones where back-arc spreading is active. They inferred a significant difference in the degree of coupling in these two cases, and attributed these differences to different stages of evolution of the subduction process.

Lay and others (1982) reviewed variations in the mode of rupture of large earthquakes and the degree of coupling for 20 subduction zones. Using maximum rupture length, seismicity patterns, percentage of aseismic slip, and source time function characteristics, they characterized the stress regime in each zone to develop a framework for evaluating future large earthquake activity. In doing so, they defined four basic categories of subduction zone behavior. Category 1 is characterized by the regular occurrence of great events with rupture lengths longer than 500 km, a large percentage of seismically released relative plate motion and increased seismicity prior to main events. Category 2 is characterized by variations in rupture length with occasional ruptures of 500 km, clustering of large earthquake activity, doublets, and frequent precursory quiescence prior to large events. Category 3 is characterized by repeated rupture over zones of 100 to 300 km in length, multiple rupture events, complex failure zones, and recurence intervals of 100 years or longer. Category 4 is characterized by the absence or infrequent occurrence of large thrust earthquakes, back-arc spreading, and an inferred large percentage of aseismic slip.

Ruff and Kanamori (1980) compared historical maximum earthquake magnitude, penetration depth, length, age of the subducting lithosphere, and convergence rate for 21 subduction zones to quantitatively correlate subduction zone characteristics and seismic potential. They used multivariate regression analyses and found that the size of the largest historical interplate earthquake on a subduction zone is well correlated (correlation coefficient of 0.802) with convergence rate and age of the subducting lithosphere. These two parameters are regarded as controlling the horizontal and sinking rates, respectively, of slabs, and thereby influence the degree of seismic coupling in the subduction zone. Ruff and Kanamori (1980) observed that earthquake magnitudes are generally larger in subduction zones with high convergence rates and young lithosphere, and that relatively aseismic subduction occurs in zones with slow rates and old lithosphere.

Peterson and Seno (1984) calculated seismic moment release rates and seismic slip rates for 24 subduction zones in order to compare the degree of seismic coupling of each subduction zone. They compared moment release rates to age of the subducting lithosphere, absolute velocities of the upper and subducting plates, convergence velocity, arc length, maximum depth, and dip of the Wadati-Benioff zone. They concluded that the moment release rate (and by inference the degree of coupling) depends most clearly on the age of subducting lithosphere and the absolute upper plate velocity, and that it does not appear to increase with convergence velocity. Zones with retreating upper plates tend to have lower moment release rates.

Building on the concept of seismic coupling and earthquake potential, Heaton and Kanamori (1984) compared some of the physical characteristics of the Juan de Fuca subduction zone with other subduction zones to evaluate the degree of seismic coupling across, and estimate the potential maximum earthquake on, the shallow plate interface. These characteristics were the age of the subducted lithosphere, convergence rate, depth of seismicity, depth of the oceanic trench, dip of the Benioff zone, topography of the subducted slab, presence of an accretionary prism, uplift of the overriding plate, and seismic quiescence. They concluded that the Juan de Fuca subduction zone shares many characteristics with other subduction zone that have historically generated large thrust earthquakes and that are interpreted to be strongly coupled. Based on a relationship between convergence rate, plate age, and observed maximum earthquakes for worldwide subduction zones, they also suggested a possible thrust earthquake with a moment magnitude (M_W) of 8.3 ± 0.5 on the shallow plate interface between the Juan de Fuca and North American plates.

As part of a comparative study of the Juan de Fuca and other subduction zones Woodward-Clyde Consultants (1984) compiled information in 29 categories for 29 subduction zones. This information was divided into four general groups that reflected different aspects of the subduction process. These groups were interplate seismicity, Benioff zone seismicity, intraplate stress normal to the arc, and geologic/geometric characteristics.

Based on the data compilation and review, the Woodward-Clyde (1984) report listed thirteen subduction zone parameters that have either been used by other investigators to categorize the seismic potential of subduction zones or appear to be useful in evaluating seismic potential for the Juan de Fuca plate. These were convergence rate, lithosphere age, back-arc spreading, depth of seismicity, trench bathymetry, dip of the Benioff zone, seafloor topography, preseismic quiescence, focal mechanisms in the subducting plate in the vicinity of the trench, focal mechanisms in the overriding plate, focal

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mechanisms in the back arc region, transverse structures/segmentation, and heat flow. Convergence rate, lithosphere age, transverse structures/segmentation, and heat flow are inherent characteristics of the subducting slab that can directly affect the nature of plate interaction and seismic potential. The remaining parameters are an expression, both direct and indirect, of the style and rate of plate interaction.

The Woodward-Clyde (1984) report also pointed out the alternative interpretations that can be derived from the present data base and concluded that: 1) For the Juan de Fuca subduction zone the youthfulness of the oceanic crust and the high heat flow suggest that the subducting slab is buoyant, which is consistent with strong coupling. Conversely, the high heat flow may affect the thermal-mechanical properties and the style of deformation (brittle versus ductile) along the interface, and this is a factor requiring additional analysis in evaluating the alternatives of seismic and aseismic subduction. 2) Correlations between seismic potential and depth of seismicity, trench bathymetry, dip of the Benioff zone, and seafloor topography are weak. 3) Focal mechanisms in the outer-rise region, the overriding plate, and the back arc region may be expressions of the state of stress and nature of coupling. Focal mechanisms for the Juan de Fuca subduction zone are compatible with weak coupling; however, the data are sparse and are subject to alternative interpretation. 4) The absence of back-arc spreading supports strong coupling across the shallow plate interface. 5) Seismic quiescence along the zone is remarkable given the length of the historical record, the convergence rate, and the contact area of the shallow interface. This is compatible with, but does not demonstrate aseismic subduction. 6) Availble data suggest the zone contains individual segments with distinct lengths and down-dip geometries although segment boundaries are presently not well-defined. Segmentation may directly affect not only potential rupture lengths and earthquake size and location, but also earthquake recurrence for the zone.

In summary, subduction zone comparisons do provide an important framework for evaluating the observations that we have from the Pacific Northwest. However, using the present data base, both from the Pacific Northwest and other zones, the comparisons do not provide a unique solution regarding seismic potential of the Juan de Fuca-North American shallow plate interface. The challenge before this working group is to develop a strategy and set of recommendations for what can or should be done to 1) better understand the physics of plate interaction in the Pacific Northwest and 2) quantify the hazard both in terms of source characterization (magnitude, location, recurrence) of, and ground motions from, earthquakes associated with the subduction zone. With this in mind I have included a list of general questions that might serve to guide some of the discussion during the workshop.

DISCUSSION QUESTIONS

1. What is the nature of coupling across the Juan de Fuca-North American plate interface? Is subduction completely seismic, aseismic, or somehwere in between?

2. What is the geometry of the subducted slab? How does it vary down-dip? Along strike?

3. What are the physical characteristics of the shallow interface? How can heat flow, geometry, and crustal structure data be used to model thermal-mechanical properties of the interface and the style of plate interaction?

4. If seismic subduction occurs: a) What is the maximum earthquake?; b) What is a realistic range of magnitudes for potential large earthquakes?; c) What percentage of the length of the interface would be expected to rupture in a future event? The entire boundary at once or shorter segments?; d) What is the recurrence interval for large events?

5. Is the subducted slab segmented? Are there onshore/offshore geological and geophysical data that indicate segmentation? To what degree might segmentation constrain the location, size, and recurrence of future earthquakes?

6. What are the kinematics of the adjacent plates (Gorda, Explorer)? How do they reflect or affect Juan de Fuca-North American interaction?

7. What is the affect of major transforms to the north (Queen Charlotte) and south (San Andreas) on stress in the North American plate? How might this affect Juan de Fuca-North American plate interaction?

8. What would be the levels and distribution of ground motions that might occur throughout the northwest from a large thrust event? How can data from Mexico and Chile be used?

9. Given the uncertainty in the present, and possibly future, data base, what is the best way to quantitatively express the subduction zone hazard for the Pacific Northwest? Are probabilistic hazard models the best way to go? What kinds of models should be used?

10. What is the largest intraplate earthquake that might be expected to occur throughout the region? What is the recurrence interval for this type of event? Is this type of event restricted to the Puget Sound area or can it occur beneath Oregon?

11. In what ways can seismologic and geodetic networks be expanded to obtain additional basic data on the plate interface?

12. Are there appropriate paleoseismicity studies that would be useful for demonstrating the occurrence, location, and repeat times of past thrust earthquakes?

13. To what degree does coastal geomorphology (terraces, uplift, subsidence) provide constraints on the style of plate interaction and the occurrence and timing of past events?

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PREDICTION OF STRONG MOTION IN THE PUGET SOUND AREA
THE 1965 SEATTLE EARTHQUAKE

By
S. Ihnen and D. M. Hadley
Sierra Geophysics
Redmond, Washington

I. INTRODUCTION

The Puget Sound region of Washington state (USA) is a major metropolitan area with significant earthquake hazard. During this century major earthquakes have occurred in 1904, 1939, 1945, 1946, 1949, and 1965, with the last two events being the most damaging. According to the compilation of Hyndman and Weichert (1983), events with magnitude six or greater have recurrence times in this area on the order of 20 years. Recently, several authors (Heaton and Kanamori (1984), Hartzell and Heaton (1984), Weaver and Smith (1983), Adams (in press)) have presented information suggesting that a great earthquake (M>8) may be a possibility in the Pacific Northwest.

The seismicity of Puget Sound can be divided into two groups (Crosson, 1972): a diffuse, shallow group with hypocentral depths less than 40 km and a deeper group which appears to loosely define a Benioff zone. The 1949 and 1965 events occurred in this second group at depths of sixty to seventy kilometers and are probably associated with tensional breaking in the subducted Juan de Fuca plate (Rogers, 1983).

A number of investigators (e.g., Mullineaux, et al., 1967, Steinbrugge and Cloud, 1965) have observed that Puget Sound earthquakes often produce highly irregular damage patterns. Regions of strikingly high and abnormally low seismic intensity may be found adjacent to one another. Although local soil conditions cause variations in intensity here as they do elsewhere, patterns of high and low intensity are often observed to cross soil boundaries. Several theoretical studies have been undertaken in an attempt to explain the spatial variability of ground shaking in Puget Sound.

Langston (1981) modeled the variations in ground motion which could be expected from a flat-layered velocity structure. While his results gave accelerograms qualitatively similar to those observed, it was necessary to invoke large lateral variations in attenuation to explain the observed amplitudes. Shakal and Toksoz (1979) examined the frequency content of the Seattle and Olympia accelerograms from the '65 and '49 events and concluded, as did Langston, that anelastic attenuation beneath Seattle must be very large.

Langston and Lee (in press) attempted to model the observed variations in intensity in the Duwamish River area using three-dimensional raytracing on a 2-D model. They found that focusing effects at the boundary between the unconsolidated glacial sediments and the recent alluvial fill could generate large variations in intensity at the surface. Their study was confined to a small portion of the Puget Sound area and the effects of lateral velocity variations were not included.

In this study, three dimensional raytracing techniques and the best available geological and geophysical information are used to predict the nature of strong ground motion from deeper earthquakes over the entire Puget Sound region. Unlike previous studies, the model used here incorporates the full three-dimensional structure of the glacial sediment layer. Anelastic attenuation effects and lateral variations in sediment velocity associated with surface geology are also included.

The region chosen for this study is an area of 8,250 square kilometers lying between 46 and 47 N latitude, 122 and 123 W longitude. It is shown enclosed in the box in Figure 1. The study area includes the cities of Everett, Seattle, Tacoma and Olympia as well as the major portion of Puget Sound.

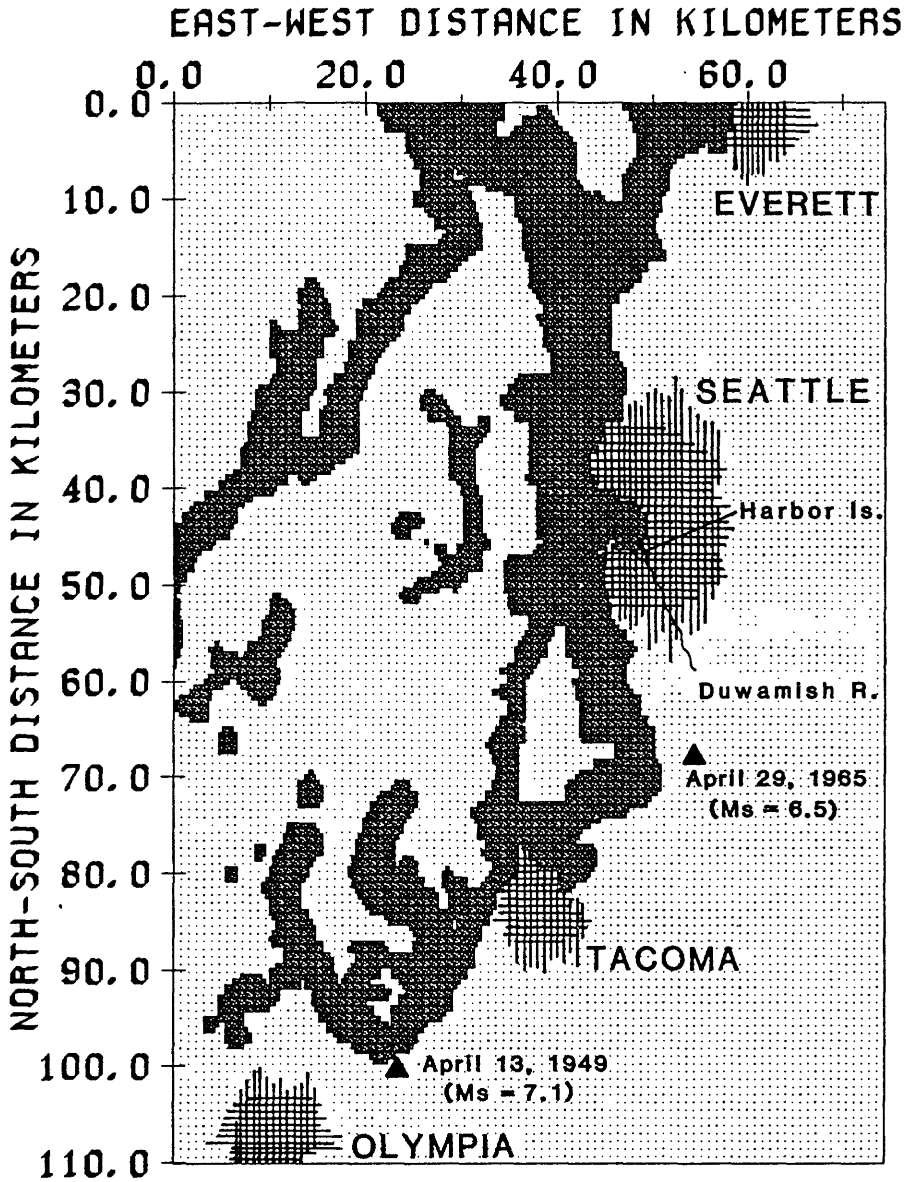

Figure 1. Reference map of study area. Origin of coordinates at NW corner is located at 48N latitude, 123W longitude. Epicenters of 1965 and 1949 earthquakes are shown by triangles.

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II. MODEL DESCRIPTION

This section describes the digital velocity model created for the ray-tracing study. The model was assembled using Sierra's MIMIC program. The purpose of MIMIC is twofold: it is used to create digital representations of geologic structures from input data and to assemble these structures into a three-dimensional velocity model suitable for ray-tracing. The model consists of a series of layers or horizons which are digital descriptions of the topography of an interface. Associated with each layer are interval velocities and material parameters. The interval velocity may be uniform or it may contain lateral variations.

The model constructed for the crust and upper mantle structure beneath Puget Sound contains seven such layers. They are, from the surface downward: (1) a water layer for modeling ray interactions with Puget Sound and related water bodies; (2) a layer of variable depth and laterally varying velocities representing unconsolidated sediments near the surface; (3,4) upper- and lower-crustal layers; (5,6) the top and bottom of the subducted Juan de Fuca plate; and (7) the upper mantle. Figure 2 illustrates a cross-section through the model and Table 1 lists the velocities and physical properties used along with the data sources.

It is anticipated that the character of strong ground motion will be strongly influenced by layer number two, the sediment layer. Considerable care has been used to assure that this layer represents the best available geological, geotechnical, and geophysical information. Figure 3 is a contour map of this sediment layer. The figure shows two large deep sedimentary basins flanking an east-west trending horst structure. The northern edge of the horst, where the sediment layer goes from zero thickness to a maximum 1.1 km depth, appears to be associated with the Mt. Si fault (Gower and Yount, in press). Note that the location map (Figure 1), this figure, and all subsequent maps cover the same area at the same scale. A useful reference point can be made by noting that the maximum depth of sediment lies directly beneath downtown Seattle.

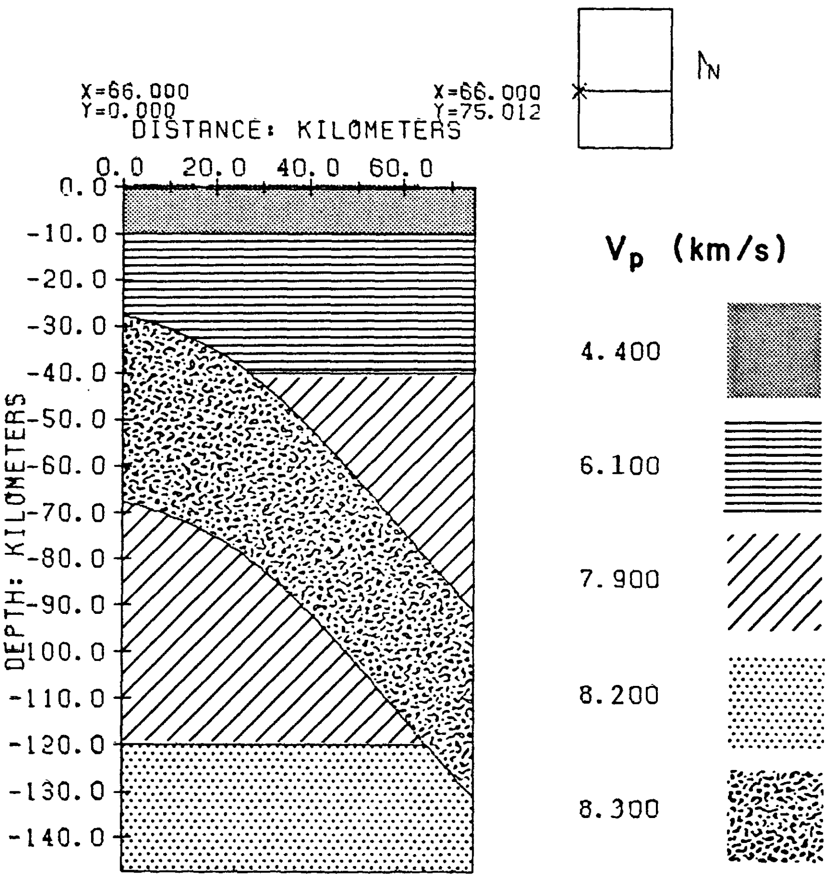

Figure 2. Vertical cross section through velocity model at latitude of 1965 event. Uppermost layers are too thin to be seen in the detail at top of figure.

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TABLE ONE
LAYER PROPERTIES USED IN VELOCITY MODEL

LAYER NO.	DESCRIPTION	DEPTH TO BOTTOM OF LAYER	THICKNESS OF LAYER	PHYSICAL PROPERTIES ABOVE LAYER	NOTES
1	Puget Sound Water Layer	0-220m	0-220m	V_p = 1.5 km/sec V_s/V_p = 0 ρ = 1.0 g/cm^3 Q_α = 10000 Q_β = 0	Digitized by hand from NOAA (1980, 1981)
2	Glacial Alluvium	0-1.1 km	0-1.1 km	V_p varies laterally from 0.370 - 2.9 km/sec ρ = 1.9 V_s/V_p = 0.41 Q_α = 65 Q_β = 29	Depth of sediments digitized from Yount, et al. (1983) for northern Sound and Hall and Othberg (1974) for southern Sound. Surface geology from Livingston (1970). Velocities chosen by the authors (see text).
3	Upper Crust	10 km	~10 km	V_p = 4.2 V_s/V_p = 0.577 ρ = 2.6 Q_α = 384 Q_β = 171	Approximation to Crossen's (1974) model.
4	Lower Crust	40 km	30 km	V_b = 6.8 V_s/V_p = 0.577 ρ = 2.8 Q_α = 519 Q_β = 231	Approximation to Crossen's (1974) model.

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TABLE ONE
(continued)

LAYER NO.	DESCRIPTION	DEPTH TO BOTTOM OF LAYER	THICKNESS OF LAYER	PHYSICAL PROPERTIES ABOVE LAYER	NOTES
5, 6	Top and Bottom of Juan de Fuca Plate	28-130 km	40 km	$V_p = 8.3$ $V_s/V = 0.577$ $\rho = 2.9$ $Q_\alpha = 708$ $Q_\beta = 314$	Position, strike and dip estimated by Michaelson (1983) from available literature.
7	Upper Mantle	120 km	80 km	$V_p = 7.9$ $V_s/V_p = 0.577$ $\rho = 2.9$ $Q_\alpha = 695$ $Q_\rho = 309$	Approximation to Crosseu's (1974) model.
	Half Space	--	--	$V_p = 8.2$ $V_s/V_p = 0.577$ $\rho = 2.9$ $Q_\alpha = 10000$ $Q_\rho = 10000$	

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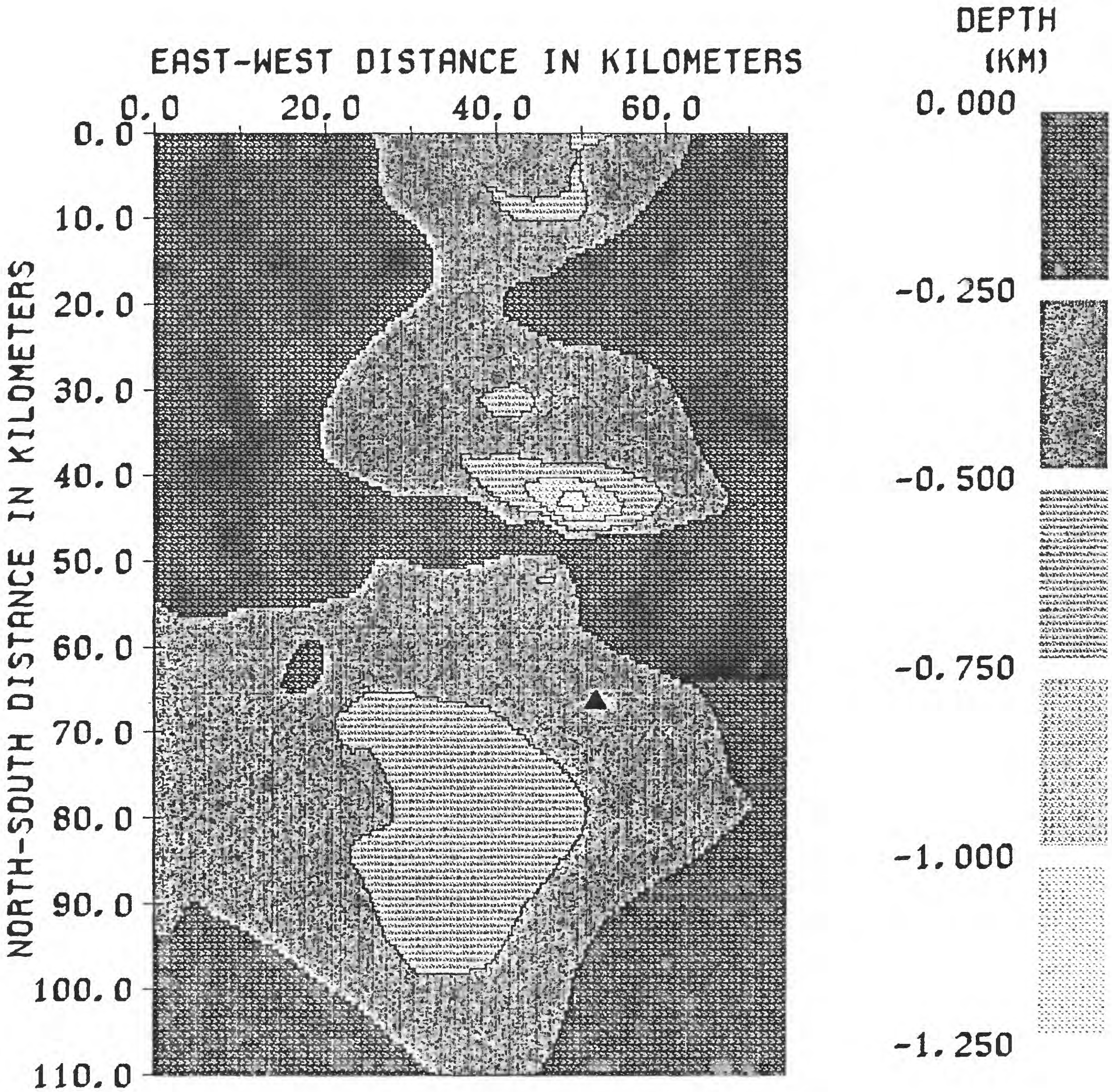

Figure 3. Contoured depth of sediments (Layer 2). Triangle is epicenter of 1965 event.

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Topography of the sediment-basement interface was digitized from the maps of Yount et al. (1983) for the northern part of the model and Hall and Othberg (1974) in the southern part. These maps are based primarily on logs from geotechnical boreholes, and actual data points are fairly sparse. Hence, the maps on which the layer is based are heavily interpreted and corresponding caution should be used in analyzing the results. For modeling purposes, the sediment thickness values given on the maps are assumed to be sediment depth values. This is equivalent to an assumption of zero topographic relief above the reference plane (sea level). While this method slightly distorts the form of the sediment interface, it does preserve the total thickness of sediments. After construction of this layer, a 1.5 km by 1.5 km boxcar average filter was applied. This slight smoothing served to eliminate undesirable very short wavelength surface features. The effects of unknown or incorrect layer geometry will be discussed later in this report. Note that the sediment layer structure is truly three-dimensional and cannot be adequately approximated by a two-dimensional model.

The interval velocity above the basement horizon is laterally variable with Vs ranging from 150 to 1220 m/sec. Each grid point in the layer is assigned a velocity corresponding to the surface geology at that point. Surface geology for King County is taken from the geologic map of Livingston (1970). Velocities were chosen by matching lithologic descriptions of the map units with consolidated sediments whose velocities are known. In the present model, the S-wave speed in the sediments outside of King County is set to a uniform 720 m/s. Figure 4 is a contour map of the sediment velocity.

In the sediment layer, Vs/Vp is assumed to be 0.41, corresponding to a Poisson's ratio of 0.4. Elsewhere in the model, S wave speeds are assumed to be 0.58 of the P velocity (Poisson's ratio of 0.25). Densities and Q-values are uniform within each layer regardless of whether the velocities vary laterally or not. However, lateral variations in the attenuation operator may still arise due to differing travel times, particularly in the low velocity sediments. Default density and Q val-

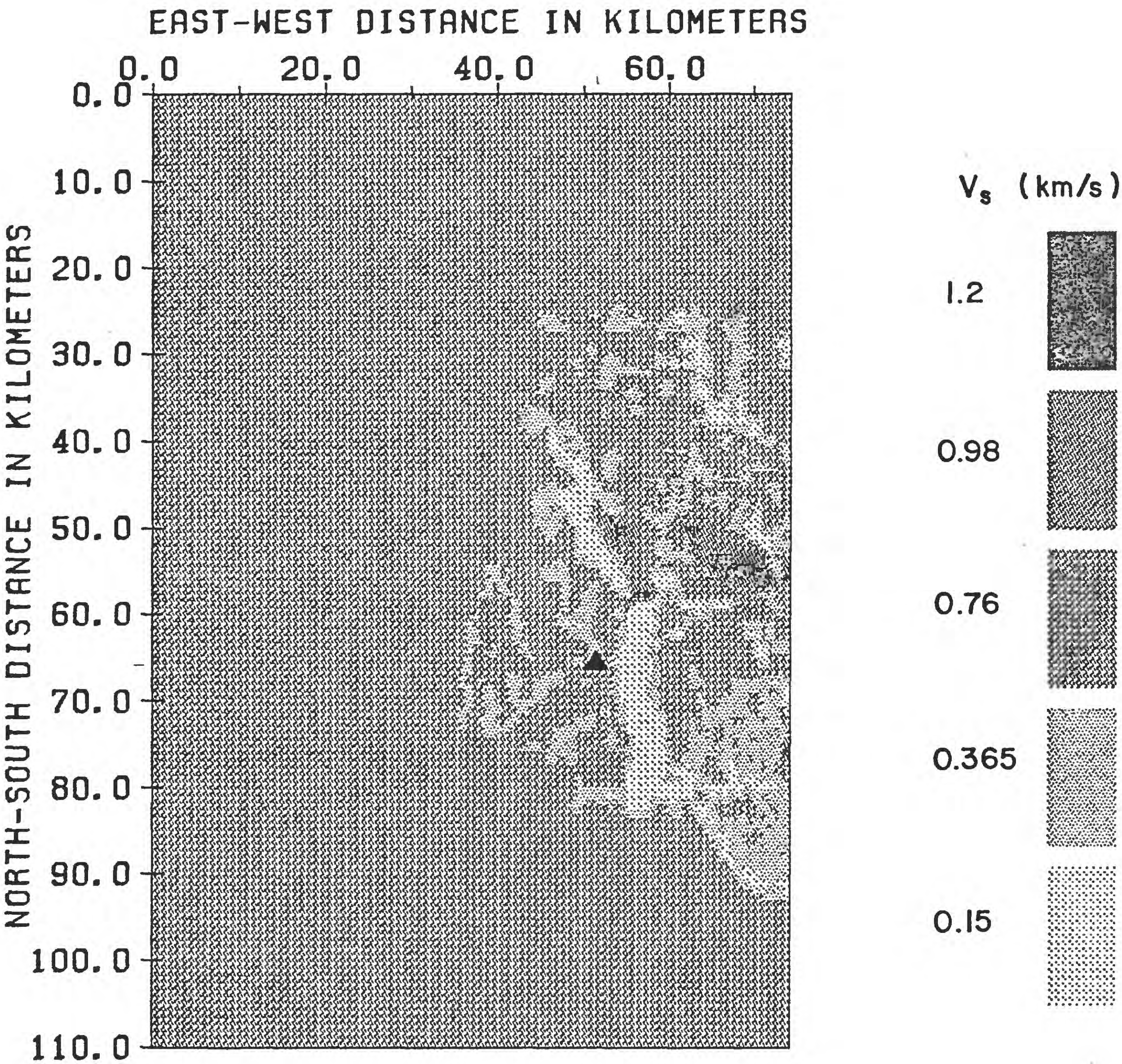

Figure 4. Horizontal distribution of S-wave speed in the sediment layer. Outside of King County, S-wave velocity is set to a uniform 720 m/s.

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ues for each layer are derived from average layer velocity using the relations:

$$\rho = 1.74\ \alpha^{0.25} \qquad (1)$$

from Anstey (1977), where Q_α is the P-wave quality factor, Q_β is the S-wave quality factor, α and β are the P and S wave speeds (km/s), and ρ is the density (g/cm3). With:

$$Q_\beta = 30\beta^{1.25} \qquad (2)$$

(Wiggins, et al., 1978) and the standard result that:

$$Q_\alpha = \frac{3}{4} Q_\beta \left(\frac{\alpha}{\beta}\right)^2 \qquad (3)$$

The velocity structure in the upper crust is a two-layer approximation to Crosson's (1976) plane-layered model. Both Crosson and Langston and Blum (1977) found evidence for a thin low-velocity zone at the base of the continental crust. Presumably such a low-velocity zone would have negligible effect on strong ground motion and it has not been included in the model.

III. THREE-DIMENSIONAL RAYTRACING

Once the digital velocity model is specified, a grid of receiver points is defined on the surface of the model and rays are traced between source and receiver. Accelerograms are synthesized using Sierra's QUIKSHOT raytrace program. QUIKSHOT is a fully three-dimensional raytracer with a WKBJ-type amplitude calculation which remains stable in the presence of caustics (Lundquist, et al. 1982, Lundquist and Mellman, 1982).

QUIKSHOT operations may be divided into three phases: setup, the shooting of a working ray set, and ray capture. In the setup phase, an array of receivers is defined, a source location and focal mechanism are input, and a ray instruction set is entered into the computer. A ray instruction is a numerical code which specifies the path a given ray takes through the model. For example, the direct S wave has one ray instruction, a ray with multiple reflections in the sediment layer has another.

After the ray instructions have been entered, the program shoots a number of working rays. These are rays with a specified ray instruction, which are shot from the source and terminate on the free surface. The ray capture algorithm then uses sophisticated gradient and search techniques in conjunction with the working ray set to find all rays which connect the source with each receiver. Finally, for each successful ray, complex amplitudes are calculated which incorporate the source radiation pattern, fully elastic reflection and transmission coefficients and geometric spreading. The effects of internal caustics, post critical phase shifts, and polarization changes at boundaries are also included in the amplitude calculation. The capture process is repeated for each station in the receiver array.

The raytrace output is fed to a post-processing program called SLIPR which organizes the result into a convenient format and performs filtering and convolution operations on the synthetic seismogram. In order to include representative source effects in the synthetic seismograms, the raytracing results have been convolved with a source wavelet suitable for a magnitude 6.5 earthquake. The wavelet chosen is the S-wave pulse from the 27 May 1980 Mammoth Lakes earthquake (14:51 GMT, m=6.3) recorded on the S15E accelerograph at Convict Lake. This accelerogram was recorded at a hard rock site very near the source and appears to be largely uncontaminated by any structure or attenuation effects. Hence it is considered to be a good representation of the acceleration source time function for a magnitude 6-6.5 event.

Anelastic attenuation is included in the synthetics by Q-filtering the source wavelet prior to convolution with the raytrace output. A separate calculation of t* (travel time divided by Q) is performed by the QUIKSHOT program for each arrival at each receiver. Hence, the synthetic accelerograms correctly account for differential attenuation effects for each ray path.

IV. RAYSET SENSITIVITY TESTING

Approximately 0.75 CPU hours on a Prime 750 computer are required to synthesize 3-component ground motion at 1600 receivers with a single ray instruction. Hence it is in the interests of efficiency to model only those ray instructions which contribute significantly to ground acceleration.

In order to determine which rays were important and which could be safely discarded, accelerograms were synthesized for an array of 14 stations in the central part of the model. These seismograms included the effect of 28 separate ray instructions including direct arrivals, converted phases, reflections off the water bottom and numerous interbed multiples. The raytrace results were convolved with a source wavelet as described above and the peak horizontal acceleration was computed for each station. Arrivals which contributed less than approximately 10% of the peak acceleration at all stations in the array were excluded from further computations.

Phases considered were the direct P and S waves with associated interbed multiples in the sediment layer, S to P and P to S conversions at the free surface with sediment layer multiples, S to P and P to S conversions at the sediment boundary, again with multiples and finally P and S waves which bounced from the upper boundary of the subducted slab before reaching the surface. Reflections and conversions off the water bottom were also included.

Not surprisingly, results show that P-waves do not contribute significantly to horizontal ground motion, given the structure in the Puget Sound Region, the 1965 focal mechanism and the large source depth. Hence, P-wave are excluded from further consideration. Slab reflections did not appear to be important and were also excluded. Extensive tests were performed to determine whether reflected or converted phases at the water bottom contributed to strong ground motion at sites near water. In general, these phases had amplitudes of only a few percent of peak, so in the interests of computational efficiency, the entire water layer was removed from the model. The eleven remaining ray instructions are the direct S, an S phase with up to five bounces in the sediment layer, an S to P conversion at the sediment boundary with one multiple, and an S to P conversion on reflection from the free surface, with two multiples. Synthetic seismograms shown in the next section incorporate these eleven phases.

V. 1965 EARTHQUAKE SIMULATION

This section describes results from a raytrace simulation of strong ground motion for the 1965 (M=6.5) earthquake. A point source at 60 km depth is used together with the focal mechanism derived from waveform studies by Langston and Blum (1977). Although some difference of opinion exists as to the position of the near-horizontal nodal plane (Chandra 1970, Isacks and Molnar 1971), most of Puget Sound lies in a quadrant where the amplitude should be very stable with respect to small changes in mechanism. Focal mechanism and hypocenter data are listed in Table 2.

Accelerograms were synthesized at each of 1584 receivers in a 48 x 33 array. The term "peak ground acceleration" (PGA) is used here to refer to the peak of the square root of the sum of the squares of the N-S and E-W ground motion time histories. No attempt was made to model absolute accelerations. Accelerations are scaled such that the observed and predicted peak accelerations match at the Tacoma strong motion station, which had a PGA of 0.067g.

The predicted log PGA contours shown in Figure 5 are strongly elongated in a north-south direction with the result that the center of the meisoseismal area lies substantially north of the epicenter. A region of erratic, but generally large, ground motion exists in the vicinity of downtown Seattle, and an area of diminished accelerations occurs east and south from this maximum. A large region of higher accelerations extends along a north-south line just northeast of the epicenter. In order to interpret the results from the 1965 simulation, accelerograms were synthesized for three additional models in which the character of the topmost (sediment) layer was varied.

Peak ground acceleration resulting from the case where bedrock is found everywhere at the surface is shown in Figure 6. In this model the variable depth and velocity sediment layer has been replaced by a uniform layer 350m thick with a very hard bedrock velocity (Vs=2.4

TABLE TWO

SOURCE PARAMETERS - 1965 SEATTLE EARTHQUAKE

DATE:	29 April 1965
TIME:	15:28 UTC
ISC EPICENTER:	47.41N 122.29W
USCGS EPICENTER:	47.4N 122.4W
DEPTH:	60 km
M_s:	6.5
M_o:	$1.4 \pm 0.6 \times 10^{26}$ dyne.cm
STRIKE:	344^o
DIP:	70^o
RAKE:	-75^o

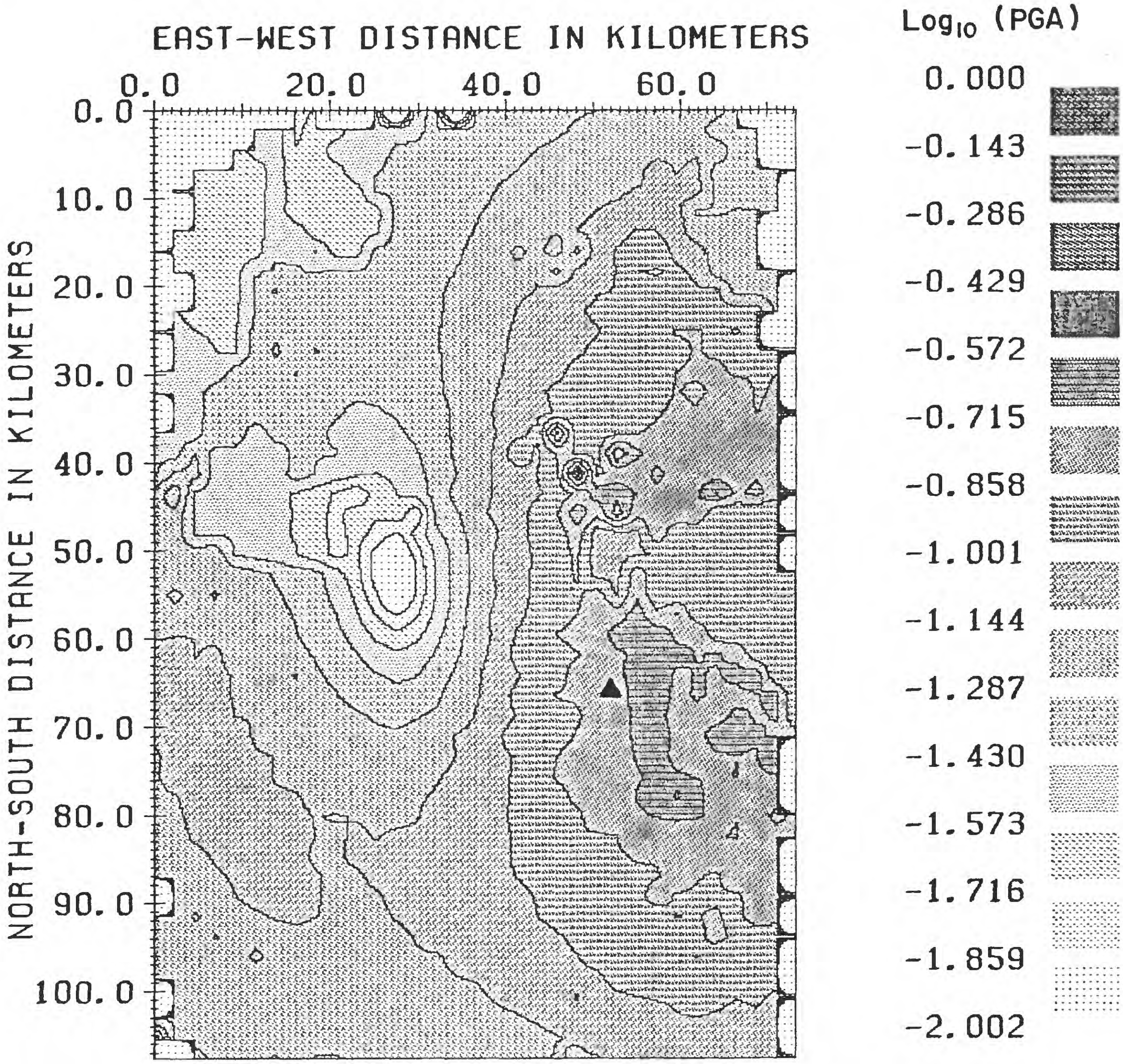

Figure 5. Contoured peak horizontal accelerations, 1965 earthquake, ISC epicenter. Note that the quantity contoured is the base ten log of acceleration, expressed as a fraction of g. Every change of 0.33 units is crudely equivalent to one seismic intensity unit (Richter, (1958), p. 140). Low values of acceleration within 2-4 km of the edge of the model are artifacts of the modeling pocedure and should be ignored. Triangle is epicenter of 1965 earthquake.

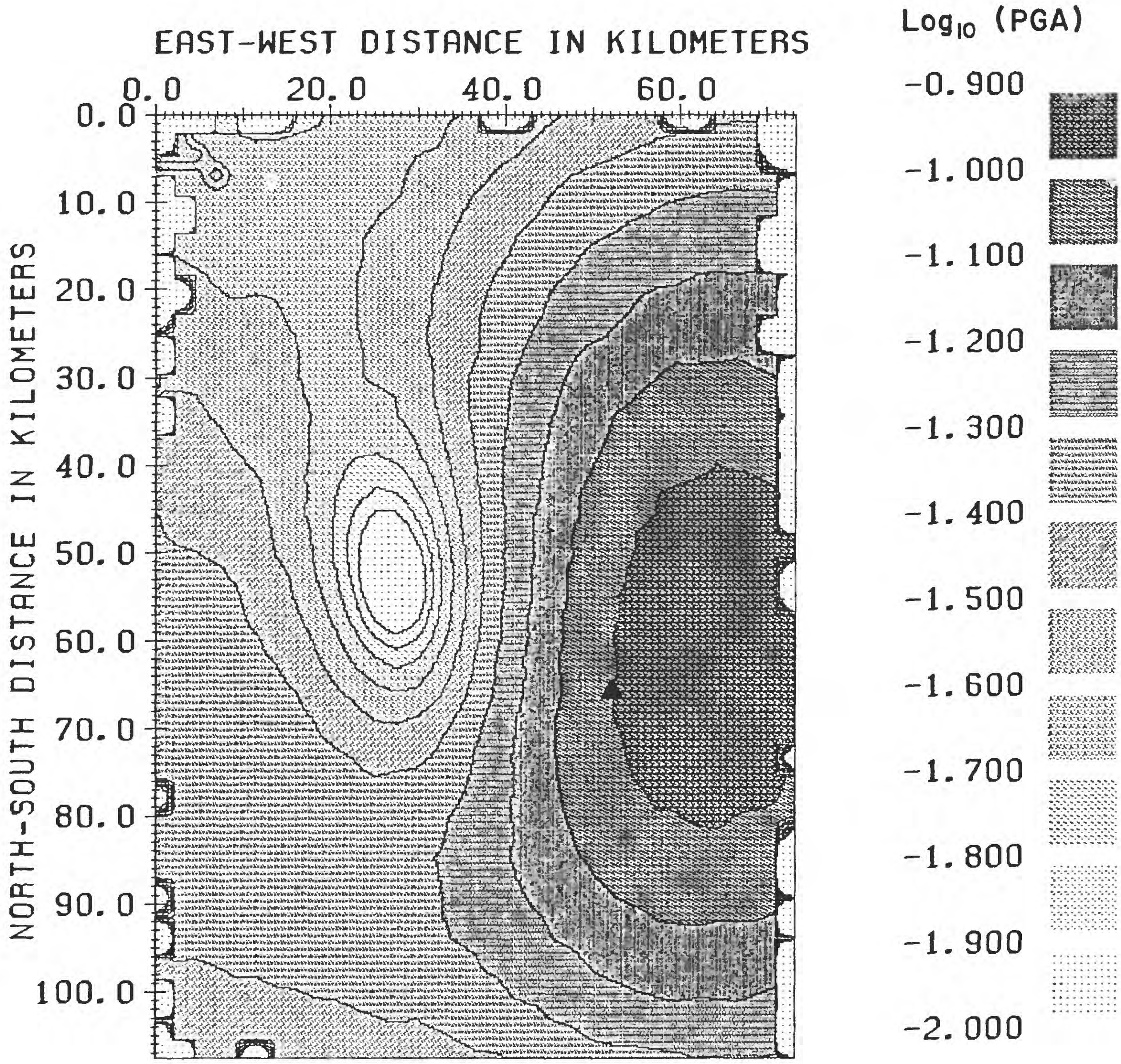

Figure 6. Contoured peak horizontal acceleration for the case of uniform bedrock at surface. Triangle is epicenter of 1965 event.

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km/s). It is apparent from this figure that the distinct asymmetry present in the PGA contours is primarily a result of the focal mechanism. Since the source is deep (60 km), geometric spreading results in only a 40% reduction in amplitude between epicenter and the edge of the model. This figure reproduces the general outlines of the PGA contours in Figure 5, however there is generally uniform ground motion near Seattle.

Figure 7 illustrates the effect of the near-surface geology on predicted PGA. In this model the basement topography illustrated in Figure 3 is replaced by a uniform layer of 350 meters thickness. The interval velocity above this layer varies horizontally within King County according to the surface geology as discussed above. Again, the focal mechanism dominates the general pattern. However, superimposed on the large-scale features are small areas of enhanced ground motion. These are associated with areas of soft alluvium at the surface. In particular, the bed of the upper Duwamish River shows up clearly as the N-S feature a few kilometers northeast of the epicenter. Increases in PGA of 50 to 100% occur here and in scattered pockets of low-velocity sediments elsewhere in the model. This result is in excellent agreement with a simple calculation for vertically incident SH waves which predicts amplification approaching a factor of two in soft sediments. Due to the large source depth, angles of incidence at the surface are always within 20 degrees of vertical.

Hopper et al. (1975) presented curves of seismic intensity vs. distance in the 1949 and 1965 Puget Sound earthquakes. They concluded that large variations in soil type, such as between the Duwamish River valley and adjacent territory, can generate increases of up to one seismic intensity unit. Figure 7 shows that our predicted values give a very similar result. Langston and Lee (in press) also found that "the total effect of the sedimentary layer is to boost high frequency amplitudes by modest factors of approximately two".

Sediment amplification effects appear to be an important cause of small-scale heterogeneity in Puget Sound ground motion. In order to

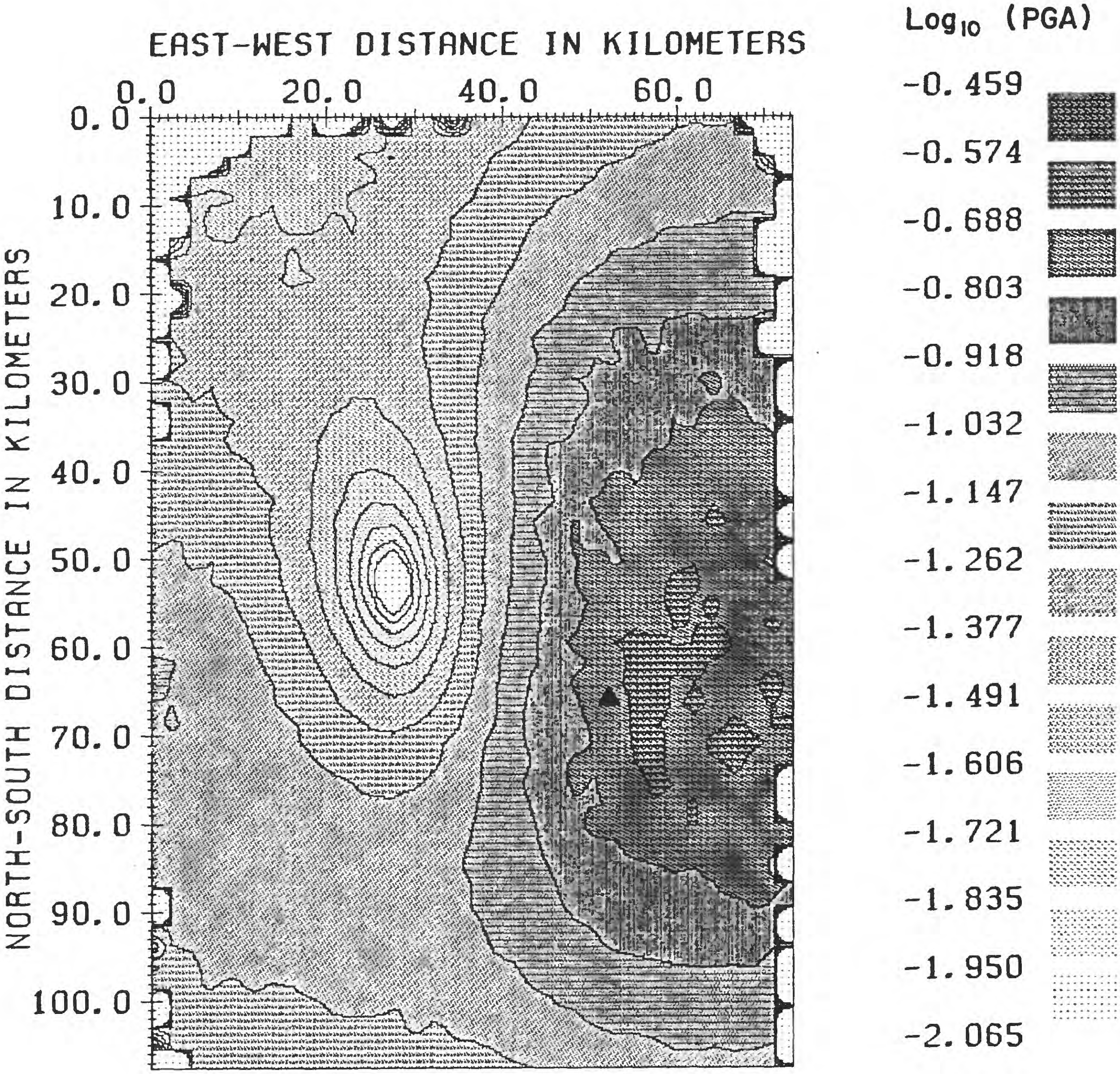

Figure 7. Contoured peak horizontal acceleration for model with a layer of laterally varying velocity but uniform thickness near the surface. Triangle is epicenter of 1965 event.

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examine the effects of focusing and defocusing by the subsurface structure, a fourth model will be considered. This model uses the topography of the sediment layer shown in Figure 3 along with a uniform, "average" S-wave speed of 720 m/s. The results are shown in Figure 8. The source of the large-amplitude medium scale variations in ground motion is now apparent. The figure shows very large, although erratic, amplification just west of downtown Seattle. This amplification is associated with focusing by the thick sediment lens shown in Figure 3, enhanced by moderately low velocity sediments at the mouth of the Duwamish River. At maximum, this focusing effect produces an amplification of a factor of five relative to the same location with a flat bedrock foundation. Should extreme low-velocity sediments occur at the surface near here, these calculations suggest that an order of magnitude increase in ground acceleration compared to bedrock is possible. It is important to note that these calculations do not consider non-linear soil behavior which, if present, would reduce or moderate the extremes in predicted PGA.

Inspection of the synthetic accelerograms from the high-acceleration region (Figure 9) reveals some details about the amplification process. In the area where very high accelerations are experienced, the peak ground motions are associated with the first and second multiple reflection within the sediments, rather than with the direct S arrival. The high amplitudes result from repeated focusing of the multiples with each reflection. Although repeated multiples are increasingly attenuated by passage through the low Q sediments, the focusing is sufficient to overcome this effect for the first few bounces.

The peak ground acceleration predicted in Figure 5 can now be seen as the product of several competing effects. The general outlines of the contours are attributable to the focal mechanism chosen, slightly modified by geometric spreading. Anywhere that low S-wave speeds are found near the surface, amplification of accelerations in the range of 50-100% can be expected and subsurface structure may cause local amplifications of as much as a factor of 5.

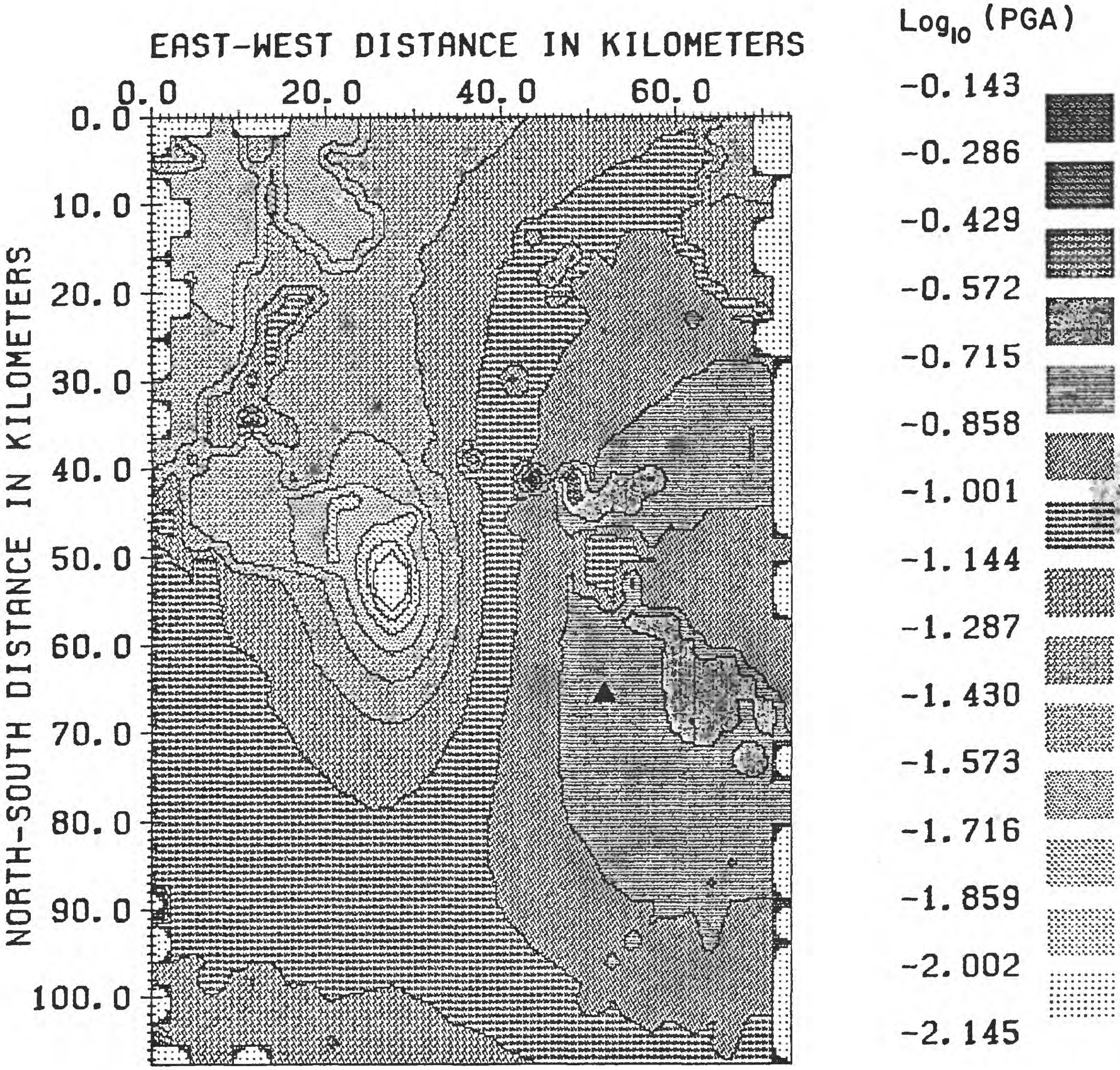

Figure 8. Contoured peak horizontal acceleration for a model with uniform velocity over basement topography. Triangle is epicenter of 1965 event.

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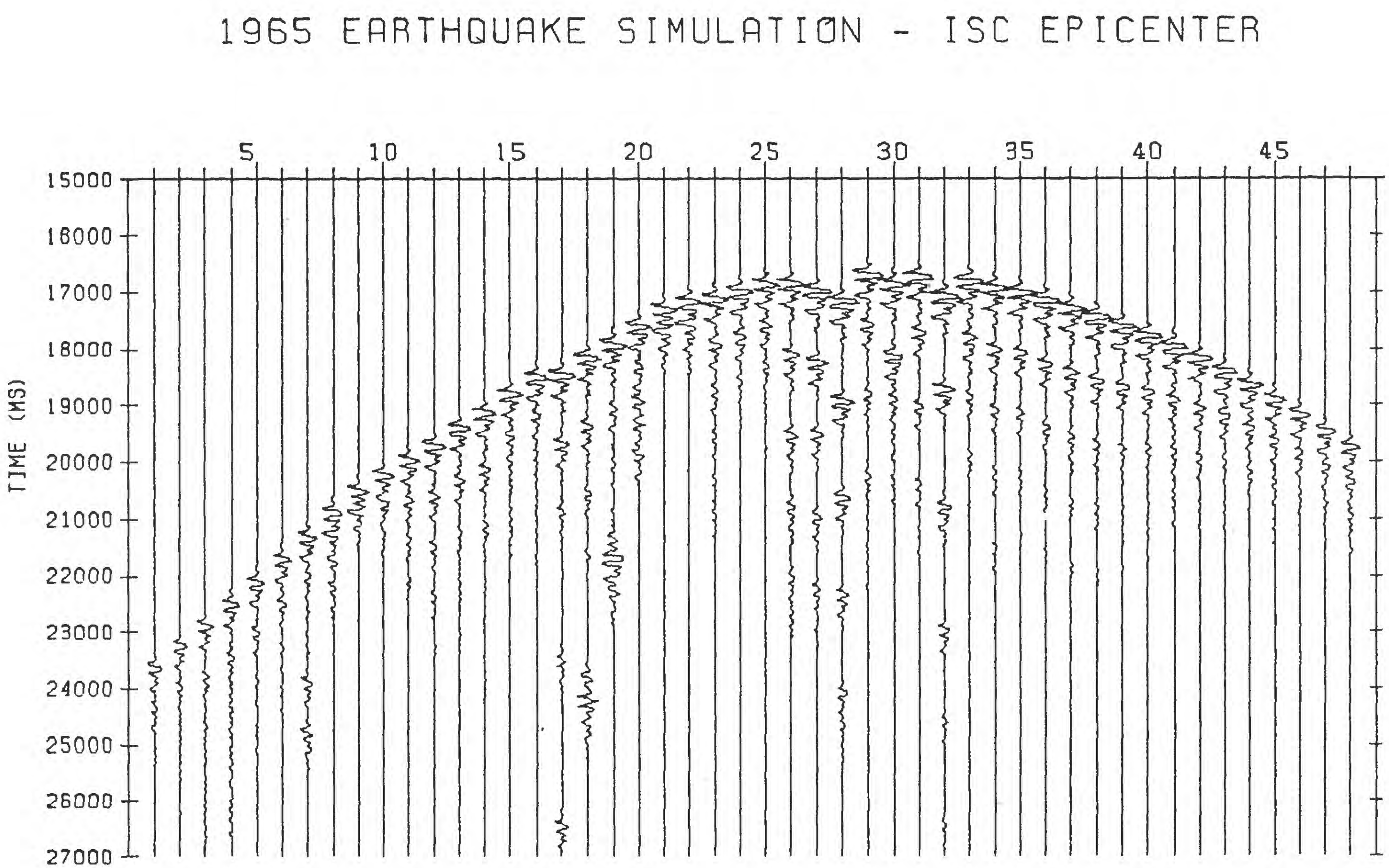

Figure 9. Time section of accelerograms along a north-south line passing through the area of largest PGA.

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Results shown here suggest that ground motion amplification relative to bedrock at a given site can be expressed as the product of a sediment amplification factor and a structure amplification factor. The first quantity would depend on local sediment velocity and is largely independent of source location, provided the source is sufficiently deep or distant to ensure near-vertical ray paths at the surface. The second factor, intended to account for sub-surface focusing and Q effects, may be strongly hypocenter-dependent. Note that even where focusing is unimportant, prediction of PGA should not be done on the basis of soil type alone. These results, along with those of Apsel, et al. (1983) demonstrate that additional factors such as soil thickness, Q, and rupture depth have a profound influence on strong ground motion.

Duration of strong ground motion can also be estimated from the raytrace results. "Duration" is defined here to mean the time elapsed between the first and last occurrences of acceleration exceeding 10% of peak. Figure 10 shows that long duration accelerations, more than ten seconds, occur over the two large sedimentary basins, and that durations on bedrock are very short. The N-S swath of long durations in the southern basin is associated with the Duwamish River Valley. These long durations are probably unrealistic since in the model, the low-velocity river-bed alluvium is assumed to extend all the way to bedrock.

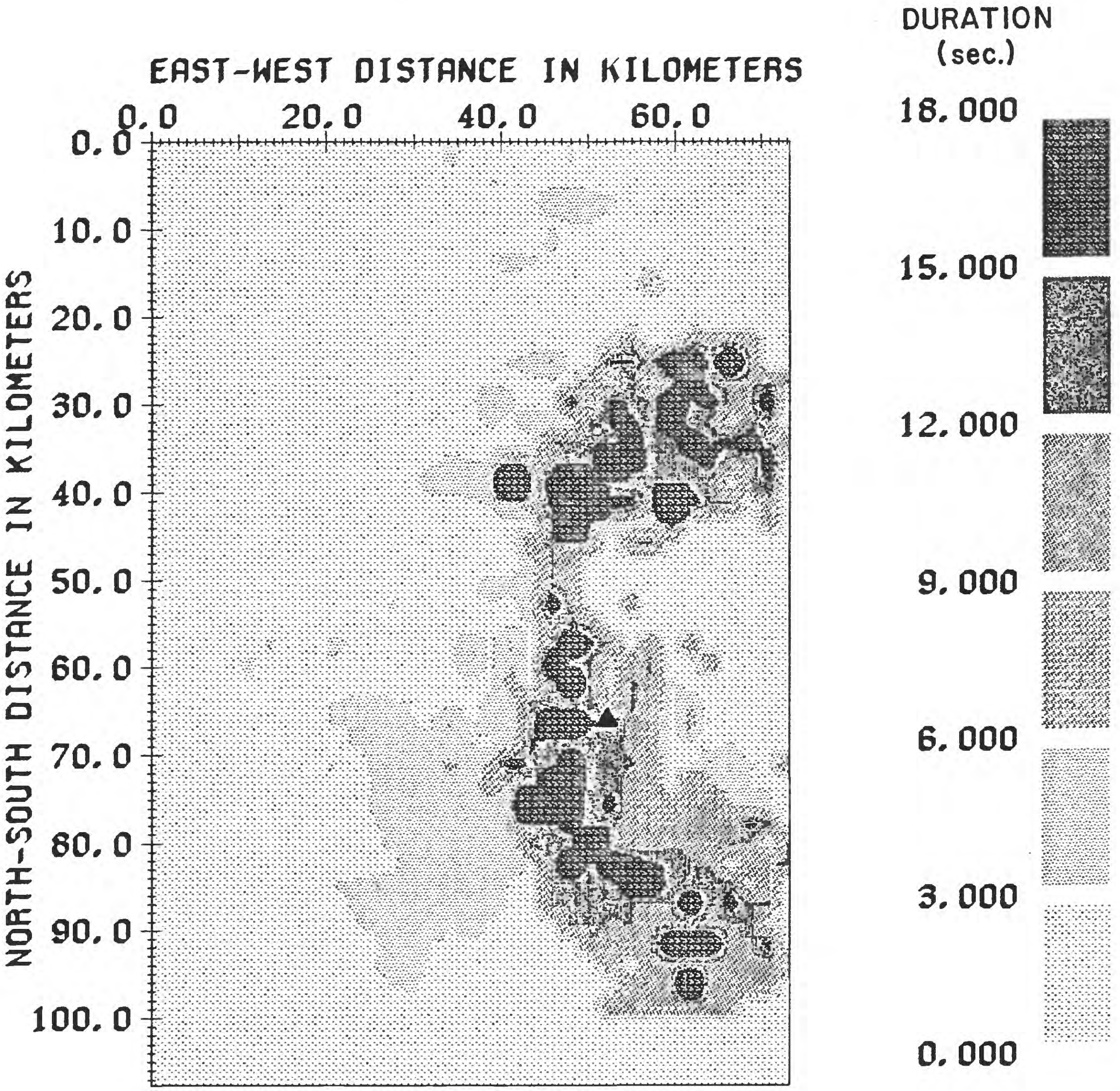

Figure 10. Predicted duration of strong ground motion in 1965 event. Triangle is epicenter of 1965 event.

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VI. DISCUSSION OF RESULTS

Unfortunately, very little quantitative acceleration data is available for the 1965 Seattle earthquake. In Figure 11, PGA values from the raytrace model are compared with data from Japanese earthquakes, as a function of epicentral distance. Japanese data are extracted from Mori and Crouse (1981) and include all entries in that volume with magnitudes between 6.0 and 6.8, depths between 40 and 80 km, and epicentral distance less than 75 km. Apart from a slight tendency for the predicted values to lie below the observed ones, there is good agreement. The minor discrepancy in mean value is probably due to the smaller average depth (47 km) of the Japanese events.

Prediction of PGA vs. distance is a difficult problem. This study provides a simple PGA curve that is consistent with both the trend in observed data and the scatter. Past attempts at simulating PGA vs. distance have generally failed to reproduce the scatter in the real data, which implies that those models were overly simplistic.

At the time of the '65 event, accelerographs were in operation at Seattle, Tacoma, and Olympia, with Carder displacement meters at the first two sites (Algermissen and Harding, 1965). When the raytrace results are scaled to match the 6.7% g PGA at Tacoma, the predicted value at Seattle is 10.6% g, in excellent agreement with the 11% observed. Although Langston (1981) did not attempt to calculate accelerations, his predicted peak velocity ratio at these two stations differs from observations by a factor of 2-3. Note that the close match of observed and theoretical PGAs was achieved without the kind of large horizontal variation in Q proposed by Shakal and Toksoz (1979).

Recorded accelerations at Olympia exceed 16% of g, far larger than the 3.6% g predicted by the model. Olympia is located at the extreme southern edge of the model in an area where the three-dimensional subsurface geology is poorly known. This study strongly suggests that the Olympia record is biased by unquantified subsurface structure.

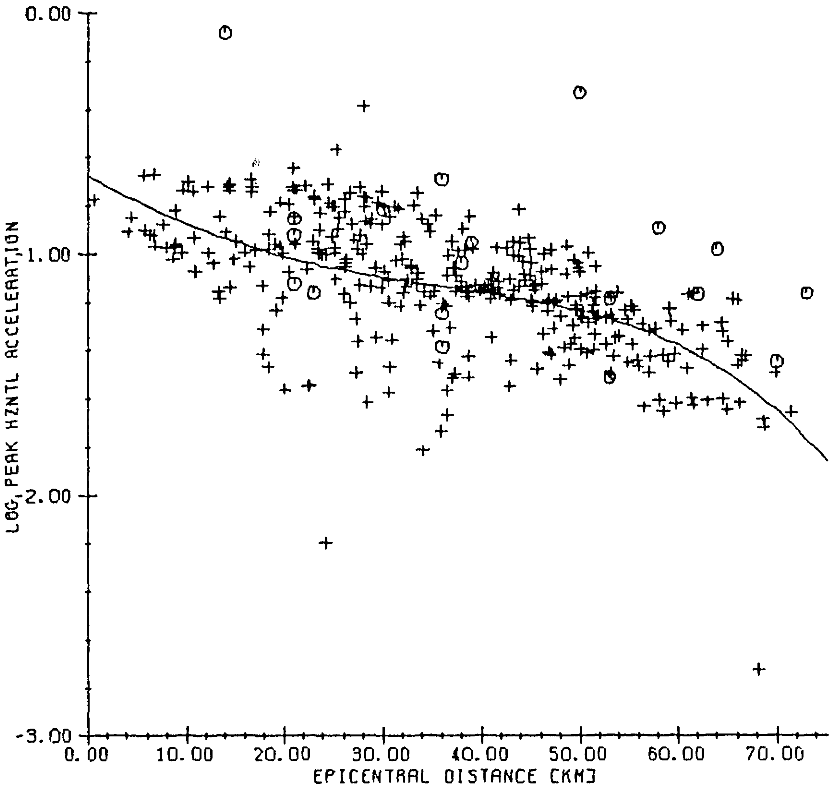

Figure 11. Plot of logarithm of peak ground acceleration (as fraction of g) vs. epicentral distance. Pluses (+) are predicted values from raytrace simulation of 1965 event. Circles are data from Japanese earthquakes given in Mori and Crouse (1981).

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Some sense of the variation in ground acceleration over a larger area can be gathered by careful examination of damage reports from this event. Yount (1983) has summarized reports of damage in the Seattle area:

> "Building damage in 1965 was relatively heavy in the lower Duwamish River area and the southern downtown area of Seattle where unconsolidated Holocene alluvium and artificial fill make up most of the substrate; but damage was relatively light in the upper Duwamish River valley just a few kilometers to the south, where similar geologic materials make up the substrate . . . Similarly, the most severe residential building damage, mostly to brickwork and chimneys, appeared to be concentrated in West Seattle, an area underlain by compact Pleistocene sands and silts; in contrast, only light damage was reported for nearby regions of Seattle such as Beacon Hill and Magnolia . . . underlain by similar . . . sediments."

The synthetic results are in excellent qualitative agreement with this description. It is generally agreed that the area of greatest damage in the '65 event was the Harbor Island region. This small island, which consists mostly of artificial fill, sits at the mouth of the Duwamish River where the river empties into Puget Sound. The model results predict this point as the location of largest peak horizontal ground acceleration, with values approaching 0.6 g. Previous investigators (e.g., Steinbrugge and Cloud, 1965) have suggested that all of the amplification at the Harbor Island site is attributable to poor quality soil. The results presented here indicate that a large part of this anomaly is due to focusing by sub-surface structure, which is then nearly doubled by the presence of low velocity sediments. The West Seattle area mentioned in the quotation from Yount suffers from the same focusing effects. However, at that site the sediments provide only 50% amplification relative to bedrock, resulting in a somewhat lower peak acceleration. Portions of the upper Duwamish River valley, described by Yount as having diminished ground response compared to areas of similar surface geology, are located near shallow bedrock, and the model predicts smaller peak accelerations there.

Langston (1981) pointed out a large discrepancy between the observed and predicted S-wave polarization angles at Seattle in the 1965 event. The Carder displacement records clearly indicate a polarization angle of approximately 40-50 degrees (clockwise from north) whereas both Langston (1981) and this study predict values near -80 degrees. Langston points out that the velocities integrated from the accelerograms and those differentiated from the displacement records appear to agree. Hence, if an instrument reversal is to blame, the reversal must have occurred on the same component on both the acceleration and displacement instruments. Langston rejects this possibility and proposes that "extreme lateral heterogeneity" may be the cause.

At first glance, this possibility seems attractive, since the raytrace results show that rays arriving at the Seattle station may pass through the face of the Mt. Si fault. Near the presumed ray intersection point there is bedrock on one side of the fault and low-velocity sediments on the other. A large number of tests were conducted using detailed velocity models of this area and a variety of fault strikes and dips to see if the polarization angle anomaly could be reproduced. Although many geometries were considered, along with exotic phase conversion schemes, no satisfactory results could be obtained. Careful consideration of the geometry suggests that even under the most extreme circumstances, polarization of rays transmitted through steeply dipping interfaces cannot be rotated through an angle greater than 90 degrees.

Langston (1981) states that his acceleration data from Seattle were digitized and corrected from the records reproduced in Algermissen and Harding (1965). Although it is difficult to compare the corrected and uncorrected data, it appears that the S58W component displayed in Langston's paper and the same component printed in the earlier work are reversed. Further, it is not apparent from the Algermissen and Harding figure whether the direction given is for pendulum motion or for ground motion. In order to avoid these difficulties we will ignore the Carder records and instead use the doubly integrated accelerograms shown in Shannon and Wilson, et al. (1980). The direction of motion and sign conventions used are clearly stated and doubly integrated records can provide excellent estimates of ground displacement (Trifunac and Lee, 1974).

It is apparent from the integrated records that both horizontal components are reversed relative to the way they appear in Langston. This means that the actual observed polarization angle is approximately -125 degrees, that is about 30-40 degrees clockwise from our prediction. Inspection of the focal mechanism indicates that only extreme variations in the fault planes could cause this discrepancy. Hence the 30-40 degree difference is probably caused by propagation through locally complex velocity structures.

As mentioned earlier in this report, the detailed topography of the sediment layer was digitized from available maps. These maps are in turn, heavily interpreted from limited data, and some discussion of incorrect layer geometry is in order. It is apparent that detailed structure of the sediment layer significantly affects the results in two places. These are the region of high accelerations beneath downtown Seattle, and the areas of diminished ground motion to the east and south of the maximum. By fortunate coincidence, it is precisely these areas which have best control of sediment depth, judging by the density of data points in the map by Yount et al. (1983). Downtown Seattle shows numerous geotechnical boreholes, and data from shipboard echo sounders extends into the harbor from Puget Sound. Hence, the digitized basement horizon is probably a good representation of the real interface and is not likely to be a large source of error. The reader is reminded that detailed geologic information is used only within King County. The rest of the model is assigned a horizontally uniform velocity for the sediments.

A potentially more serious source of error arises from limitations in the raytrace method. This method is strictly correct only in the limit of infinite frequency. This means that raytracing produces accurate results only when the size of geologic structures being considered is comparable to or longer than a wavelength. Given an "average" S-wave speed of 720 m/s in the sediments, and the dominant frequency of about 5 Hz in the source wavelet, the characteristic wavelength appears to be about 150 meters. Since the important focusing effect arise from a lens with sediments more than a kilometer thick, these results appear to be well within the range where raytracing is valid.

VII. SUMMARY

We conclude that three-dimensional raytracing provides an accurate and relatively easy way to estimate variations in strong ground motion arising from sediment and structural amplification. Our simulation of the 1965 Seattle earthquake correctly predicts the ratio of peak ground accelerations at Seattle and Tacoma as well as accurately modeling the observed variations in seismic intensity. The predicted variation in peak ground acceleration with distance reproduces both the trend and scatter seen in observations of similar Japanese earthquakes.

For deeper earthquakes in the Puget Sound region, sediment effects may be found wherever soft soils occur at the surface and can yield local amplifications of up to a factor of two compared to bedrock. Amplification by subsurface structures may generate local increases of up to a factor of five, although only in very confined areas. The inopportune combination of focusing and low velocity sediments at the same site could conceivably produce a factor of ten magnification in accelerations compared to bedrock.

Amplification of acceleration relative to bedrock may be expressed as the product of a sediment amplification factor and a structure amplification factor. The former is dependent upon the local sediment velocity but is largely independent of source locations, provided that the source is deep. The latter is probably somewhat hypocenter dependent, but is important only in a few isolated areas.

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SCIENTIFIC AND ENGINEERING LESSONS LEARNED FROM DAMAGING HISTORIC EARTHQUAKES

by
Walter W. Hays
U.S. Geological Survey
Reston, Virginia 22092

INTRODUCTION

A damaging earthquake provides an opportunity to acquire unique technical information about the physical effects of ground shaking, surface fault rupture, earthquake-induced ground failure, regional tectonic deformation, and inundation from seiches and tsunamis (Figure 1). This information and the facts and lessons derived from it can be utilized in research studies, in the assessment of earthquake hazards and risk for specific urban areas, in mitigation and preparedness actions, and in the implementation of loss-reduction measures (Hays, 1981). The following types of technical investigations are typically conducted following an earthquake (Algermissen, 1978; Marshall, 1985):

1. Geologic Studies - Conduct field work to determine the nature, degree, and spatial distribution of surface faulting, regional tectonic deformation, landslides, liquefaction, and inundation from tsunamis and seiches.

2. Seismological Studies - Deploy arrays of portable seismicity instruments to improve the locations of earthquakes in the aftershock sequence, to define the spatial extent of the fault rupture zone, and to determine the focal mechanism(s).

3. Engineering Seismology Studies - Deploy arrays of portable strong motion accelerographs to measure the characteristics of strong ground motion at various locations. When used in conjuction with accelerograms of the main shock, these records can be used to derive soil amplification factors, to measure duration of shaking, and to estimate the amplitude and frequency characteristics of the ground acceleration, velocity, and displacement at locations that sustained damage, but that did not record the main shock.

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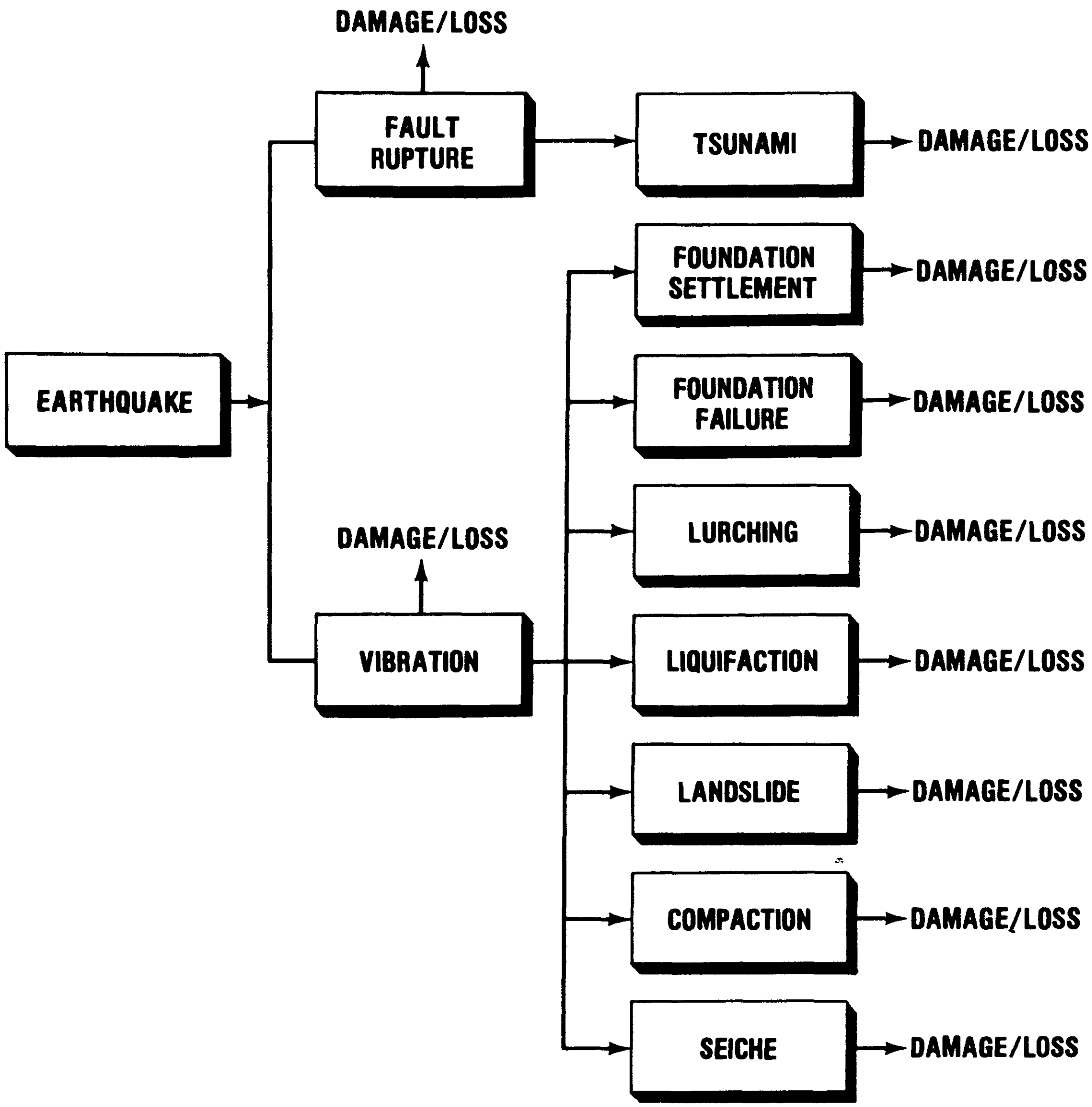

Figure 1.--Schematic illustration of the types of physical effects that can occur in an earthquake

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4. Engineering Studies - Conduct investigations on a building-by-building scale to determine the nature, degree, and spatial distribution of damage to low- and high-rise buildings, lifelines, single family dwellings, and critical facilities. The quantification of damage is given in terms of Modified Mercalli intensity and/or ground motion parameters and provides information needed to set design criteria and construction practices (Hays, 1985).

Collectively, these studies provide a basis for:

- improving the understanding of the causative physical mechanism of surface faulting, regional tectonic deformation, landslides, liquefaction, seiches, and tsunamis.

- correlating the occurrence of earthquakes with regional tectonic elements to define seismogenic sources (and in coastal areas tsunamigenic sources).

- identifying regional tectonic elements that are active as well as inactive.

- improving the knowledge of the amplitude, spectral composition, temporal, and spatial distribution of ground shaking and its correlation with damage.

- improving the state-of-knowledge on seismic zoning.

- improving the state-of-practice on land use and engineering design and construction.

- improving the seismic design provisions of building codes.

- improving the state-of-practice in lifeline engineering

- legislation to implement new knowledge.

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RESULTS OBTAINED FROM PAST EARTHQUAKES

In the past two decades, a major effort has been made by the Federal Government, the U.S. Geological Survey, the National Science Foundation, the Federal Emergency Management Agency, the Earthquake Engineering Research Institute, and other institutions to learn as much as possible from damaging earthquakes. Because major damaging earthquakes have occurred relatively infrequently in the United States, damaging earthquakes in foreign countries have also been studied, particularly in those cases when either their tectonic setting was similar to that of a part of the United States or when the design and construction practices in the country were similar to those used in the United States. Some of the most important historic earthquakes of the past two decades that have contributed important knowledge toward the goal of earthquake hazards reduction include:

1. 1964 Prince William Sound, Alaska, earthquake--This great (M_W= 9.2) earthquake occurred in one of the most active tectonic areas of the world where the Pacific tectonic plate is being subducted under the North American tectonic plate at a rate of about 6 cm/year. It caused widespread regional tectonic deformation over an area of at least 77,000 square miles--a characteristic feature of great earthquakes (Hansen and others, 1966). Structural damage and collapse occurred in buildings located at distances of more than 60 miles from the epicenter. Damaging tsunami waves were generated by the earthquake and affected both local and very distant locations. Sensitive clay formations failed and caused extensive ground failures in 30 blocks of downtown Anchorage. No strong motion accelerograms were recorded in the earthquake. The science of earthquake prediction was initiated after the great Prince William Sound earthquake.

2. 1971 San Fernando, California, earthquake--The moderate (M_S = 6.4) San Fernando earthquake occurred on a thrust fault in the Transverse Ranges structural providence, not previously recognized as active. It produced the largest horizontal ground shaking ever recorded (at that time) at a site underlain by rock near the epicenter--1.24g at Pacoima

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dam (Department of the Interior and Department of Commerce, 1971). Severe damage was experienced in buildings designed according to the seismic design provisions of a modern building code. More then 200 accelerograms were added to the existing strong ground motion data sample. These records provided a basis for comprehensive damage studies and the reevaluation of seismic design criteria for critical facilities (hospitals, dams, nuclear power plants) and lifelines (highways, bridges, gas, water, electric, sewers, airports, harbors). Lifeline engineering began as a result of the extent of damage sustained by lifelines in the earthquake. The Pacoima dam accelerogram stimulated debate over the effects of soil and rock and the local topography on ground shaking. An extensive array of portable strong motion instruments were deployed to record the aftershock sequence. These data provided information on site amplification, the effects of topography on ground motion, and the estimated spectral composition of the main shock ground motion at sites which sustained damage, but did not record it. The concept of a sesimic safety element as a part of the community's general plan was introduced after the San Fernando earthquake.

3. The 1972 Managua, Nicaragua, earthquake--This moderate (M_s = 6.2) earthquake occurred on a shallow well known strike-slip fault system beneath the city as in 1931 (Earthquake Engineering Research Institute, 1973). It caused severe damage to buildings that were designed according to the earthquake-resistant design provisions of a modern building code. A network of portable strong motion instruments were deployed to augment the single strong motion record of the main shock obtained at Esso Refinery (peak horizontal acceleration of 0.39g and peak vertical acceleration of 0.33g). They provided insight into the characteristics of ground shaking at sites that did not record the main shock and site effects. The city was relocated in the 1970's to avoid the system of active faults identified in the postearthquake investigations.

4. The 1976 Guatamala earthquake--This large (M_s = 7.5) earthquake was generated by left-lateral slip on the Motagua fault, a well known

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strike-slip fault zone marking the active boundary between the North American and Caribbean plates (Espinosa, 1976). The fault ruptured over a distance of about 180 miles, the most extensive surface rupture in the Northern Hemisphere since the 1906 San Francisco, California, earthquake which was generated by right-lateral slip on the San Andreas fault. The westward propagating fault rupture caused extensive damage to buildings, roads, and the railroad system. Structural damage from the ground shaking was extensive, ranging from hospitals and buildings in Guatemala City designed in accordance with the seismic provision of a modern building code to the collapse of nonengineered adobe structures in a number of communities located 10 to 60 miles from the epicenter. Hundreds of landslides were triggered by the ground shaking generated by the main shock and the thousands of aftershocks that followed during the next several months. Although no accelerograms of the main shock were recorded, the Modified Mercalli intensity data obtained from detailed surveys of the damage distribution provided a basis for constructing a preliminary seismic zoning map of Guatemala for use in redevelopment of the city. Earthquake prediction was stimulated by this earthquake. The National Earthquake Hazards Reduction Program of the United States was initiated in 1977, partly as a result of the magnitude of this disaster.

5. The 1976 Tangshan, China, earthquake--This large (M_s = 7.8) earthquake that occurred under Tangshan was a surprise. Tangshan was located in a seismic zone of the Chinese building code that did not call for earthquake-resistant design. The buildings of the city, consisting mainly of unreinforced brick, were unable to resist the strong ground shaking and the forces of the dynamic fault rupture. Eighty-five percent of the city's buildings collapsed or were severely damaged and several hundred thousand people were killed. More than 6 years were required to rebuild one-half of the city.

6. The 1978 Argentina earthquake--This large (M_s = 7.4) earthquake produced a very important new result--that significant liquefaction can occur at distances of more than 120 miles from the eipcenter of an

earthquake. This result means that the potential for liquefaction at a site must be considered for levels of ground shaking as low as Modified Mercalli intensity VI when saturated, young, fire grained sand deposits exist at the site.

7. The 1979 Imperial Valley, California, earthquake--This moderate (M_s = 7.5) earthquake which had its epicenter in Mexico on the well known Imperial fault occurred in the midst of a dense array of seismic instruments that included both short-period vertical and strong-motion seismometers (Johnson and others, 1982). It provided a unique opportunity to study in detail the changes in seismicity both attending and preceeding a moderately strong earthquake and the characteristics of ground shaking producing damage. The earthquake generated the most comprehensive set of strong ground motion data ever recorded from a damaging earthquake. The data were unique because they included: a) the first set of accelerograms ever obtained close to a faults rupture zone activated in an earthquake, b) the first data set of accelerograms from an extensive array located in a severely damaged building (the Imperial County Services Building), and 3) the first data set from an array on a highway overpass bridge located less than 1/2 mile from the fault rupture zone. The strong motion data also included the largest vertical ground acceleration (1.66 g) ever recorded anywhere in the world. Because another earthquake of about the same magnitude had occurred in the Imperial Valley in 1940, comparative studies of the distribution of damage and the correlation of intensity data with strong ground motion parameters were possible. For the first time, data were available to extend seismic wave attenuation to the near field for strike-slip faults.

8. The 1980 El Asnam, Algeria, earthquake--This large (M_s = 7.3) earthquake, the largest historic earthquake of North Africa, occurred as a consequence of the collision of the Eurasian and African tectonic plates. The Oued Fodda fault, a well known 26 mile long active thrust fault, ruptured the surface from the southwest to the northeast over a distance of 21 miles. About 85 percent of the buildings in El Asnam (now called Ech Cheliff located 6 miles east of the eipcenter)

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collapsed or suffered severe damage (Earthquake Engineering Research Institute and the National Research Council, 1982; Unesco, 1985). Although no records of the main shocks were obtained, engineers conducting post earthquake investigations concluded that the level of vertical ground acceleration exceeded the horizontal acceleration and may have approached 1g. Construction was frozen in Ech Cheliff for more than 4 years in order to permit the completion of a comprehensive seismic microzoning study of Northern Algeria and the incorporation of the results in land use, building codes, and construction practices. The Algerian building code was modified extensively to reflect the new knowledge gained in the seismic microzoning study. Damaging earthquakes had also occurred in the vicinity of Ech Cheliff in 1922, 1934, and 1954.

9. The 1983 Coalinga, California earthquake--This moderate (M_s = 6.7) earthquake occurred in an area of moderate seismicity along the eastern front of the Coast Ranges (Earthquake Engineering Research Institute, 1984). It occurred on faults in Anticline Ridge which, although they had been identified previously as potentially seismogenic, were not considered as the likely location of the next moderate earthquake in California. The ground shaking at Pleasant Valley, 5 miles from the epicenter, was 0.54g horizontal and 0.37g vertical. The earthquake devastated the central business district of Coalinga, which consisted mainly of unreinforced 1- and 2-story brick masonry buildings constructed in the early part of the 20th century. In contrast, newer reinforced brick, block masonry, or reinforced concrete buildings performed very well sustaining only nonstructural damage. The earthquake demonstrated that an industrial facility (e.g., oil company facilities) can withstand high ground motions if its structures are well designed and constructed and if its equipment is anchored. Schools built before the 1933 Field Act either collapsed or had to be demolished; whereas, schools built after 1933 performed well with only nominal damage.

10. The 1983 Borah Peak, Idaho, earthquake--This large (M_s = 7.3) earthquake provided conclusive validation of the importance of

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studying Holocene (11,000 years B.P.) and Late Pleistocene (125,000 years B.P.) fault scarps to assess the potential for future large earthquakes (Stein and others, 1985). In the Borah Peak earthquake, a 21 mile long normal fault rupture was formed. It repeated with astounding precision the Holocene fault scarp that had been excavated and examined in detail 10 years earlier, proving once again that Holocene fault scarps provide an unsurpassed tool for identifying likely sites in the Great Basin for future earthquakes. In contrast, microseismicity provided no clue of the 1983 earthquake; no earthquakes having a magnitude greater than or equal to 3.5 have occurred in the epicentral region of the Borah Peak earthqauke during the past 20 years. About 30 giant sandblows formed or were revitalized near the epicenter assigned a Modified Mercalli intensity zone VII. The fault slip, length, and width of the 1983 earthquake provide a technical basis for assessing the maximum seismic moment and magnitude of future seismic events, especially in the heavily populated Wasatch front, Utah, which has not experienced a large earthquake since the area was settled in 1845.

11. The 1985 Chilean earthquake--This large (M_s = 7.8) earthquake occurred in the subduction zone west of Chile where the Nazca tectonic plate is being subducted under the South American tectonic plate (Earthquake Engineering Research Institute, 1985). The Nazca plate dips to the east under Chile at approximately 20^o. Damaging earthquakes have occurred in the subduction zone near Chile about once every 10 years. The largest earthquake in history (M_w = 9.5) occurred in 1960. The 1985 earthquake had special seismological significance because an extensive network of strong ground motion accelerographs were operating at the time of the earthquake and some 30 records of the ground shaking were obtained. The levels of peak horizontal and vertical ground acceleration reacted 0.67g and 0.85g respectively. This data sample, the first comprehensive sample from a subduction zone earthquake, showed that the ground shaking was strong, rich in both high and low frequencies, and had long duration. Although damage from the earthquake was extensive and losses reached approximatley $2 billion, many modern reinforced concrete buildings performed very

well. As expected, adobe buildings were generally destroyed and small wooden homes were typically undamaged. A reinforced concrete hospital in San Antonio sustained considerable structural damage. Many buildings experienced foundation failure or minor settlement due to ground failures. Water systems were severly affected due to ruptures of the aqueducts. The death (176) and injury (2,500) tolls relative to the damage were surprisingly low. Information from this subduction zone earthquake is relevant for Puerto Rico, the Puget Sound, Washington, area, and Southern Alaska, three areas of the United States having the potential for large to great subduction zone earthquakes.

12. The September 19, 1985, Mexico Earthquake--This great earthquake, initially rated as $M_s = 7.8$ but later upgraded to $M_s = 8.1$, occurred as a consequence of subduction of the Cocos tectonic plate beneath the North American plate. The existence of a possible seismic gap in this portion of the Cocos plate and a general forecast of a large earthquake having an average reucrrence interval of about 35 years had been made in 1981. The specific time of the earthquake had not been predicted, however. This earthquake was noteworthy because more than 200 tall buildings located in Mexico City, about 250 miles from the epicenter, collapsed partially or totally, causing an estimated 5,000-10,000 deaths, numerous injuries, and economic losses of $5-10 billion. The extraordinarily high degree of damage at this large epicentral distance was partly due to amplification of the long period ground motion by the 50 meters thick water--saturated sediments of a former lake bed forming the foundation under Mexico City. The lake beds were recognized in 1964 by Zeevaert as having a characteristic site period of about 2 seconds, the natural period of vibration of a typical 20-story building. Past distant earthquakes (e.g., 1962 Mexico earthquake) had also caused damage in Mexico City that was attributed to site amplification. In the 1985 earthquake, six buildings collapsed at the Mexico General Hospital and about 400 doctors, nurses, and patients were trapped in the ruins of the Juarez hospital located 8 blocks from the Presidential Palace. Government buildings, as a group, sustained considerable damage. Long distance

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telecommunications with the rest of the world was eliminated for several days after the earthquake due to the destruction of the main microwave transmitter and the lack of a redundant system. Because of prior planning by US and Mexican scientists and engineers, a number of strong motion accelerographs were in place at the time of the earthquakes. These strong motion data, together with that data acquired in the March 3, 1985, Chile earthquake provide an unpresidented strong-ground motion data sample for subduction zone earthquakes. A building code as strict as any adopted in the United States had been adopted and implemented in Mexico City since 1977. It included a factor for soil conditions.

CONCLUSIONS

On the basis of world wide experience with damaging earthquakes, the following lessons have been learned:

1. Earthquakes tend to recur where they have occurred in the past. The recurrence intervals for great earthquakes are now thought to range from about 1 per century in Alaska, to about 1 every 140 years in California, to about 1 every 500-700 years in the Mississippi Valley area. Moderate and large earthquakes occur more frequently.

2. A long fault (greater than 20 miles) is required to generate a large or a great earthquake.

3. The parameters of the fault (rupture mechanics, length, width, slip rate, type) control the main features of the amplitude, frequency composition, and duration of ground shaking that is input to the foundation-structural system.

4. An earthquake-resistant building has a lateral-force-resisting system that is:

    a) continuous (transfers all forces from their point of application to their point of resistance),

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b) <u>ductile</u> (materials are stable when deformed beyond yield limits), and

c) <u>complete</u> (no missing links, inadequate joints, or brittle elements).

5. The primary cause of damage to buildings are:

a) use of lateral-force-resisting systems that are <u>not</u> seismically resistant (for example, unreinforced masonry, adobe, brittle concrete columns),

b) omissions in engineering analysis (for example, neglect of torsion effects, overturning effects, static equilibrium of all forces),

c) lack of adequate connections and detailing,

d) poor quality of construction,

e) underestimation of the amplitude, frequency composition, and duration of ground shaking that the building will experience in this lifetime, and

f) underestimation of the geotechnical properties of the foundation materials with respect to their potential for failure under the ground motion load.

Significant advances have been made and will continue to be made in direct proportion to our ability to take advantage of the opportunity to learn from damaging earthquakes and to correct our mistakes.

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THE 19 SEPTEMBER 1985 MEXICO EARTHQUAKE: TECHNICAL PROBLEMS

by
Walter W. Hays
U.S. Geological Survey
Reston, Virginia
and
E. V. Leyendecker
National Bureau of Standards
Gaithersburg, Maryland

ABSTRACT

The September 19, 1985, Mexico earthquake reminded scientists and engineers of the importance of considering soil amplification effects in earthquake-resistant design. The Mexico earthquake illustrated the "worst case"--the ground response and the building response occurring at approximately the same period, 2 seconds. This resonance phenomenon was predictable on the basis of similar experiences in past earthquakes. A number of areas in the United States also exhibit significant predictable soil amplification effects. Special steps are needed in these areas to mitigate the potential damage and losses that could occur in future earthquakes.

INTRODUCTION

On Thursday morning, September 19, 1985, at 7:18 a.m., a great earthquake having a magnitude (M_s) of 8.1 occurred at a depth of about 11 miles in the Mexico trench subduction zone along the boundary of the Cocos and North American tectonic plates. The epicenter was located near the town of Lazaro Cardenas on the border between the states of Michoacan and Guerrero. Parts of Mexico City, the World's most populated urban center with more than 18 million people and more than 1 million engineered structures, experienced severe damage, in spite of the fact that Mexico City was 250 miles from the epicenter.

The earthquake was caused by a 125 mile-long rupture along the boundary of the Cocos and the North American tectonic plates. The Cocos tectonic plate is slowly being subducted at the rate of about 3 inches per year underneath the North American plate. The zone of subduction stretches for more than 1,000 miles along the Pacific coast of Central America. The Mexico trench subduction zone is well known. It has ruptured in the past and has been the source of large earthquakes that have shaken Mexico City as well as the central and southern parts of Mexico. Similarly as in 1985, parts of Mexico City experienced severe damage in 1957 and 1979 from earthquakes in the subduction zone. A seismic gap (a segment of the interface between the Cocos and North American tectonic plates that has not ruptured in past large earthquakes, but which has the potential of producing a future large to great earthquake filling the gap) was recognized in the Michoacan-Guerrero area by McNally in 1981. She made a general forecast of a future earthquake. The 19 September 1985 earthquake is generally considered to have filled a portion of the Michoacan-Guerrero seismic gap.

EFFECTS OF THE EARTHQUAKE

The 1985 Mexico earthquake was noteworthy for several reasons. The effects of the earthquake are synthesized from several reports (National Academy of Sciences, 1985; Beck and Hall, 1986; and Rosenblueth, 1986) and are summarized below:

1) An estimated 10,000 people were killed in the earthquake and many more people were injured. Economic losses are estimated to have reached $5 to $10 billion. One quarter million people were left homeless.

2) Both the epicentral region, located near Lazaro Cardenas, and parts of Mexico City were assigned an intensity of IX on the Modified Mercalli Intensity scale, an unusual phenomenon. No other historic earthquake anywhere in the world has had locations 250 miles from the epicenter that were assigned an intensity of IX.

3) The earthquake caused partial to total collapse of about 300 five to twenty story buildings in Mexico City, located some 250 miles from the epicenter. Search and rescue operations were an important element of the initial response to the earthquake.

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4) Hospitals were severely affected by the earthquake. Six buildings collapsed at the Mexico General Hospital. About 400 doctors, nurses, and patients were trapped in the ruins of the Jurarez Hospital

5) Government buildings as a group were severely damaged in the earthquake. The specific explanation of the high degree of damage to this group of buildings is not yet known.

6) Because of prior planning by American and Mexican scientists and engineers, a number of strong motion accelerographs were operating at the time of the earthquake in both the epicentral region and in Mexico City.

7) The instruments in the epicentral region registered a peak horizontal ground acceleration of 0.18 g as did the instruments in Mexico City that were underlain by soft unconsolidated deposits of an old lake bed. Other instruments in Mexico City underlain by stiffer rock-like material registered a peak horizontal ground acceleration of 0.04 g, or less.

8) The duration of shaking in Mexico City was long, on the order of 3 minutes.

9) In spite of the "bad news" that several hundred buildings in Mexico City collapsed and several thousand more had to be demolished or strengthened, the "good news" is that the severely damaged buildings represent less than 1 percent of the more than 1 million engineered structures in Mexico City. In terms of the philosophy of a building code--"to resist major earthquakes without collapse, but with some structural and nonstructural damage"--the outcome from the point of view of the building code was reasonable, except in the lake bed zone underlying Mexico City. In that zone, the code was inadequate to resist the large forces.

Rosenblueth (1986) lists seven factors (besides the severe shaking) that contributed to the overall structural damage. They are:

1) Pronounced asymmetry of buildings.
2) Corner locations.
3) Weak (soft) upper and middle stories.
4) Pounding of adjacent buildings.
5) Poor foundation.
6) Excessive mass.
7) Prior damage in past earthquakes.

WHAT CAUSED THE SEVERE DAMAGE IN PARTS OF MEXICO CITY?

Much of the extraordinary degree of localized damage in the lake bed zone of Mexico City was predictable. It was caused by a double resonance phenomenon involving the response of the underlying lake bed and the response of the five to twenty story buildings to the amplified 2 second period ground shaking (Rosenblueth, 1986). Worldwide experience in destructive earthquakes (e.g., 1957, 1962, and 1985 Mexico; 1967 Caracas, Venezuela; 1970 Gediz, Turkey) has shown that the kind of ground that a building is founded on affects the amplitude, spectral composition, and duration of the ground shaking input into the building and the type and degree of damage it receives. Scientists and engineers have recognized and documented in the technical literature of earthquake engineering and engineering seismology since the 1800's that lateral and vertical changes in the physical properties of the soil-rock columns underlying a site modify the amplitude level, the spectral composition, and the duration of the ground motion recorded at the surface in a predictable manner (MacMurdo, 1824; Seed and Idriss, 1969; Seed and others, 1972; Tezcan and others, 1972; Hays, 1980; Singh, 1985). The soil-rock column underlying a particular site acts like a filter, causing the amplitude of the surface ground motion to be increased (amplified) in a narrow range of periods (or frequencies) and decreased in other period ranges. The amplitude of the enhanced ground motion is a function of the contrast in physical properties (shear-wave velocity, density, material damping) between the soil and the underlying rock, the geometry of the soil rock interface, and the surface and subsurface topography. The dominant period of the enhanced ground motion is a function of the thickness, geometry, shear modulus, and shear-wave velocity of the soil column. Because soil behaves in a strain-dependent manner, the level of dynamic shear strain induced in the soil is the most important factor, causing the amplitude to decrease and the period to increase as the level of strain increases.

A soil column, like a building, has a natural period of vibration (Figure 1). the characteristic period T_s of a soil column is given by the relation

$$T_s = \frac{4H}{V_s} \quad (1)$$

where H is the thickness of the soil column and is V_s the average shear-wave velocity of the soil measured under conditions of low strain. The period for a building T_b is given approximately by the relation

$$T_b = \frac{N}{10} \quad (2)$$

where N is the number of stories.

Although many areas of technical controversy exist, studies of ground response, building response and damage from past earthquakes have clearly shown two facts:

1) Amplification of the ground motion by a factor of 5 or more in a narrow period band centered around the characteristic period of the soil column is caused by a contract in the shear-wave velocity and the thickness of the soil-rock columns, and is essentially independent of strain up to levels of about 0.1 percent (Hays, 1980; Toki and Cherry, 1972).

2) The greatest levels of shaking in a building occur when the vibration of the building coincides with the natural period of vibration of the column of soil overlying rock-like material.

Rock-like material is defined as any material having a shear-wave velocity of 760 m/sec or greater; whereas, soil has much lower shear-wave velocities, typically in the order of 100-500 m/sec.

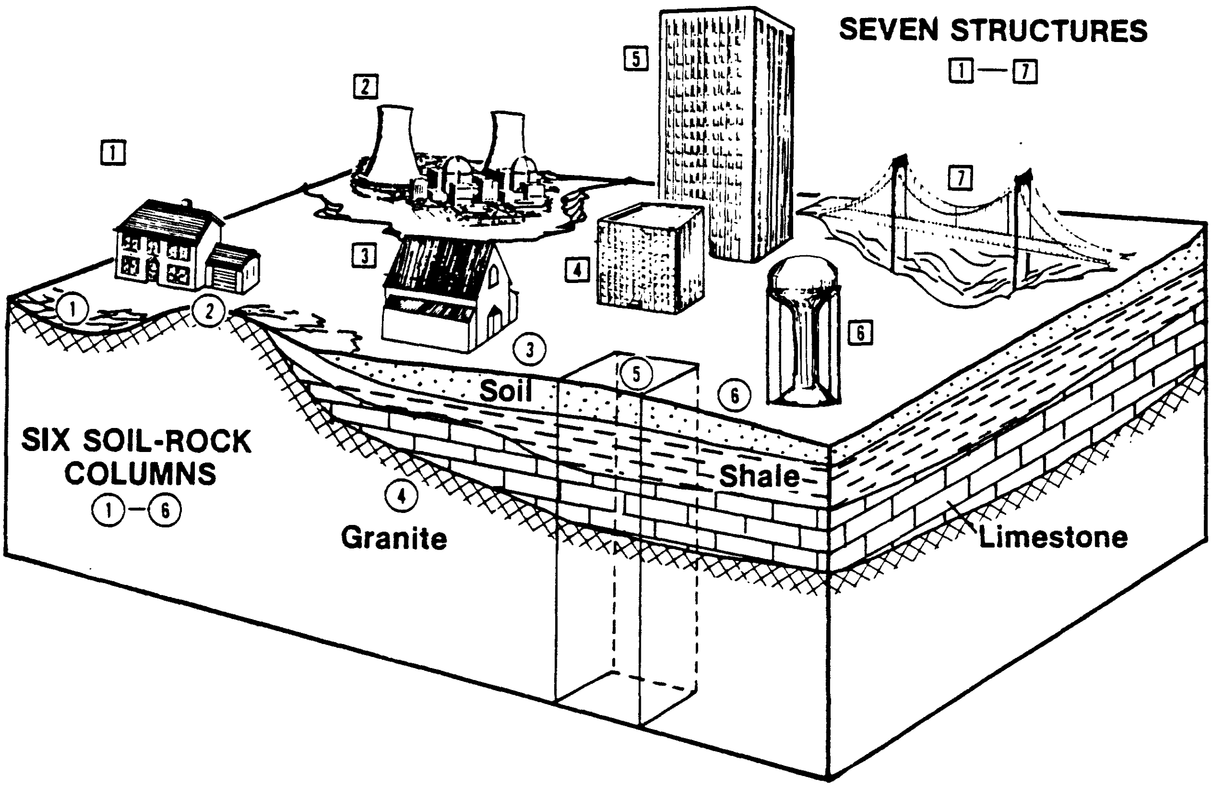

Figure 1.--Schematic illustration of six soil-rock columns and seven types of structures. Each soil-rock column and each structure have a fundamental nature period of vibration. If the dominant period of the earthquake-induced ground response coincides with the dominant period of the structural response, severe damage and collapse can occur.

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Site Physical Parameters and Their Effects on Ground Motion

Understanding the physics of local ground response requires consideration of the ground-motion time histories. Typical horizontal acceleration, velocity and displacement time histories display the superposition in time of elastic waves that have traveled a wide variety of paths between the earthquake source and the recording site (Figure 2). It is impossible to delineate all of the travel paths involved because one would need to know the details of the geology between the source and the receiver to a depth of perhaps the Mohorovicic discontinuity (i.e., in the order of 30 km). Although such detailed information is usually not available, both theoretical considerations and experience indicate that the seismogram is composed of body and surface waves. The body waves are the familiar compressional (P) and shear (SV and SH) waves which travel from the source to the recording site along paths which extend deep into the Earth's crust. Because of the nature of these travel paths, the energy associated with these wave types is vertically incident on the site geology from below. These waves mainly cause short-period (i.e., periods less than 1 second, (high frequencies) which are efficient in causing low-rise buildings to vibrate. The surface waves (Love and Rayleigh), on the other hand, propagate through channels or wave guides which are bounded above by the surface of the Earth. Thus, they traverse the site geology laterally rather than being incident from below. They mainly cause long-period (low-frequency) vibrations which are efficient in causing high-rise buildings to vibrate. Because the body and surface wave types travel at different velocities, they are separated in time on seismograms recorded some distance from the epicenter. The separation of the seismogram into contributions due to the arrival of body and surface-wave types means that both types of elastic waves must be examined in order to evaluate local ground response effects in a comprehensive manner.

Figure 3 illustrates the time histories of horizontal acceleration, velocity, and displacement observed in Mexico City from the September 19, 1985, Mexico earthquake. The striking feature of these strong motion time histories is the dominant 2-second period of the accelerogram which was recorded 250 miles kilometers from the epicenter of the magnitude (Ms) 8.1 earthquake. This phenomenon was caused by the filtering effect of a 50-meter thick soil column

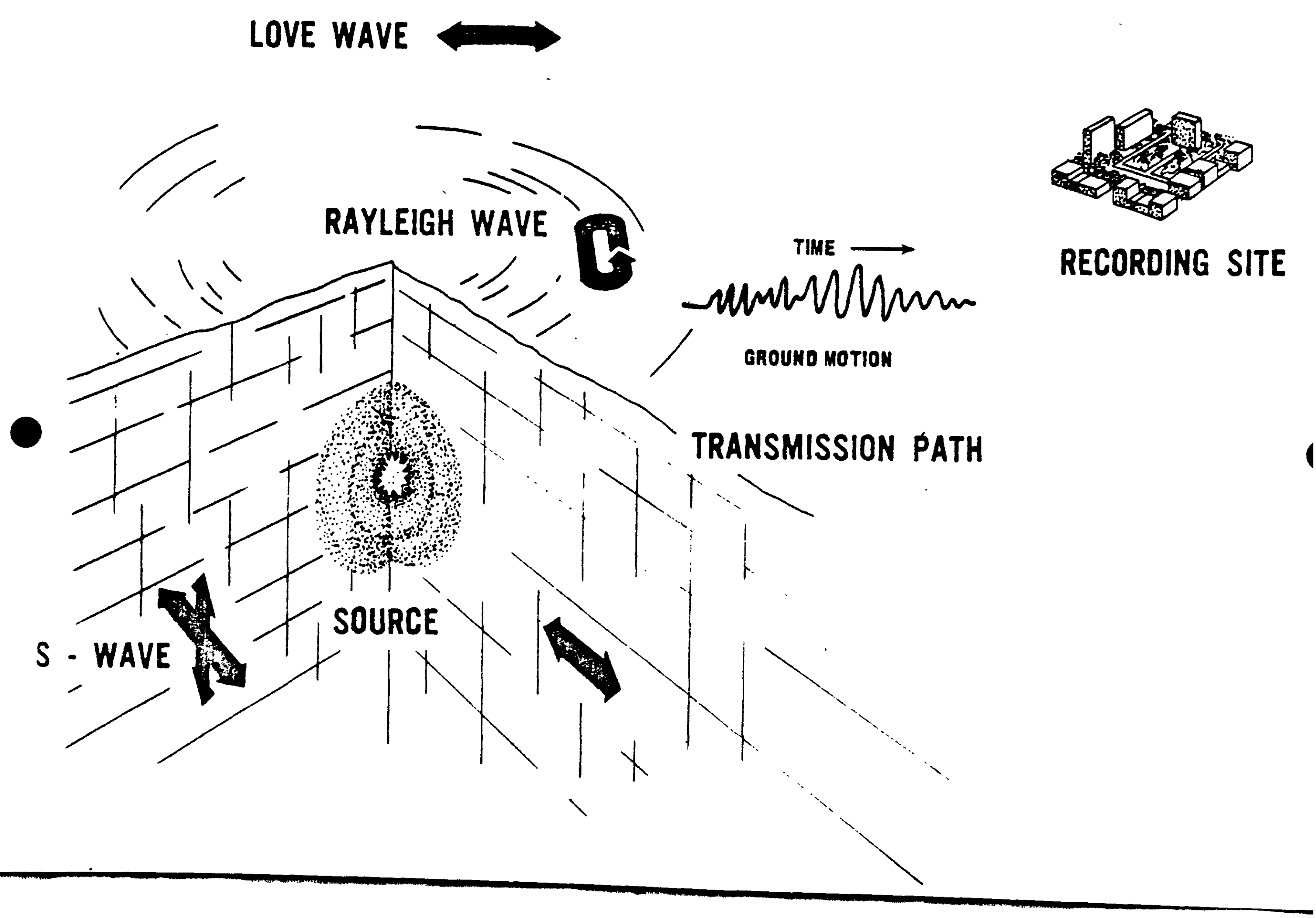

Figure 2.--Schematic illustration of the elements that contribute to the amplitude and frequency composition of earthquake ground motion recorded at a site. The local geology underlying the recording site acts like a filter and can significantly amplify certain frequencies of the ground motion input to a building. The building also acts like a filter and can amplify the input ground motion even more.

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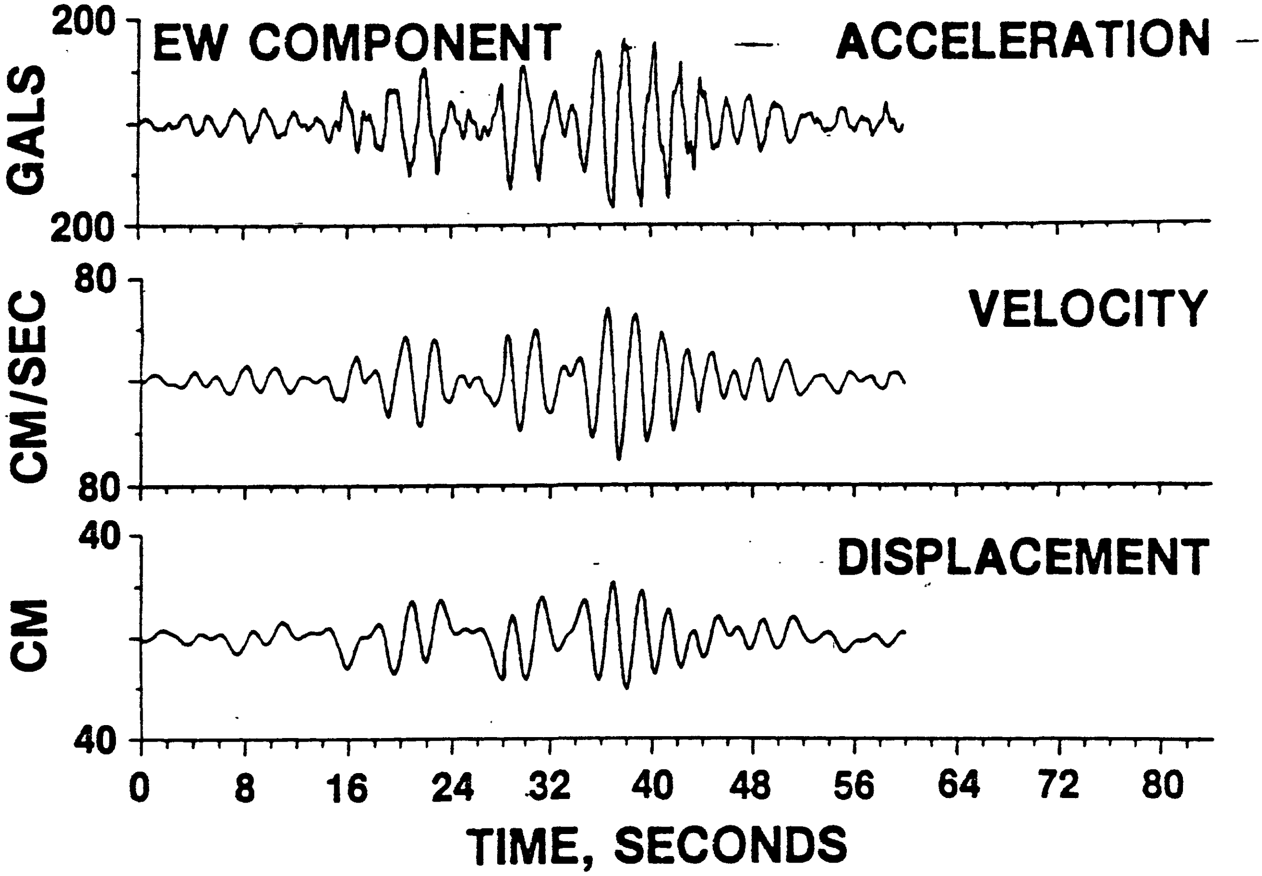

Figure 3.--Accelerogram (top) recorded at a free field location on the surface of the 50-meter thick lake beds forming the foundation in parts of Mexico City. The epicenter of the September 19, 1985, Mexico earthquake was located some 400 km to the west. The strong 2 second period energy in the accelerogram and the velocity (middle) and displacement (bottom) time histories derived from it are a consequence of the filtering effect of the lake beds which amplified the ground motion, (relative to adjacent sites underlain by firmer rock-like materials) about a factor of 5. The coincidence of the dominant period of ground shaking (2 seconds) with the fundamental period of vibration of tall buildings contributed to their collapse. These records were provided by the Universidad Nacional Autonoma de Mexico.

representing deposits by a former lake bed that now underlies parts of urbanized Mexico City. The shear wave velocity of these deposits is about 100 m/sec; therefore, their characteristic period is 2 seconds--the approximate natural period of a 20-story building (Zeevaert, 1964). When one allows for the normal range of variation in both the shear-wave velocity and the thickness of the soil column, the characteristic site periods in Mexico City can easily vary from 0.5 to 2 seconds and coincide with the range of natural periods of vibration of typical 5- to 20-story buildings, the classes of buildings in Mexico City that were most severely damaged.

Where in the United States have Similar Soil Amplification Effects Occurred?

A number of researchers have published information about local ground response in different parts of the United States. The areas having potential for site amplification in future earthquakes include:

1) San Francisco region--The San Francisco Bay mud causes the most significant effect. The short periods of ground motion are amplified by as much as factor of 10 (Borcherdt, 1975).

2) Los Angeles region--The varying thicknesses of alluvium cause short-period (0.2-0.5 second), intermediate-period (0.5-3.3 seconds), and long-period (3.3-10 seconds) amplification, depending on the location in the Los Angeles basin. The mean amplification factor varies from 2 to 5 (Rogers and others, 1985)

3) Nevada--A classic example of body wave amplification was observed in Tonopah, Nevada, where a site underlain by fill experienced short-period amplification of a factor of 7 at a period of 0.14 seconds relative to an adjacent site underlain by rock (Murphy, and others, 1971) Hays, 1978). The classic example of surface wave amplification was observed in Las Vegas where the varying thicknesses of alluvium amplify the long-period (2-3 second) surface waves by a factor of about 10 with the greatest response occurring at sites underlain by thick, water saturated deposits of clay and silt (Murphy and Hewlett, 1975).

4) Wasatch Front, Utah--Salt Lake City, Ogden, and Provo, the principal cites along the 210 mile-long Wasatch fault, are founded on several different types of soil deposits related to the filling of the Great Salt Lake basin. These deposits amplify the ground motion in the period band 0.2-0.7 second by as much as a factor of 10 (Hays, 1986).

5) Parts of the Mississippi Valley--The July 1980 Kentucky earthquake caused damage in some locales that was explained in terms of site amplifications phenomena. Many locations having thin, stiff soil columns as well as thick, soft soil columns exist in the Mississippi Valley area.

6) Boston--The Boston area has zones of landfill and poor ground that could potentially amplify earthquake ground motion.

CONCLUSIONS

Lessons for other parts of the United States--Many important lessons can be extracted from the experience of the 1985 Mexico earthquake. Three general lessons are applicable to many parts of the United States and are summarized below:

1) Buildings located on soil deposits are most likely to experience severe damage if the dominant vibration periods of the ground and building coincide. Urban development should avoid this condition if possible, or make certain that proper engineering is performed if it cannot be avoided.

2) Building codes must explicitedly address the problem of double resonance between the ground and building. Earthquake-resistant design criteria must be stringent enough to account for the potential amplification of ground motion by the local soil rock columns. Design considerations must extend to stairways and other nonstructural elements; otherwise, search and rescue efforts are adversely is affected.

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3) Emergency response plans must include consideration of search and rescue operations of the type experienced in 1985 in Mexico City--a worst case scenario.

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THE POTENTIAL FOR GROUND FAILURES IN THE PUGET SOUND AREA

by

W. Paul Grant
Shannon & Wison, Inc.
Seattle, Washington

INTRODUCTION

Earthquake induced ground failures, such as liquefaction and landslides, have resulted in substantial casualties and major property losses in various parts of the world. It has been estimated that property losses from ground failures exceeded $200 million in the March 27, 1964 Alaska earthquake and losses of about $800 million resulted from the June 16, 1964 Niigata, Japan earthquake (Keefer, 1983).

Earthquake induced ground failures during historic earthquakes in the Puget Sound Region have also resulted in substantial damage to buildings, bridges, highways, railroads, water distribution systems, and marine facilities. As the Puget Sound Region is located in a moderately active seismic zone, the potential of ground failures in future earthquakes is relatively high. It is the purpose of this paper to discuss types of ground failures that have occurred locally during past earthquakes and could likely occur during future events. It is recommended that earthquake hazard studies be performed to delineate areas of potential ground failure on a regional basis. The findings of these studies could be used by public and private agencies as a planning tool to evaluate the impact of earthquake induced ground failures on proposed building development as well as to develop disaster response plans and mitigating measures.

GEOLOGY AND SEISMICITY

As a basis for understanding the potential for earthquake induced ground failures in the Puget Sound region, it is necessary to have some familiarity with the regional geology and seismicity of the area.

Seattle and its environs lies within the Puget Lowland physiographic province, which is a broad, north-trending, structural and topographic depression that is bounded by the Olympic mountains on the west and the Cascade range on the east. Bedrock within the region is largely composed of highly folded and faulted Tertiary rocks of sedimentary and volcanic origin. While bedrock is exposed locally in various areas, it is typically overlain by several thousand feet of Quaternary sediments that have been deposited during several glacial advances. Allvuium and man-made fill mantle the Pleistocene deposits in the lowlying areas along the Duwamish and other rivers.

The Puget Lowland is an area of moderately high seimsic activity. Most of the earthquakes in the region have occurred at comparatively shallow depths of less than about 15 miles; however, the larger events have occurred at depths of more than 25 miles. The primary cause of this seismicity is believed to be related to the differential motion occurring along the boundary between the North American and Pacific lithospheric plates. Historic earthquakes within the Puget Sound Region have not been directly associated with any known or postulated faults (SW-AA, 1978). The two largest historic earthquakes in the region were the magnitude 7.1, April 13, 1949 Olympia earthquake and the magnitude 6.5, April 29, 1965 Seattle-Tacoma earthquake. Both events were deep seated, with focal depths greater than 37 miles.

TYPES OF GROUND FAILURES

Ground failures may occur as a result of both direct and indirect effects of an earthquake. Surface rupture, as related to faulting, would be a direct effect of an earthquake. Surface faulting is not perceived to be a problem in the Puget Sound area as the thick mantle of glacial sediments would tend to mask any movement of the underlying bedrock. Ground failures most likely to occur in the Puget Sound region as an indirect effect of an earthquake include liquefaction, landslides, differential compaction, and lateral spreading.

Liquefaction is a phenomena in which a saturated deposit of loose sand may lose its strength and essentially behave as a liquid during a strong earthquake. The occurrence of liquefaction would likely result in settlement and structural damage of buildings founded on the liquefied soil.

Landslides could also be indirectly triggered by the ground shaking which accompanies an earthquake. Earthquake included landslides could fall within one of several classifications including 1) shallow slides on steep slopes, 2) slumps and block slides, 3) soil flows, 4) rock and soil avalanches, and 5) subaqueous landslides. Each of these types of slides could cause property damage by the impact of the debris upon a structure, or by the loss of lateral support to structures founded upon or uphill from the slide mass.

Other types of ground failures that could result from an earthquake include differential compaction, which results in the settlement of loose deposits of sand and lateral spreading, which is a combination of liquefaction and landsliding.

EVALUATION OF LOCAL GROUND FAILURES

The number of various types of ground failures reported for the 1949 and 1965 Puget Sound earthquakes is as follows (Keefer, 1983):

	1949	1965
Liquefaction	5	2
Landslides	20	21
Lateral Spreading	4	2

The above failures resulted in some damage to buildings, bridges, highways, railroads, and underground pipes; however, no quantitative estimate was made of the dollar loss solely attributed to ground failures. While the above statistics would indicate that earthquake induced ground failures have not been overwhelming in the Puget Sound area, it is noted that both historic earthquakes resulted in relatively small levels of acceleration in Seattle (less than 0.10 g). Much greater damage, possibly an order-of-magnitude higher than the historic levels, could occur if the Puget Sound area were to experience a magnitude 8 or 9 subduction zone earthquake, such as postulated by Heaton and Kanamori (1984).

During both the 1949 and 1965 earthquakes, the ground failure damage appeared to be concentrated in the lowlying areas along the Duwamish and fill areas adjacent to the waterfront. It is anticipated that similar damage patterns would develop in future earthquakes. Landsliding that was triggered during the historic earthquakes was primarily located in areas with steep slopes or bluffs, where there was a low population density. Since hillside slopes in Seattle have experienced increased development since 1965, it is anticipated that property losses from landslides would be greatly increased in a future large earthquake.

FURTHER STUDY

Considering that earthquake induced ground failures may pose a substantial threat to structures located within the Puget Sound Region, further studies should be accomplished to develop seismic hazard maps of the region, indicating areas of potential instability. The purpose of these hazard maps would be to aid the public and private sector in land use planning, building development, and planning for disaster response. Specifically, the maps could be used to locate projects out of high seismic risk areas or to plan for high foundation costs for structures located within these areas. Similar studies have been developed for the cities of San Diego and San Francisco (Power and others, 1982; Roth and Kavazanjian, 1984).

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TSUNAMI AND FLOOD HAZARD PREPAREDNESS AND MITIGATION PROGRAM FOR ABERDEEN

By
Jane Preuss
Urban Regional Research
Seattle, Washington

OBJECTIVES AND ASSUMPTIONS

Grays Harbor is vulnerable to a major tsunami event generated by an earthquake in the Shumagin gap area of the Aleutian Islands. It is also subject to recurring floods. Because of this dual risk, it was determined that a multi-hazard mitigation and preparedness plan should be prepared for the community. Specific objectives of the project described in this paper are to develop a program for flood hazard mitigation and a plan for reconstruction after a devastating tsunami. These plans would be designed to minimize property damage. In addition, a preparedness and evacuation plan is proposed which will be implemented during the immediate response period. Methodological objectives of the project are to develop a prototype approach for integration of disaster preparedness and mitigation into the on-going comprehensive planning process.

THE PLANNING CONTEXT

Land Use

Aberdeen with a 1980 population of 18,755 is located in southwest Washington. Its city limits span the north and south banks of the mouth of Chehalis River as it discharges into Gray's Harbor. The City also spans the Wishkah River which flows south through eastern Aberdeen and discharges into the Chehalis River. The economy is based primarily on the forest product industry, the fishing industry and to a lesser extent the sport fishing/ recreation industry. All of these industries are seasonal, heavily cyclical and, especially the timber and fishing industries, depend on a world-wide export economy. The recreation industry depends on a regional clientele.

In North Aberdeen the flood plain extends approximately one-half mile inland in a northern and southern direction from the Chehalis River and 800 feet on either side of the meander of the Wishkah River. Land uses within the northern flood plain of the Chehalis River are primarily industrial and commercial. They include the Grays Harbor port and extensive log storage facilities. The Aberdeen Central Business District, which is the primary

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business district for Grays Harbor County, is located at the confluence of the Wishkah and Chehalis Rivers and extends west approximately 6 blocks along the Chehalis River and 4 blocks along the Wishkah. A secondary sewage treatment plant completed in 1981 is located on the northern edge of the Chehalis River. Land uses in the remainder of the northern flood plain are primarily residential with scattered commercial.

The southern flood plain of the Chehalis River is less intensively developed than the northern flood plain. The 100 year flood plain which follows the 10' contour encompasses virtually all of South Aberdeen. Industrial areas, scattered along the waterfront, consist of log storage and related forest product facilities. The rest of South Aberdeen is residential with some commercial development including the South Shore Mall constructed on dredge spoils in 1981. Undeveloped areas are predominantly wetlands.

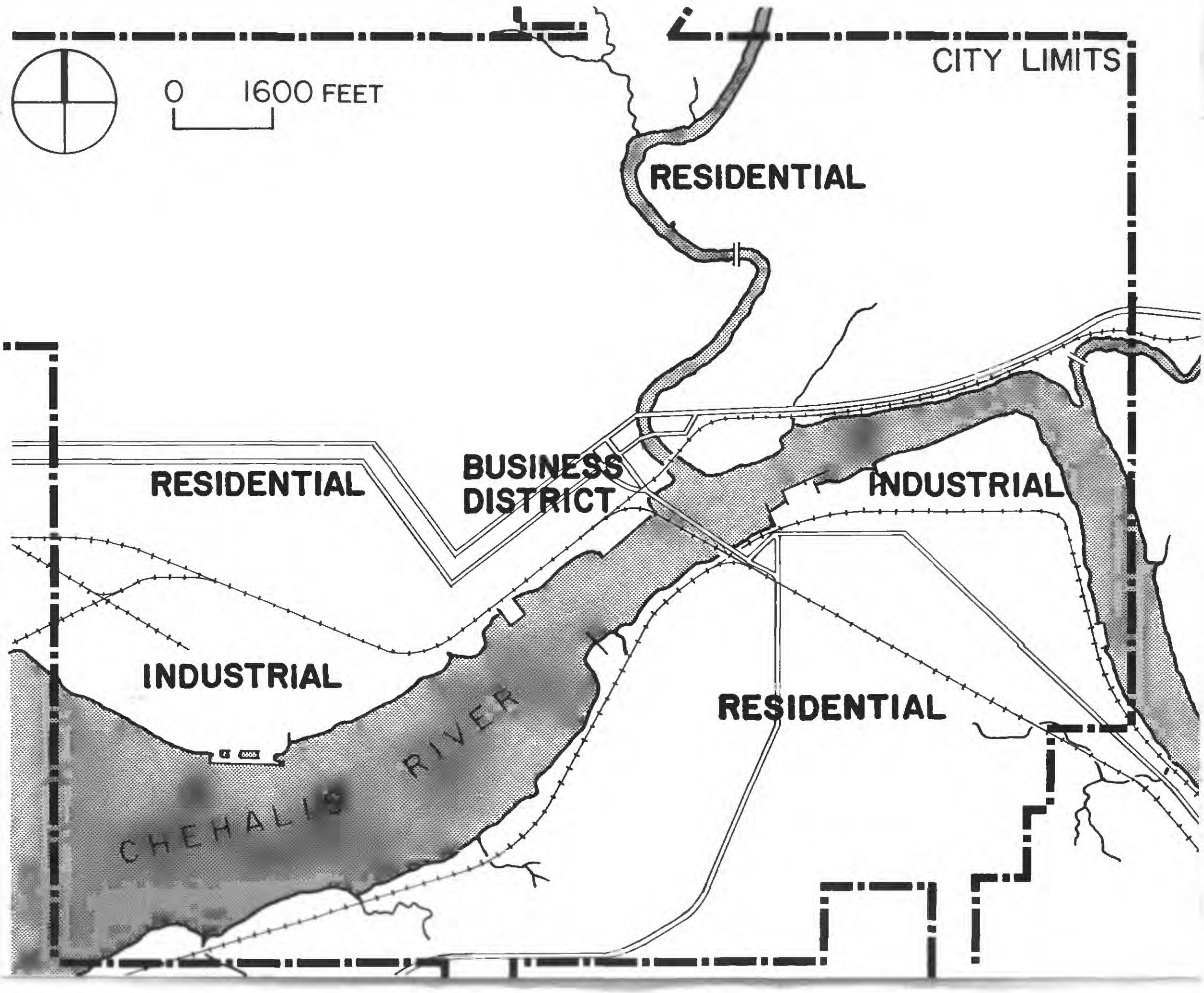

Figure 1: Land Use

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Flood Protection Measures

Aberdeen has a system of dikes along the north and south banks of the Chehalis River and Grays Harbor. The dikes are heavily vegetated with cottenwood, alder, a variety of grasses, and low growing shrubs. Over topping and breaching of the dikes begins when water levels reach approximately 8.5 to 9 feet NGVD. These dikes will not protect the city from major floods since the tops are below the 10 foot, 100-year tidal elevation.

THE HAZARD

Flooding

Tidal influence from Grays Harbor extends up the Chehalis and Wishkah Rivers. Flooding in Aberdeen is the result of high riverflows caused by winter rainfall generated by Pacific weather fronts combined with tidal

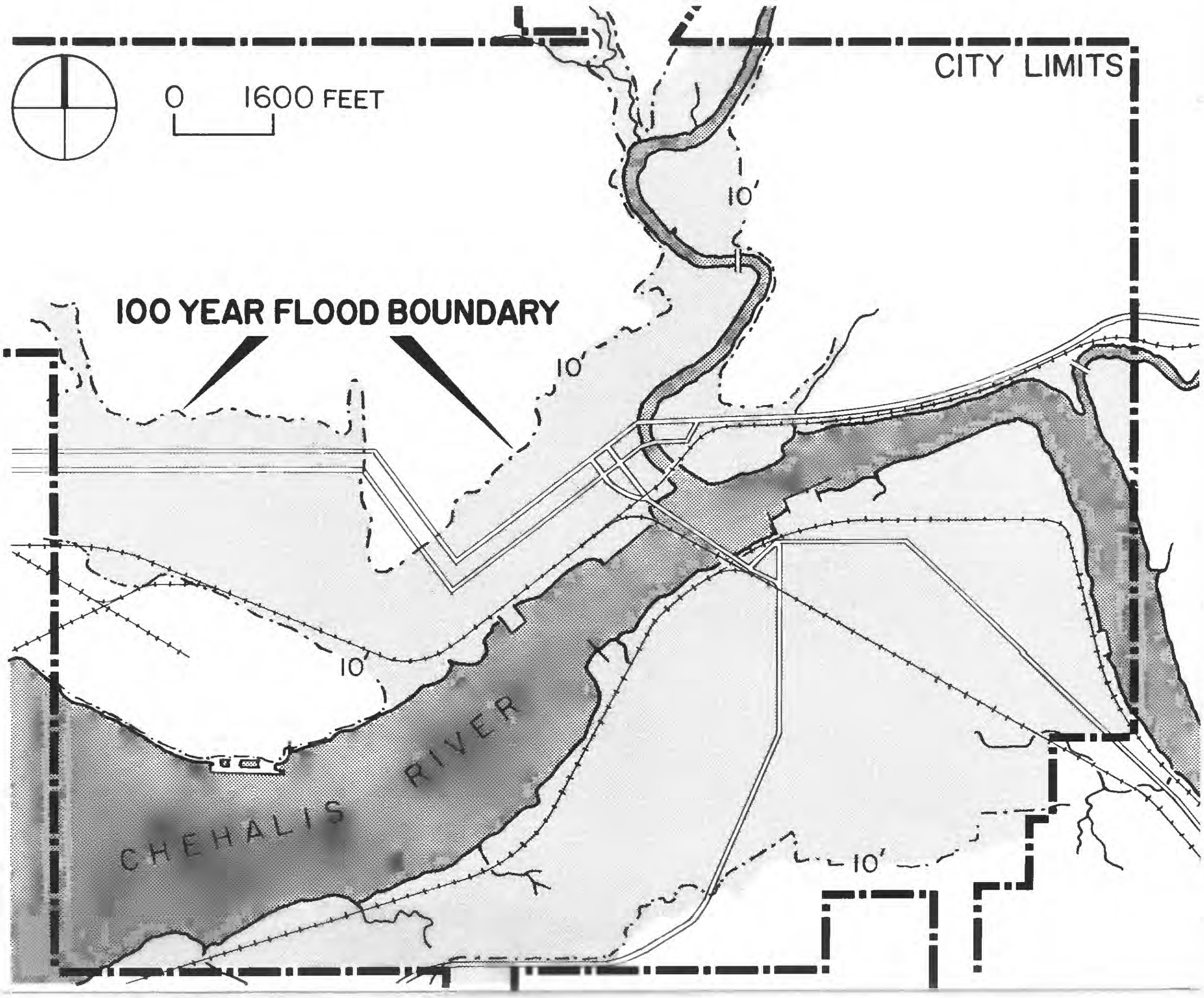

Figure 2: City of Aberdeen: 100 Year Flood Boundary (NFIP)

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flows and low barometric pressure. High river flow conditions can be aggravated by backup of the city's storm drainage system when intense local runoff is prevented from entering the rivers because of high water. Flooding along lower sections of the small streams is primarily caused by high water in the rivers backing up to the creeks and inundating low areas.

For a variety of reasons including unusual weather patterns and clear cutting in the vicinity the frequency of flooding has increased dramatically in recent years. For example, eight of the 18 highest floods recorded since 1912 have occurred since 1972, four of which have been since 1981.

Table 1
Highest known Floods in Order of Magnitude - Grays Harbor*

Order No.	Date of Flood	Elevation above Mean Lower Low Water Datum
1	December 17, 1933	14.8
2	December 1934	14.5
3	December 1923	14.2
4	November 1913	14.2
5	November 14, 1981	14.2
6	December 3, 1982	14.1
7	1912	14.0
8	December 11, 1977	13.9
9	December 1920	13.9
10	December 21, 1972	13.8
11	December 11, 1973	13.8
12	January 27, 1983	13.8
13	November 24, 1983	13.8
14	January 27, 1964	13.7
15	December 18, 1960	13.7
16	December 13, 1941	13.7
17	December 13, 1977	13.7
18	November 30, 1951	13.6

*Sources: 1) June 1971 Flood Plain Information report by the Corps of Engineers which lists the ten highest recorded floods, based on MLLW datum and 2) Internal City of Aberdeen Engineering Department Memo regarding Flooding from Ron Merila to Rudy Balgaroo, December 8, 1983.

Tsunami Susceptibility

Because of their destructiveness, the primary concern of community planners is for a tsunami. Tsunami risk is two-fold: a) if it arrives during late October to late March it could occur during periods of heavy rain/elevated river flows or b) if it occurs during the summer months there would be high population concentrations in the harbor (daytime industrial and recreational pleasure boats) which could result in heavy life loss.

Grays Harbor and the City of Aberdeen are potentially vulnerable to tsunamis which are generated in conjunction with an earthquake occurring in the Shumagin Gap area of Alaska. According to Davies, et. al. (1981) the Shumagin seismic gap, a segment at the plate boundary along the eastern Aleutian arc has not ruptured during a great earthquake since at least 1899-1903. Because at least 77 years have elapsed since the Shumagin Gap last ruptured in a great earthquake and repeat times for the 1938 rupture zone and part of the Shumagin Gap are estimated to be 50 to 90 years, a high probability exists for a great earthquake to occur during the next one to two decades. Very large or great earthquakes in the region of the Shumagin Gap can be expected to generate large tsunamis, which could impact the Pacific shorelines.

Recently a time-dependent two-dimensional numerical model was developed to study the generation and propagation of a possible tsunami generated from an earthquake in the Shumagin Seismic Gap. Kowalik and Muhrti (1985) estimated that the leading wave of the tsunsmi will take about three hours to arrive at the southern British Columbia coast and the northern coast of State of Washington State.

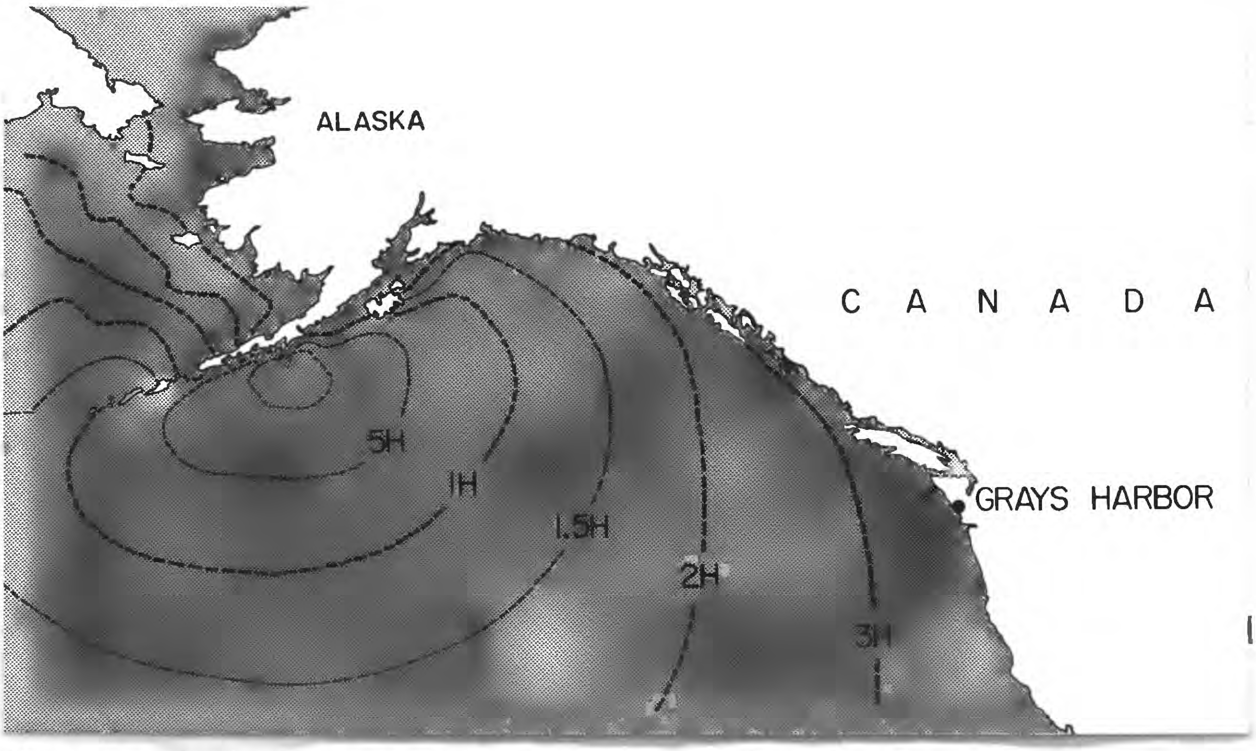

Figure 3: Estimated Arrival Time for Tsunami Wave Front Generated in Shumagin Gap
Source: Kowalik and Muhrti

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The amplitude of a tsunami in the deep ocean off the Washington Coast is expected to be approximately 100 cm (Kowalik and Muhrti, 1985). As the tsunami enters shallower water in the coastal region the, amplitude can be expected to be magnified by approximately 2.5 to 3. Thus, as it enters the coastal area by Ocean Shores the wave height would be 2.5 to 3 meters (8 to 9.75 feet). For comparative purposes it should be noted that the tsunami generated in conjunction with the 1964 Alaskan earthquake measured 9.75 feet at Ocean Shores.

The wave is expected to break at the mouth of Grays Harbor, then decrease in amplitude to approximately 3 feet by the time it reaches Aberdeen.

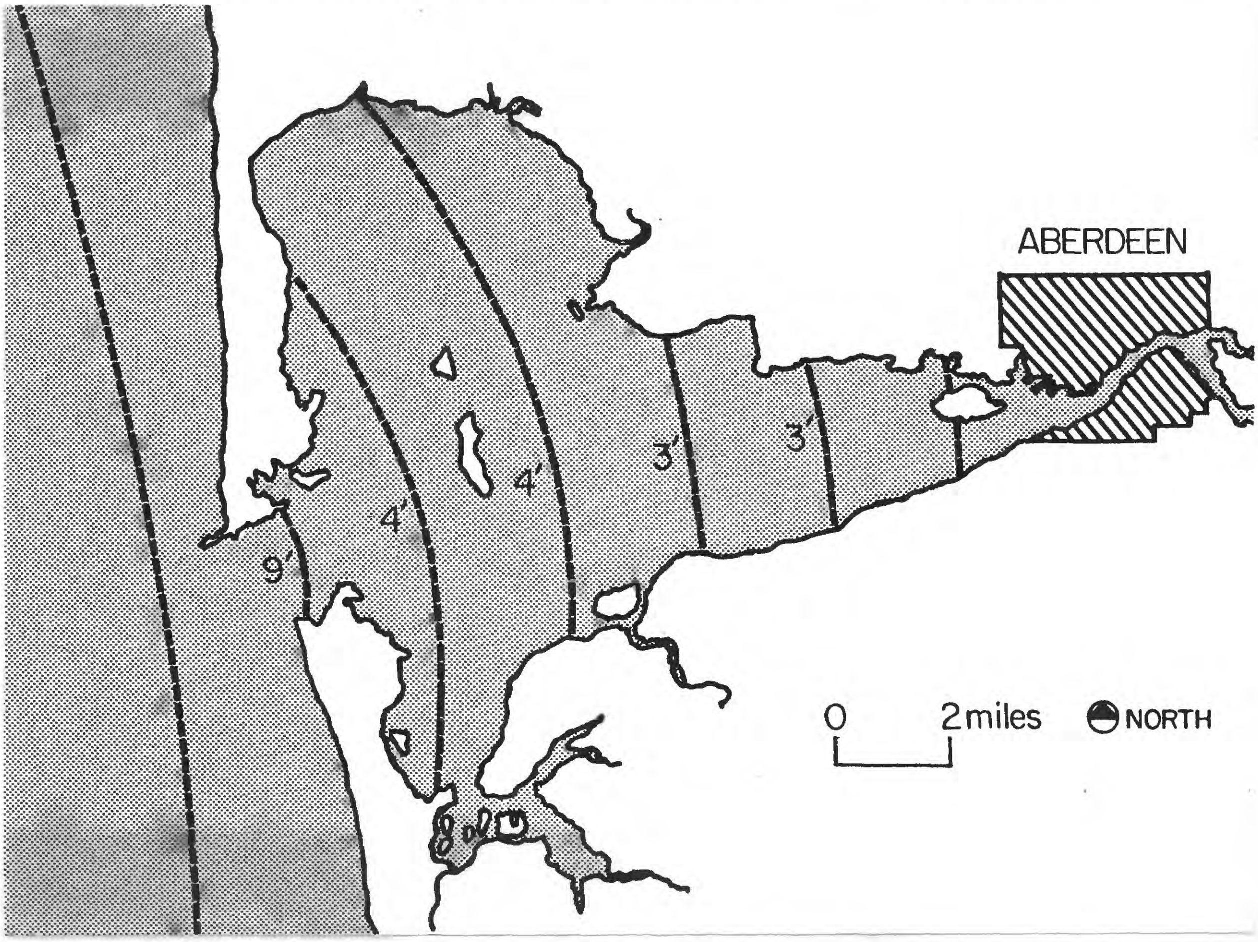

Figure 4: Estimated Wave Amplitude within Grays Harbor

Note: In order to develop more precise projections of tsunami amplitudes within the harbor it is necessary to determine whether the wave will have a bore/amplified configuration. The present large area deep water analysis will be coupled with a coastal model which uses a fine triangular grid and also takes into consideration local harbor resonance. Further analysis is being undertaken on this issue by Kowalik and Muhrti.

DISASTER SCENARIO

The Scenario

A scenario was developed to project the conditions for which Aberdeen must be prepared in the event of a tsunami or major flooding. This scenario combines characteristics of recent floods (11 out of the 18 highest) with tsunami conditions recorded on the nearby Columbia River in 1964.

Between November 27 and December 12 the City of Aberdeen experienced a continuous and heavy rainfall. The effects of the rains were compounded by high astronomic tides and low barometric pressures. The higher high tide on December 11 was 11.9 feet. In addition on December 11 there were 90 mile per hour winds. High tides occurred at 12 noon and 1:39 a.m. During the storm the combined high tide and elevated river flows at the Port of Grays Harbor staff gauge read 13.8 feet. The resulting flooding affected South Aberdeen in the area around U.S. Highway 101 and North Aberdeen along the Wishkah River. The flooding lasted throughout the night.

On December 12 at 5 a.m. there was a magnitude 7.9 earthquake in the Shumagin Gap area of the Aleutians. A tsunami generated in the Aleutian trench arrived off the Washington-Oregon coast in approximately 4 hours which was 9 a.m. When the incident wave was 50 miles off-shore it was approximately 100 cm high, however as it approached shallow water the speed decreased from 450 miles per hour to 50 miles per hour. As the speed decreased and as the wave crossed the continental shelf into shallow water its magnitude was amplified by a factor of 2.5 to 3. At 9:15 a.m. the 8 to 9 foot wave arrived at the mouth of Grays Harbor and broke as it entered the one mile wide mouth. The energy of the wave dissipated considerably as the harbor widens to approximately 13 miles and then narrows in a triangular form to the mouth of the Chehalis River. By the time the first wave reached Aberdeen its amplitude had been reduced to 3 feet.

There were 5 waves of which the second was the largest. At the time of the first wave the rising tide was measured at 10.2 feet. The 3 foot tsunami was therefore added to the high tide and elevated river flow. The wave period for the tsunami was 20 minutes and by the third wave when the tide was at its highest, and the total flood elevation was 16.8 feet.

Effects of the Scenario

The underlying purpose of the scenario was to identify conditions which could either be mitigated and/or for which the community could be prepared in the event of a tsunami or major flooding. These effects were subsequently used as the basis for developing a three part multi-hazard strategy which would be implemented 1) in the immediate response period, 2) to mitigate damage from a major flood or "mild" tsunami and 3) to establish a program for reconstruction after a devastating tsunami.

Preparedness Assumptions

- All emergency service personnel had been on duty since the December 10 flood warning.
- Tsunami warning issued two and one half hours before arrival of first wave.
- Large ships, which require two to four hours to travel from Aberdeen to the mouth of the harbor/open ocean, were not evacuated because high tide is required for ships to pass through the harbor mouth.
- Railroad cars (some containing flammable materials) stored in the port switch yard not already hooked up to engines were not evacuated.

Primary Effects

- Dikes breached and weakened by the 13.8 foot flood on December 11 were further weakened by the first tsunami wave, the draw down of which caused severe scouring. The second tsunami wave destroyed the dikes.
- Ground already saturated by the flooding lost its bearing capacity. There was a high incidence of foundation failure/houses floated off of their foundations along the Wishkah River, and in South Aberdeen. Virtually all the residential areas in South Aberdeen were destroyed. Extensive ground failure occurred along the waterfront industrial areas.
- State Highway 101 and U.S. 410 (Wishkah Boulevard) were impassible from water and debris and could not be used by emergency vehicles. Bridge traffic over the Chehalis River between North and South Aberdeen was interrupted.

Related Secondary Effects

- Logs floating on the rivers or loosely stored on land (not in large stacks) become battering rams against houses, businesses, parked railroad cars, and other facilities such as the sewage treatment tanks. One railroad tank car exploded and fire broke out among the nearby timber storage areas.
- The main waterline broke along Wishkah Boulevard which inhibited fire fighting.
- Pleasure and small fishing boats carried inland into residences and commercial structures. The "resting places" of others impacted circulation routes.

PROPOSED PLANNING FRAMEWORK

Assumptions

The impacts identified for the tsunami/flooding event were addressed through two subplans designed to implement a dual planning framework. Part I is a Mitigation and Post Event Redevelopment Plan. Part II is a Preparedness and Response Plan.

Although the hazard per se is a geophysical event occurring in a defined geographic area the characteristics of remedial and mitigating measures as well as preparedness and response activities are essentially a function of use. Industry and residential areas are the predominant uses within the projected tsunami inundation area. The industrial areas are located adjacent to the rivers, while residential uses occur throughout the flood plain. The following planning framework is therefore organized according to use.

Part I - Mitigation and Post Event Redevelopment Plan

As mentioned in the scenario the tsunami amplitude at Aberdeen has been projected at approximately 3 feet above the 25 year flood; resulting in an inundation area which is coterminious with the 100 year flood plain. The eventual destructiveness of the tsunami event has however not been identified because it has not been possible to project the velocity of the tsunami. Uncertainity with respect to the velocity results in the necessity to develop two planning responses. One is a high velocity event created by a bore wave configuration which would devastate the inundation area. The other is a low velocity event with essentially the same impacts as a major flood.

A. Redevelopment Plan for High Velocity Bore Wave Event

A high velocity bore type configuration amplifies the height and velocity of the incident wave and therefore inflicts a much higher level of damage. The underlying assumption of the Post Event Redevelopment Plan is to developer and enact advance legislation for reconstruction of the high risk area prior to a disaster in order to expedite financing and responsive redevelopment.

Residential Sub-Plan

The underlying assumption of a devastating tsunami event is that residential uses in the high risk area will be virtually destroyed by foundation failure, by impact forces from "debris" such as floating houses, cars and lumber from industrial uses in the vicinity, and by secondary impacts such as fire. The objective of the reconstruction plan is therefore to eliminate or at least minimize the secondary effects associated with the industrial uses thereby protecting residential uses from the effects of future events.

The primary emphasis of the residential sub-plan is to prohibit residential use in the high risk area after reconstruction. The displaced residential uses will be replaced on higher ground through the combined implementation of three programs. In reviewing the following programs it must be stressed that sufficient housing can only be provided through a combination of all three programs. No one option is sufficient.

- Absorbtion of Existing Vacant Housing
  Because of the presently depressed economy there are presently many vacant units which could accommodate the displaced population. Although the units are scattered throughout Aberdeen there is a particularly high number in the west end. A fairly high percentage of the displaced residents could therefore be accommodated by the existing supply of vacant units. The primary disadvantage to relying on this option as a source of replacement housing is that the tsunami could occur when there is a strong economy when there may be few vacancies.

- Create New Residential Tracts within the Present City Limits.
  An inventory of the land within the city limits revealed that the only undeveloped areas outside the projected tsunami/flood plain are on high ridges along the perimeter of the city. These ridges have sweeping regional views and are expensive. Because of their comparatively high values these properties are inhabited by families in the upper, upper-middle and middle income ranges. The majority of the residents in the low lying flood plains have moderate incomes. Thus, even if damaged housing is replaced at full replacement value the resulting higher property taxes of the expensive ridge sites could make long term carrying costs prohibitive for the majority of displaced residents. Another

problem with reliance on ridges for full replacement is that the amount of developable not slide prone land does not equal the amount of land required to replace the residences.

- o Annexation

  Since the undeveloped land available within the Aberdeen corporate limits is less than the number of acres to be vacated two additional areas were identified outside of, but contiguous, to the City limits. Both tracts of land are within the path of expansion and could conceivably already be annexed to Aberdeen by the time a disaster occurs. Both areas are geographically close to the South Aberdeen residential communities which would be displaced are relatively level and would be significantly less expensive to develop than the ridges.

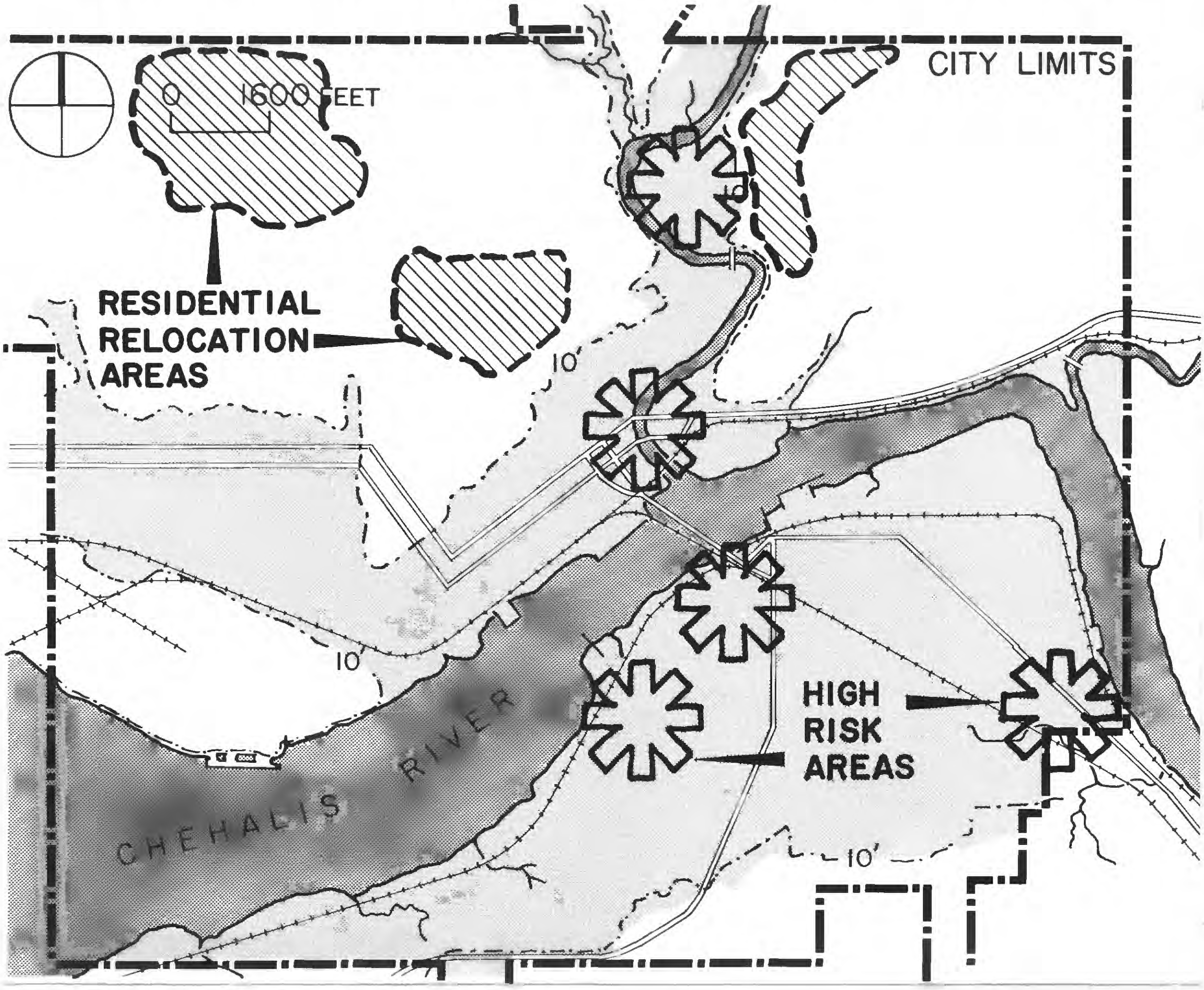

Figure 5: High Risk and Residential Relocation Areas

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Industrial Sub-Plan

Expanded Industrial Park

A major hazard from a high velocity event is generation of debris such as logs, fire, and the spread of hazardous and flammable materials. A high percentage of the damage to the residential uses will be the results of "secondary" impacts generated by the industrial uses.

The remainder of the devastation area would be used for recreation and supporting commercial uses. Wetlands within the flood plain would be preserved. In order to support the expanded industrial park an aggressive attempt would need to be made to attract new industry. it is anticipated that State and Federal assistance would be required to attract the industry to Aberdeen's large deep water port facility and a desirable protected freshwater harbor. The majority of the high risk lands vacated by the residential redevelopment plan be designated as an industrial part. The risk creating industrial uses will be redeveloped with protective buffering to minimize "secondary impacts" if there is a repeat event.

The redevelopment plan also proposes reconstruction of a more efficient buffer and protective dike system. This dike could be integrated with a recreation/bikeway plan and a protective planting/strip park.

Another recommendation is that a series of low protective walls be constructed which are designed to keep "debris" such as logs within the industrial area. These type of low walls are extensively used in Japanese port areas which are vulnerable to tsunamis.

B. Mitigation Plan for Low Velocity Non-Breaking Wave Event

The water level generated by a flood or low velocity non-breaking tsunami wave will be under 3 meters. While it will cause extensive disruption and inconvenience it will not be devastating.

Residential Sub-Plan

The plan for a less than devastating event proposes mitigating measures to minimize damage. These measures emphasize elevating structures, waterproofing, and maintaining the existing dike system.

Aberdeen subscribes to the U.S. Flood Insurance Program and adopted Flood Prevention Ordinance No. 5578, on May 6, 1981. This ordinance requires a minimum floor elevation of 10.0 feet above grade for new residential and commercial construction. In addition housing rehabilitation grants require that floor elevations be raised when remodeling costs are more than 50 percent of the value of the structure. Assuming that federal funds are available, additional requirements of post disaster mitigation efforts could mandate elevating vulnerable units as part of the reconstruction. New construction standards would require building elevations and waterproofing.

Figure 6: Many houses in South Aberdeen are Presently Elevated

Industrial Sub-Plan

The majority of the existing industrial uses relate to timber storage and shipment of forest products. Most of these facilities are on the water side of the dikes. The primary value of the uses is however in the inventory, not in the structure and the supporting holding yards have for the most part been elevated to above the 100 year flood height. It is expected that this embankment will hold in the event of a low velocity event.

PREPAREDNESS PLAN

Boundaries of Critical Issues

The objective of the preparedness plan is to develop a program for evacuation to minimize the population exposed to risk. The boundaries of the preparedness district are the 500 year flood plain, which is coterminous with the 50 foot elevation.

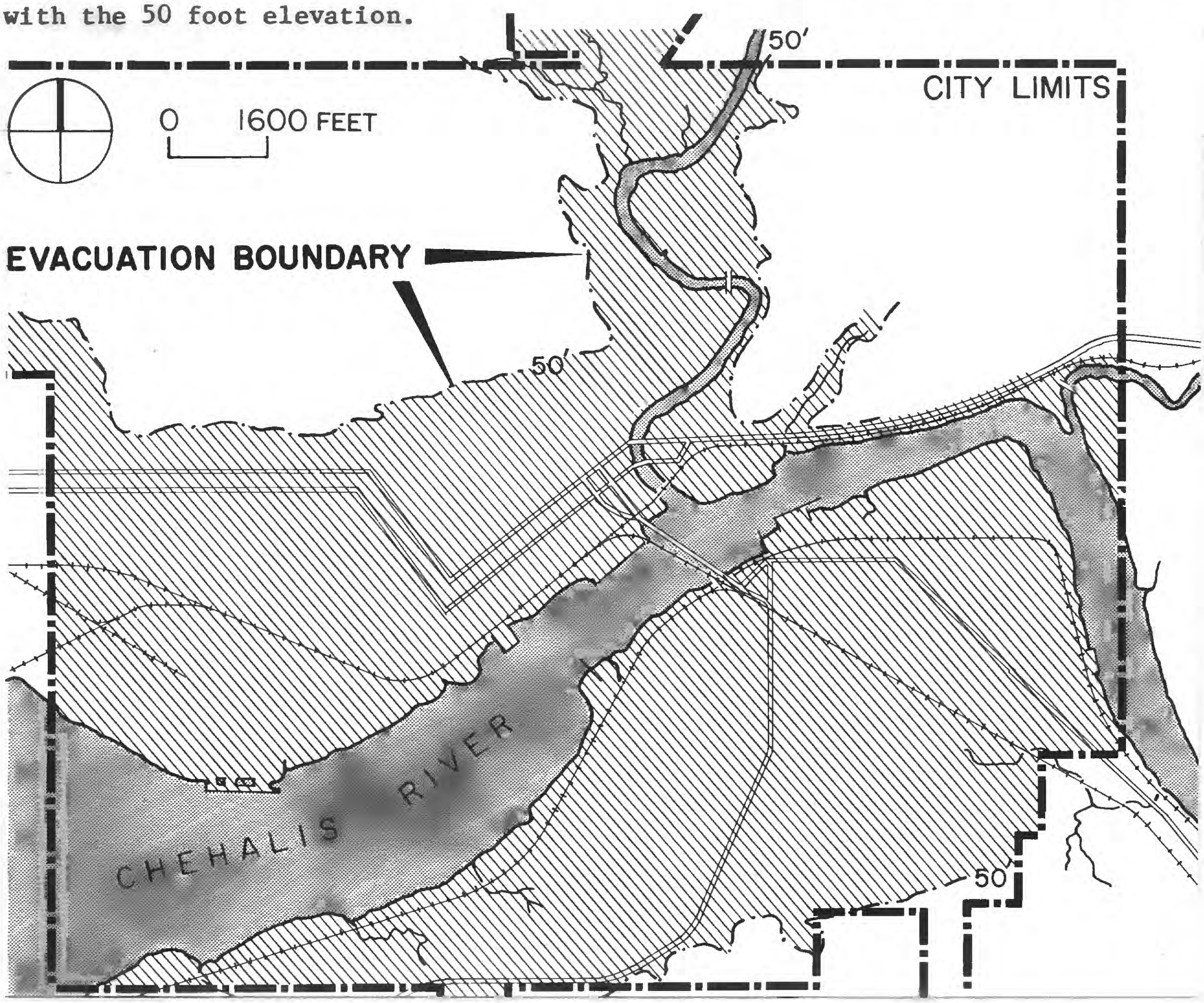

Figure 7: Evacuation Boundary

Identification of Target Populations

The planning process first identified characteristics of the at risk population by defining residential areas and special need groups (such as those who are in the nursing homes) located within the flood plain. Subsequently, warning procedures, evacuation routes and evacuation procedures were designed.

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Residential areas in North and South Aberdeen are projected to experience the highest flooding levels. According to the 1980 census the approximate population of South Aberdeen residing in the flood plain is 4,500 while in North Aberdeen the population residing in the flood plain is approximately 5,000. Evacuation contingency plans were therefore designed for 9,500 people.

Approximately 25% of an impacted population is traditionally expected to utilize emergency reception centers. Because of the comparatively short period that the tsunami would require people to be away from their homes this project assumes that approximately 30% of the population will utilize the two centers in North and South Aberdeen. The remainder of the population are expected to evacuate to high ground probably with friends and relatives either inside or outside the City limits.

Between 20 to 30 non-ambulatory post-surgical patients therefore reside in the nursing home located within the high risk zone. This relatively constant acute need population is the result of recent medicare policy discharges post surgical patients as soon as possible in order to reduce costs. These patients will require an intensive committment of emergency personnel because they must be evacuated to hospitals in North Aberdeen. The Fire Department estimates the evacuation procedure will require 1 to 1.5 hours.

Warning

It is expected that a tsunami warning will be issued by the Pacific Tsunami Warning Center in Alaska via the National Weather Services two to two and a half hours before arrival of the first wave. The general evacuation notice and process will be coordinated by the Grays Harbor Department of Emergency Services.

All the police and fire stations in both North and South Aberdeen are within the flood plain. Immediately upon issuance of a tsunami watch from the National Weather Service (prior to the confirmed warning) the Fire Department will move its equipment out of the hazard area to high ground.

Each of their vehicles can act as a mobile command post for the remainder of the warning and response period. Upon receipt of the warning ambulances will immediately begin to evacuate the nursing home patients.

Evacuation Plan

The objective of the preparedness plan is to integrate emergency response into on-going traffic/transportation planning. Accordingly, the subsequent approach is structured around route maintenance and traffic flow.

The first step in preparing the evacuation plan was to analyze the existing street rights-of-way map prepared by the City of Aberdeen Engineering Department. On-site examination revealed that many of these rights-of-ways are in fact unimproved. A modified base map indicating the locations of the unimproved rights-of-ways was therefore prepared to indicate the areas with potential traffic routing problems. Once the accurate base map was made available it became possible to identify optimal evacuation routes. Major linkages were then correlated with the geographic limits of the hazard and with the location of designated refuge centers in North and South Aberdeen.

Vehicular Evacuation

Assuming that there will be 2.5 persons per vehicle, it is estimated that approximately 4,000 vehicles will simultaneously enter the street system upon issuance of the evacuation warning. A critical planning issue was therefore evaluation of the impact of 4,000 evacuating vehicles on the level of service and accident rates for each of the major traffic routes into and out of Aberdeen.

A major problem identified during the routing analysis was the impact of the sudden high level of traffic on the Chehalis Bridge, which is the only direct connection between North and South Aberdeen. It is also the linkage to the major coastal highway routes. Traffic accidents on the bridge across the Chehalis River are a reoccurring problem during rush hour. Because of the availability of alternative (albiet less convenient routes) the Chehalis River Bridge will be closed to all non-emergency vehicles and traffic will be routed in an east-west direction. The bridge, which is a draw bridge, will however remain in a down position because it is structurally safer if impacted by the wave than it would be if open.

In South Aberdeen it was found that there is a need for traffic signal syncronization and over-ride to an amber flashing mode. In North Aberdeen the signals can already be syncronized.

Other

There are many large ships in the harbor. Evacuation of ships will be dependent on tidal levels, however, it takes more than the warning period to reach the open ocean. Evacuation, therefore, does not appear to be a viable option. All ships shall be as securely anchored as possible.

In so far as possible railroad cars should be removed from the switch yard. All railroad cars with flammable or toxic materials will be given top priority.

CONCLUSIONS

This project demonstrates a dual planning methodology which combines preparedness activities designed to save lives with objectives to minimize property damage and responsibly plan for reconstruction. This multi-hazard, multi-faceted approach also facilitates integration of hazard preparedness into on-going community operations, such as are exemplified by land use/ annexation reviews and public works improvement plans for traffic signal upgrade.

A note of caution must be interjected at this point. In order to implement the preparedness plan it is essential to educate the public concerning appropriate behavior during an emergency. This educational process will be the on-going responsibility of the Department of Emergency Services in conjunction with local Aberdeen officials.

Acknowledgements:

Research for this paper was funded by a Hazard Mitigation Assistance grant from FEMA to the State of Washington Department of Emergency Services. Contributions to the project from Bob Freitag, Community Planner, FEMA Region X; Lora Murphy, Acting Deputy Director, State of Washington Department of Emergency Services; Bill Langford, Coordinator, Gray's Harbor Department of Emergency Services; Ron Morilla, Assistant City Engineer, Aberdeen; and Rudy Balgaroo, Director, Public Works, Aberdeen are acknowledged. Richard Hodge, Urban Regional Research prepared the graphics.

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TSUNAMI RESEARCH IN THE UNITED STATES
1983-1985

By

E. N. Bernard
National Oceanic and Atmospheric Administration
Seattle, Washington 98115

I. INTRODUCTION

Tsunami Research in the United States has been active during the period January 1983 to June 1985. The following reports of ongoing and completed Research were compiled from information provided by the following researchers: Jerry Hebenstreit, George Carrier, John Filson, Doak Cox, Paul Krumpe, Bernard Le Mehaute, James Lander, Charles Mader, Jane Preuss, William Van Dorn, Robert Reid, James Houston, Richard Behn, and K. T. Thirumalai. Their help is gratefully acknowledged.

This report is organized into two distinct groupings: 1) completed research as represented by publications in Section II and 2) ongoing research currently funded by five federal agencies in Section III. The 16 journal articles are readily available through most library services. The other 29 publications cited are available from the authors. Sixteen ongoing research projects are supported by the following agencies: the National Science Foundation (10), the National Oceanic and Atmospheric Administration (3); the Agency for International Development (1); the U.S. Geological Survey (1); and the Army Corps of Engineers (1). The research topics of the 16 projects are distributed among the following research categories: tsunamigenic earthquakes (1); tsunami generation (1); tsunami propagation (2); terminal effects (5); instrumentation/observations (2); tsunami warning (2); social response/risk anaylsis (3).

For further details on these continuing projects, the reader is invited to contact the principal investigator or program manager identified with each project.

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2. <u>Science of Tsunami Hazards - 1984, Vol. 2, Nos. 1 & 2</u>

A Tsunami Avoidable Susceptibility Index

Joseph Morgan

National Geophysical Data Center Databases Supporting Investigations of Geological Hazards

Patricia A. Lockridge

Use of the ABE Magnitude Scale by the Tsunami Warning System

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A Landslide Model for the 1975 Hawaii Tsunami

Charles L. Mader

Probable Aleutian Source of the Tsunami Observed in August 1872 in Hawaii, Oregon, and California

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Verification, Calibration and Quality Assurance for Tsunami Models

Wm. Mansfield Adams

Modeling of Tsunami Directivity

A. Zielinski

N. K. Saxena

A Tsunami Preparedness Assessment for Alaska

George W. Carte

3. Proceedings of 1983 Tsunami Symposium. Edited by E. N. Bernard, 273 pp. (March, 1984)

U.S. researchers contributed 10 papers to these proceedings including:

Regional Tsunami Warnings Using Satellites
E. N. Bernard, G. T. Hebenstreit, J. F. Lander, and P. F. Krumpe

The Alaska Tsunami Warning Center's Automatic Earthquake Processing System
T. H. Sokolowski, M. E. Blackford, G. W. Fuller, and W. J. Jorgensen

A Preliminary Investigation of Tsunami Hazard (Abstract Only)
C. C. Tung

Synthesis of Tsunami Wave Excitation by Normal Mode Summation (Abstract Only)
S. N. Ward

Tsunami-Resistant Gauges for Epicentral Sea-Level Studies
R. Bilham

The Nonlinear Response of a Tide Gauge to a Tsunami
H. G. Loomis

Open Ocean Signature of Tsunami on the Sea Floor: Observation and Usefulness (Abstract Only)
J. H. Filloux

Long Wave Observations Near the Galapagos Islands (Abstract Only)
E. N. Bernard, H. O. Mofjeld, H. B. Milburn, and E. G. Wood

Numerical Simulation of a Tsunami on a Triangular Mesh
H. G. Loomis

Propagation of Tsunami over Three-Dimensional Shelves (Abstract Only)
T. Y. Wu, H. Schember

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III. ONGOING RESEARCH

1. National Science Foundation Grants

A. "Comprehensive Planning in Tsunami Hazard Zones," 18 months. Principal Investigator: Jane Preuss, Urban Regional Research, Suite 200, 616 First Avenue, Seattle, WA 98104, (206) 624-1669.

Based on an analysis of the actual experience of a waterfront community in Alaska, Urban Regional Research will develop an urban planning approach for use in tsunami zones. Their technique involves simulating a tsunami of approximately the size generated by the 1964 Alaska quake and then analyzing the projected inundation levels and impacts on land uses in the area studied. Recommendations resulting from the study will be made for several different sizes of area affected. For the entire region of the study, the researchers will identify all threatened areas and develop long-range guidelines designed to minimize the number of lives lost. Travel time of the tsunami will be used to develop a temporal framework for emergency response procedures. Subsequently, effects will be identified on the smaller scales typically used by planners, and the near-shore and on-land characteristics of tsunamis will be used to predict impacts and develop long-range techniques to minimize damage.

B. "A Study of Tsunamis: Their Coastal Effects," 12 months, Principal Investigator: F. Raichlen, California Institute of Technology.

Tsunami is a hazard to life and property along coastlines of the United States. This project is for a second year continuation to study the effects of tsunamis on coastlines. During the first year, investigations were made on the transient excitation of harbors with sloping bottoms and boundaries and the run-up of tsunami on beaches. Significant accomplishments made during the first year study include an evaluation of shoreward generation of the wave momentum and experimental results to verify the wave response.

Continuation of this study has potential to provide engineering guidelines on the impact of tsunami waves on coastlines and harbor response to tsunamis.

C. "Use of Long-Period Seismic Waves for Fast Evaluation of Tsunami Potential of Large Earthquakes," 12 months, Principal Investigator: H. Kanamori, California Institute of Technology.

This is the final year continuation award to determine the tsunami potential of large earthquakes. The first phase investigations in this project have produced a method to determine the source parameters of tsunamigenic earthquakes and have established the interrelationships between the tsunami period and the seismic moment of tsunamigenic earthquakes.

This continuation award will complete the second and final phase investigations and provide results to improve the reliability of the existing tsunami warning systems.

D. "Mechanics of Tsunamis at a Shoreline," 24 months, Principal Investigator: H.Y. Yeh, University of Washington.

This award is made under the Research Initiation Grant program. This project completes a theoretical and experimental study to examine tsunami transformation near a shoreline and the ensuing run-up and the drawdown process. The results will provide an insight into the energy dissipation mechanism of a tsunami. One of the major components of this investigation is the development and implementation of an intense laser-slit generator for the experimental verification portion of this project.

E. "Improved Numerical Modeling and Computer Techniques for Predicting Tsunami Inundation," 12 months, Principal Investigator: W. M. Adams, University of Hawaii

This research is concerned with predicting in real-time the amount of inundation along a coastline which will occur due to a tsunami running up

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on shore. The method used is based on a physical run-up model containing coefficients which are adjusted to combine the physics pertinent to a tsunami and the estimated best-fit using any available historical data. A numerical computation technique has been developed using a finite difference approach. This model provides a great deal of flexibility in representing coastal configurations and relief. The technique is being tested on a number of areas for which data are available. The program will be modified to operate on small sized computers which are now readily available. This will permit very economical further studies and make possible more widespread practical use of the inundation model.

F. "Tsunami Modelling of Nearshore Response," 12 months, Principal Investigator: A. C. Vastano, Texas A&M University

A proven technology to provide a timely warning of an impending tsunami is at the present time not available. Available methodologies to predict tsunami are generally based on the first generation tide gauge data and are inadequate. Engineering data on the tsunami wave train effects need to be developed for a tsunami alert system.

This project focuses on the application of numerical data from a tsunami wave train and estimates the spectral response and potential coastal hazards. The investigations will continue the results of the ongoing cooperative tsunami research activities with the Japanese (Tohoku University) and the tsunami signature data obtained from the recently installed tsunami gauges on Wake Island (University of California, San Diego) and will provide vital engineering information required to develop a practical tsunami alert system.

G. "Wake Island Tsunami Instrumentation," 24 months, Principal Investigator: W. G. Van Dorn, Scripps Institution of Oceanography, University of California, San Diego.

The essence of this proposal is that the installation of a special diagnostic tsunami station at Wake Island will, in effect, provide a means of "calibrating" other Pacific tide stations as elements of an array, by virtue of which the response at any station can be determined relative to a tsunami source and one or more station responses elsewhere.

H. "Effects of Tsunamis in the Gulf of Alaska," 36 months, Principal Investigators: Z. Kowalik and T. Murty, University of Alaska

The areas along the southern coast of Alaska and the Aleutian Islands are areas where major earthquakes are frequently located. Some of these earthquakes are accompanied by large tsunamis. Unfortunately, the most densely populated regions of Alaska and Canada are within the reach of tsunami run-up, a detailed knowledge of which is essential for the evaluation of hazards posed by tsunamis. Consequently, it is proposed here to initiate systematic studies of tsunami run-up characteristics for the coastal areas of the Gulf of Alaska.

For the proposed investigations, using the bottom deformation as a tsunami source, a time-dependent two-dimensional numerical model will be developed to study the generation and propagation of the tsunami from a major earthquake located offshore of Alaska. To deduce the detailed distribution of the tsunami amplitude at the coast, the large area model will be coupled to a coastal model which will use an irregular triangular grid. The numerical results will be tested against historical data.

The tested numerical models will be applied to generate tsunami wave from the major expected earthquakes in the Shumagin and Yakataga seismic gaps recently identified by others. All these studies will be carried out in close cooperation with a number of institutions, namely, Alaska Tsunami Warning Center at Palmer, Alaska, Institute of Ocean Sciences, British Columbia, PMEL at Seattle, and the University of Alaska in Fairbanks.

I. "A Dispersive Gravity Wave Model for the Generation and Propagation Phase of an International Tsunami Alert System," 24 months, Principal Investigators: R. O. Reid and R. E. Whitaker, Texas A&M University.

This study represents one step towards the general goal of developing an International Tsunami Alert System which would allow real time estimates of the amplitude and arrival times of the leading several wave crests of a tsunami event at coastal communities distant from the tsunami source region.

J. "Study of Tsunami Terminal Effects," 12 months, Principal Investigator: H. G. Loomis, University of Hawaii

It was emphasized in two recent tsunami workshops that there is a significant lack of knowledge of tsunami terminal effects. Increased research efforts in this area should be treated as a priority item in the future.

It was also found that over the last decade Japanese scientists have made good progress on various problems involving flood zone planning and engineering design of naval/marine facilities and structures. Their research findings and experiences will be useful to the U.S. researchers and engineers if properly surveyed, investigated, and translated into usable forms.

2. National Oceanic and Atmospheric Administration

A. Tsunami Hazard Reduction Utilizing Systems Technology (THRUST)

NOAA's Pacific Marine Environmental Laboratory has embarked on a three year project (entitled THRUST) to create a pilot regional tsunami early warning system. The project, which is being developed for Chile, will utilize existing instrumentation connected to GOES satellite communication systems to establish an early warning system. The scientific team working on the project includes: E. N. Bernard, R. R. Behn, F. I. Gonzalez, G. T. Hebenstreit, J. F. Lander, G. Pararas-Carayannis, and Hugh Milburn.

The project has completed all the pre-event work including:

1) the development of an up to date tsunami data base and the production of a "Tsunami in the Pacific Basin" map;

2) the implementation of a numerical model to simulate the effects of a tsunami on the Valparaiso harbor, Chile. Preliminary maps have been assembled. These maps provide inundation estimates derived from the numerical computations, and the location of important facilities such as hospitals, fire stations, water supplies, and communication services;

3) the creation of a Standard Operating Plan (in draft form).

Design for instrumentation of the project has been completed. Procurement for all instrumentation has been initiated and instrumentation is expected to be at PMEL by the summer of 1985. At that time all instruments will be tested.

May 1986 is the projected date of installation of the instrumentation in Chile. There is a scheduled one-year test period of all instrumentation. Upon completion of the test, the title of all instruments will be transferred to Chile (about January 1988).

B. Deep Ocean Tsunami Management Program.

E. N. Bernard of NOAA's Pacific Marine Environmental Laboratory is conducting research to measure deep ocean tsunami characteristics. Since 1982, ten deployments of self-contained bottom pressure recorders have measured the pressure for 30 months near 90°W, 02°S and 110°W, 0°. The program is expected to continue as long as NOAA ship time remains available. Details of the instrument package and accuracy of measurements are found in the article "Long Wave Observations Near the Galapagos Islands," J. Geophy. Res., vol. 90, no. C2, pp. 3361-3366, 1985.

C. Report for Tsunami Data Activity, World Data Center-A for Tsunamis.

The World Data Center-A for Tsunamis is operated by the U.S. Department of Commerce as part of the National Geophysical Data Center of NOAA. Mr. J. F. Lander's principal activity has been working on a project sponsored by the Office of U.S. Foreign Disaster Assistance, Agency for

International Development to determine for a developing country. This pilot study for Chile is called THRUST (Tsunami Hazard Reduction Utilizing Systems Technology). The National Geophysical Data Center (NGDC) and the World Data Center-A it operates have a major role in the pre-event data collection including the compilation, cataloging, and synthesis of all available information on tsunami sources and effects to support modeling, planning, and education purposes.

A major effort of this pre-event data collection was the development of a digital tsunami data base consisting of information on the source (location, cause, validity, and magnitude) and effects (location of effects, wave heights, damage, and numbers of deaths). The initial event list was prepared by Doak Cox during a sabbatical at the World Data Center in an effort to revise and update the Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean by Iida, Cox, and Pararas-Carayannis. Additional information was added from World Data Center files for earthquake epicenters, magnitudes, and depths. Tsunami effects including wave heights, damage, and numbers of deaths were added from several sources including the Catalogues of Tsunamis of the Western and Eastern Coasts of the Pacific Ocean by Soloviev and Go. Currently, the data base consists of about 1450 events since 49 BC, all Pacific locations reporting tsunami effects in the 20th Century and all earlier tsunamis reporting waves of 1.5 meters or larger. More information is available for some areas such as Hawaii and Chile. Other in-depth regional studies will be completed as time permits. The tsunami data are useful in the preparation of tsunami maps and lists of tsunamis having certain characteristics such as location, wave height, damage, and effects.

A wall size, multicolor map depicting Pacific Basin Tsunamis (1900-83) has been published using the NGDC/WDC-A digital data base. The map shows the locations of 405 events (including earthquakes, volcanic eruptions, and landslides) that caused tsunamis. Tables list dates of the events, event parameters, number of deaths, and destruction. An initial free distribution of about 100 copies of the map has been made to all THRUST participants, key emergency and civil defense offices, and international tsunami organizations including members of the International Oceanographic

Commissions, International Coordination Group for the Tsunami Warning System in the Pacific (IGC/ITSU), and members of the Tsunami Commission of the International Union of Geodesy and Geophysics (IUGG).

In addition to the digital tsunami data, NGDC/WDC-A continues to acquire analog data primarily in two formats: marigrams (tide gauge records showing evidence of a tsunami) and tsunami photographs. Interesting acquisitions in the past year include a set of digitized marigrams for 33 Chile station events, 28 digitized records of five major tsunami events recorded at U.S. stations in the Pacific, and a set of 35 marigrams for the May 1983 tsunami in Japan, and 6 marigrams from Hawaiian stations that recorded the March 1985 Chilean tsunami. Additional records of this latest event have been requested. The World Data Center received photographs of the May 1983 tsunami in Japan, of the March 1957 tsunami in Alaska, and of the 1960 tsunami in Chile.

Bathymetric data and seismograms of tsunamigenic earthquakes continue to be available. The World Data Center supplied a request for 5-minute gridded bathymetric data for the Pacific Ocean to Norman Ridgeway of the New Zealand Oceanographic Institute to be used in the calculation of tsunami travel times. The World Data Center also receives requests for information on occurrence of tsunamis in specified regions and for historical information about a specific event.

A publication describing Chilean tsunamis, which will be completed in 1985, includes locations, operation dates, and characteristics of the tide stations, available recorded seismographic data, historical occurrences and effects, analyses, available photographs, and references. This report will be prepared jointly with Chilean experts and issued as a World Data Center-A report.

Future projects include a continual refining and supplementing of data now in the data files and an extension of the data to include tsunamis in the Mediterranean and Caribbean Seas and Atlantic Ocean. Information on source dimensions, as inferred from earthquake aftershocks, and information on focal mechanism will also be added to the file over the next several years.

3. U.S. Army Corps of Engineers.

Dr. James Houston of the Waterways Experiment Station has initiated a study of tsunami flood levels in Alaska for the Federal Emergency Management Agency.

4. U.S. Geological Survey.

Mr. John Filson reports that the U.S.G.S. will publish a study entitled "Tsunamis--Hazard Definition and Effects on Facilities" in 1985.

5. Agency for International Development's Office of Foreign Disaster Assistance (OFDA).

Mr. Paul Krumpe is the program manager for OFDA, which is sponsoring the THRUST project described on page 9.

IV. ORGANIZATIONAL NEWS

The Earthquake Engineering Research Institute formed a tsunami subcommittee with Jane Preuss as Chairperson in May 1985.

EVALUATION OF POTENTIAL LOSSES IN THE PUGET SOUND AREA
THE DEVELOPMENT OF AN UPDATE

By

Bruce C. Olsen
Consulting Engineer
Seattle, Washington 98101

Introduction

In 1974 a study was made for the purose of determining poaaible earthquake losses in the Puget Sound Area. This study was based on the potential effects of either of two hypothetical earthquakes, the location and magnitude of which were established by the U.S. Geological Survey. Conclusions of this study were published in 1975 as Open File Report 75-375. The results have been used by emergency service personnel for planning and study purposes. The present paper is a review of that study with consideration given to a possible methodology for bringing it up to date.

Background

The original study was made for the purpose of informing emergency service agencies of the potential hazard to people, structures and lifeline functions. It was based on a methodology derived from that which had been employed by Karl V. Steinbrugge in studies made for San Francisco and Los Angeles, modified to suit variations existing locally. It involved extensive analysis by the Geological Survey of the intensity of shaking to be anticipated over the area of the study, as caused by each of the hypothetical earthquakes. This, in turn, was translated into damage and injury estimates by correlating location of facilities with areas of differing intensity, locating population with regard to time of day, and making engineering estimates of possible damage to buildings and lifelines based on the nature of the construction, its age and general condition.

Data Sources and Updating

There is a forerunner to the problem of updating. In 1980 there wasa combined update prepared for the study which had been made for San Francisco in 1972 and that for Los Angeles in 1972. This report provides some guidance for any similar update study which might be made for the Puget Sound area. The California update dealt with the same matters which had been included in the original studies and updated items in a directly comparable manner, including deaths, injuries and damage to functions of vital need. To accomplish this the report included an investigation of population changes and the altered construction inventory used as a basis for extrapolating changes. A more specific assessment of hospital and other medical facilities was also included. The original studies did not deal with monetary losses, but were considered in the update on the basis of assessor's records.

An updating for the Puget Sound area would deal with the same material. One has only to drive through or fly over this area to appreciate the vast change that has occured in the ten years since the last study was made. As an example, Bellevue, which was still primarily a bedroom community at that time has in the intervening years become an independent major city, with all of the attributes of an urban community. Some other areas have experienced somewhat similar rapid growth, while others show little population change, but a marked change in activities.

Assumptions and Steps in Updating

In the 1975 study we looked at earthquake losses in two parts. The first was that of Deaths, Injuries and Homeless, and the second was that of Vital Needs. Vital Needs include a group of essential functions or elements including Communications, Fire Prevention, Police, Electric power, Gas, Water, Streets and Highways, Medical Facilities and Services Food Supplies and Schools.

Each of these elements was evaluated in terms of information available at the time of the report, including census data and related demographic material. In the California update it was assumed that population changes would be

1971, the Imperial Valley earthquake of October 15, 1979 and the Coalinga, California earthquake of May 2, 1983, in any of which the building damage maight be matched in similar construction in the Puget Sound area. On the other hand, the Tangshan, China earthquake of July 28, 1976 is not likely to be comparable to local experience because of difference in construction types, population distribution and other factors.

Geological factors should normally expect to remain constant, since they are generally dealt with in terms of tens of thousands of years. In the Puget Sound area however, we lack the well-defined faul pattern of the San Andreas, and any new publication tending to define possible areas of rupture may have an effect on the assessment either of location or magnitude. Similarly, recently published material claims that the area could experience greater earthquakes than previously anticipated. This may be debated or refuted, but in the meantime makes for a more conservative evaluation.

Finally, while not directly related to potential loss, status of Public Awareness, and appreciation of the earthquake potential has a bearing on how a community or geographic area will respond to and cope with an earthquake. Public awareness leads to cooperation with political action or regulation aimed at hazard mitigation. It is difficult to assess the impact of the Seattle Earthquake Safety Education Program in promoting actions to mitigate earthquake hazards, but the fact of its existence is a matter to be considered in the evalualtion process.

Prior studies have dealt on with the physical effects of the disaster, the injuries and outages with which the emergency personnel are immediately concerned at the time of and immediately following the earthquake. The major earthquake has the additional feature of extremely high monetary losses, as well as damage resulting in widespread unemployment also bearing on monetary losses. Whether an updated study follows the California procedure of utilizing assessor valuations or some other scheme, the fact remains that economic impact cannot be denied and must be an included element.

proportional to building inventory changes between the time of the original study and the update report. Similarly, the class of construction was assumed to be related to population changes. These assumptions are judgemental and are dependent on intelligent application of information available to provide rational results.

In dealing with Vit Needs proportioning to population changes may not be valid, and a more detailed study of actual changes in specific services and facilities is required. As an example, urban population growth is countered by shrinking in urban public school registration. This has resulted in physical elimination of some and closure of other schools, and a reduction in some hazards. Other essential facilities, such as hospitals, are limited in number, and changes can be tracked in detail, while the location of new facilities can be compared with prior intensity data to help assess potential damage.

While population growth tied to construction inventory may have been valid for California, there may be other factors worth considering here. With Boeing as a major employer, the entire Tacoma-Seattle-Everett corridor fluctuates with the fortunes of that corporation.Similarly, large military and naval installations, while essentially self-sustaining, add to the population and service requirements of the area.

In 1949, the Smith Tower was almost the only high-rise building in the entire Puget Sound area, with a scattering of other buildings generally not exceeding fifteen stories in height. This accented the attention given to the extensive damage in old unreinforced masonry buildings.By the time of the 1965 earthquake Seattle had added the Space Needle, the Washington Building and the Sea-First Building, but not much more, while other Puget Sound communities were equally inactive. Between 1965 and 1975 there was a general spurt in construction activity throughoutthe area, without experience record concerning its earthquake resisance. Meanwhile we have remained throughout the area with a substantial backlog of older unreinforced masonry buildings. In view of this our update needs to involve a careful reading of experienced gleaned from other areas which have experienced earthquakes, and which have had comparable structures. This might include the San Fernando earthquake of February 9, Conclusions

1. Since we do not have a well-defined fault system, prediction with regard to location is uncertain. As a result a "worst case" assumption, such as Earthquake "B" in the 1975 report should be selected.

2. Assessment of Deaths, Injuries and Homeless can be roughly updated proportioned to population change. In doing so it must be rational and with careful judgement concerning the effect of population center shifts.

3. Vital Needs can also be calculated on the basis of population changes, however specific attention should be given to readily identifiable elements.

4. Updating by extrapolation from a prior report is valid ony from the original report, and then only within a limited time following publication of the original.

EARTHQUAKE AWARENESS, PREPAREDNESS AND MITIGATION

by

Patricia A. Bolton
Battelle Human Affairs Research Centers
4000 NE 41st Street, Seattle, WA 98105

INTRODUCTION

The purpose of this discussion is to present some of what is known about social responses to the earthquake hazard and to earthquake events. "Social responses" can include actions taken by individuals, families and other groups, emergency management personnel, research and business organizations, and government decision makers and agency staff at the local, state, and federal level. Considerable research has been done in the past three decades on hazard awareness and on disaster preparation and response. Only a small portion of this research has dealt with the earthquake hazard specifically, and only a very small portion of it has dealt with the social response to the earthquake hazard in the Puget Sound area of Washington. To the extent that earthquakes and other hazards share similar characteristics or have similar consequences to people and property, lessons can be shared across such events, and lessons from other areas of the United States can provide insights into likely responses in Washington state.

Nisqually Wildlife Refuge Office Building	SMA-300	48.083°N 122.717°W	USGS	Ground Level
Olympia Highway Test Lab	SMA-136	47.03°N 122.90°W	USGS	Ground Level
Orting Pierce County Rock Quarry	SMA-642	47.07°N 122.21°W	USGS	Ground Level
Ross Dam Upper Gallery Right Abutment	SMA-3987 SMA-3986	48.73°N 121.07°W	SDL	Minimal Instrumentation
Seattle Bulk Mail Facility	SMA-3931	47.29°N 122.32°W	USGS	Ground Level
Seattle Federal Building	SMA-2718	47.60°N 122.33°W	USGS	Basement
Seattle Pier 20	SMA-1931	47.58°N 122.35°W	USGS	Ground
Seattle SEATAC Airport Concourse C	SMA-134	47.42°N 122.30°W	USGS	Basement
Seattle Ship Canal Bridge	SMA-2535	47.66°N 122.32°W	USGS	Ground Level
Seattle West High School	RFT-512	47.58°N 122.39°W	USGS	Basement
Seattle V.A. Hospital	SMA-775	47.56°N 122.31°W	VA	Sub-Basement
Spokane V.A. Hospital Building #3	SMA-772	47.70°N 117.48°W	VA	Ground Level
Shelton Fire Station	SMA-301	44.218°N 123.108°W	USGS	Ground Level
Stanwood Snohomish Co. Library	SMA-173	48.247°N 122.346°W	USGS	Ground Level

Tacoma City-County Building	SMA-307	47.25°N 122.45°W	USGS	Basement
Tacoma V.A. Hospital Boiler Room	SMA-777	47.130°N 122.570°W	VA	Ground Level
Tolt River Dam Crest Abutment Toe	SMA-5132 SMA-5133 SMA-5131	47.69°N 121.69°W	SDW	Moderate Instrumentation
Tumwater Seismograph Station	SMA-640	47.015°N 122.908°W	USGS	Ground Level
Vancover V.A. Hospital Building #4	SMA-771	45.64°N 122.66°W	VA	Ground Level
Walla Walla V.A. Hospital Building #109	SMA-776	46.06°N 118.36°W	VA	Ground Level
Wynoochee Dam Upper Gallery Lower Gallery Downstream	SMA-1236 SMA-1250 SMA-1235	47.39°N 123.60°	COE	Moderate Instrumentation

*BR Bureau of Reclamation
COE Corps of Engineers
SDL Seattle Dept. of Lighting
SDW Seattle Dept. of Water
USGS U.S. Geological Survey
VA Veterans Administration
WSDOT Washington State Dept. of Transportation

Definition of a few terms:

- Minimal instrumentation is 2 accelerographs per ground/structure system.
- Moderate instrumentation is 3 or more accelerographs per ground/structure system with at least one instrument outside of the structure at a ground site.
- Extensive instrumentation consists of 12 or more remotely placed sensors that allow a rigorous analysis of structural response during an earthquake.

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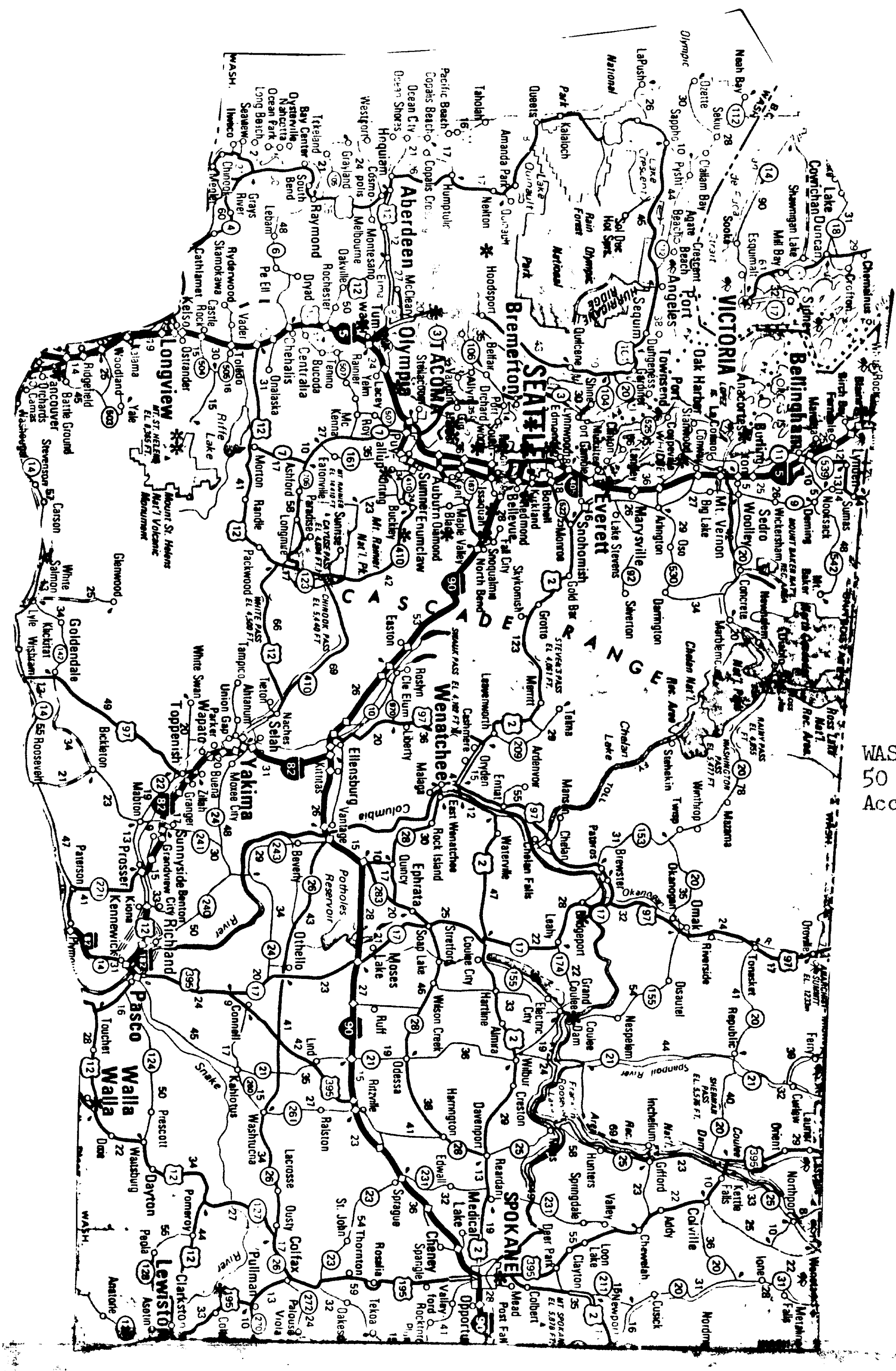
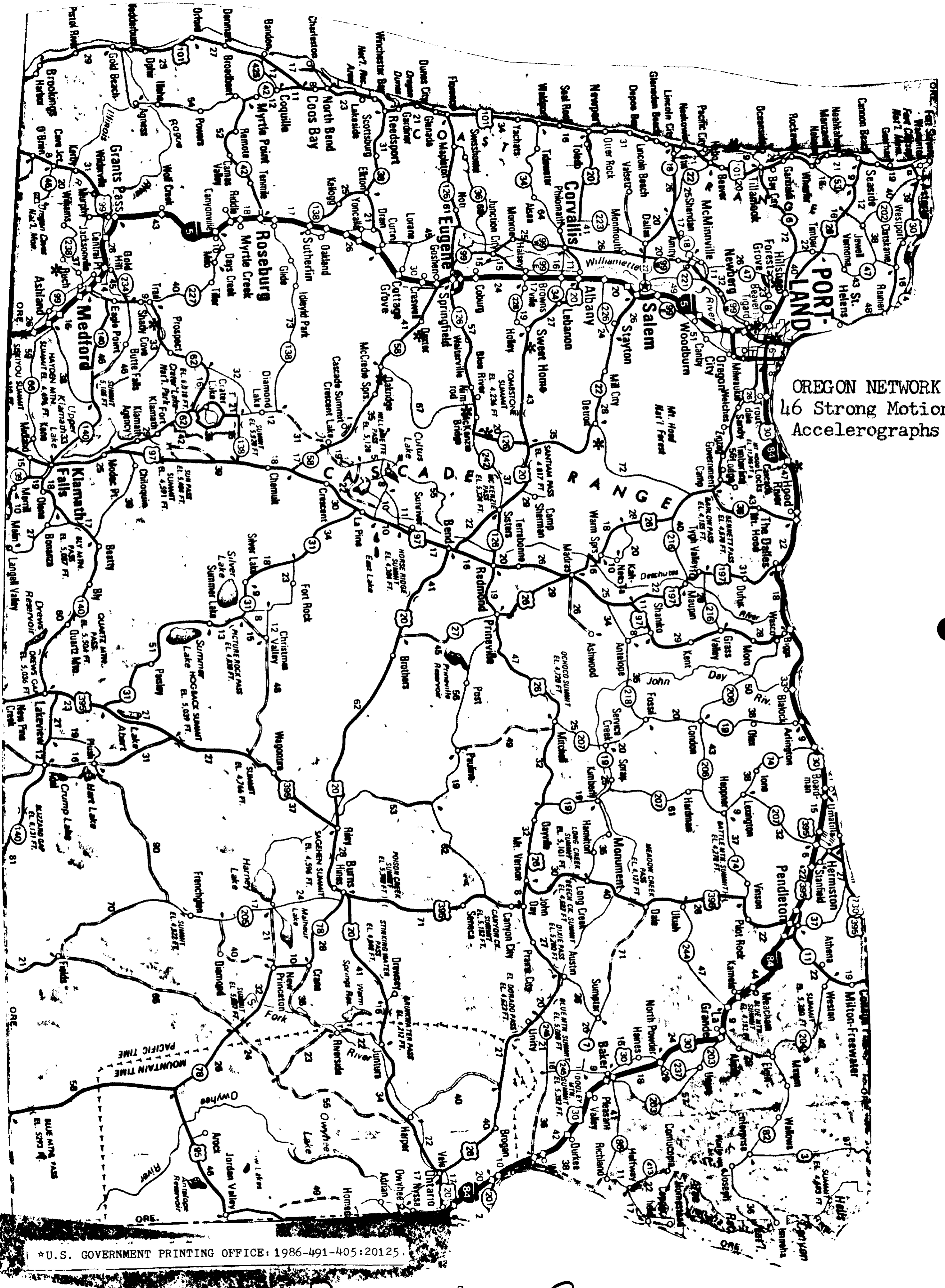


WASHINGTON NETWORK
50 Strong Motion
Accelerographs



OREGON NETWORK
46 Strong Motion Accelerographs

*U.S. GOVERNMENT PRINTING OFFICE: 1986-491-405:20125

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One of the purposes of this workshop is to make available the latest information on the earthquake hazard in the Puget Sound region. The U.S.G.S. and others in the scientific community are making considerable effort to better understand the earthquake hazard. The premise is that the availability of more and better information will lead to better responses to the hazard by private and public decisionmakers. That is, decision makers will be more likely to be aware of the hazard, have a more accurate view of what the risk is to their interests, and be more likely to take more effective measures to prepare for or prevent the consequences of a future earthquake event. However, research on social response indicates that to a great extent, actions taken to prepare for or mitigate the consequences of earthquakes are not as comprehensive as would be possible in terms of the information available on the earthquake hazard.

Information and Action. A simple model of response is that actions (responses) taken before, during and after an earthquake will be determined by the amount and type of information available to a particular decisionmaker (e.g, the head of a household, a city official). However there is not a direct behavioral link between the availability of information and the taking of some action. This is because the model for the relationship between information and action includes a variety of social and psychological factors that affect whether or not the hazard is perceived as creating a definite risk to valued items or activities, and whether or not actions related to earthquake risk reduction are viewed as more important to engage in than other actions. That is, an effective response to information on the hazard depends on the actor being aware of what is at risk from the hazard and having some motivation to take the appropriate action to reduce losses. In summary, the model is as follows:

Information ⟶ Awareness ⟶ Motivation ⟶ Action

Starting at the left hand side, information is gained through experience (such as having experienced the 1965 earthquake in Seattle and Tacoma) or through education--which is learning about something basically second hand. Awareness with respect to earthquakes can be of two kinds--awareness of the existence of the hazard in a particular area, and awareness of what is at risk from this hazard, i.e, what will be affected if an earthquake of a certain magnitude occurs. Merely knowing there is a hazard is rarely enough to motivate a decisionmaker to act. There must be some recognition that ones own interests will be affected (e.g., ones home and family; the community's school buildings). Once a decisionmaker is aware of the hazard and has considered it in terms of what actually is at risk, he or she may well decide to do something about it. Actions can be done for personal reasons, or taken in behalf of others. We act as individuals to protect our own person, our family, and our property and we act as professionals or as government representatives to take actions in behalf of our clients, our constituencies, our community, or our society.

The decisions about whether or not to take actions, and on whose behalf are affected by a variety of factors. Much of our response behavior is social in motivation--we are motivated to take specific actions because of roles we are playing such as parent, or firefighter, or building official, or state representative. Our ability to take these actions effectively may be constrained by various economic, political and legal factors. What factors we are taking into account will depend to some degree on the time frame of the action--whether the action is before, during, or after the earthquake. Preparedness and mitigation are undertaken before the event, protective actions are taken during, and relief, recovery, and reconstruction activities follow.

Although it would be possible to discuss research findings on each of these types of actions, I have selected only a few areas that seem most appropriate to this workshop. First I will review some findings on the effects of earthquake awareness on actions taken in preparedness for earthquakes, and second, what happens to people during earthquakes. Then I will review what has been found out about making preparedness planning more effective. Last I will go over some of the factors that affect the implementation process of earthquake hazard mitigation activities.

INDIVIDUAL AWARENESS AND RESPONSE

It has been found that individuals may be aware of the hazard--for example, "know" that earthquakes are a possibility in their area. Experiencing an earthquake of medium or greater intensity probably is a very effective way to develop awareness of the hazard. Also information about the hazard, if it is repeated often and in different forms and from different sources can create at least a general awareness. Studies in California have indicated, for example, that there is a fairly high level of awareness of the earthquake hazard there, although this does not mean that people will also perceive earthquakes in terms of their own risk; that is, in terms of the likely consequences to them. Also, having an awareness of a hazard is not the same as giving it salience. People can be aware of a hazard without being particularly concerned about it, relative to other concerns.

Several years ago a study was conducted in Southern California during a period of time when there had been considerable publicity about a geologic event referred to as the Palmdale Uplift, which some scientists thought might presage an earthquake. This situation was also accompanied by publicity about two different predictions of imminent earthquakes, (one prediction was later withdrawn; one was not borne out). Under these conditions of high publicity about fairly specific hazardous conditions, a survey was done of 1450 residents in the Los Angeles area. Following are a few of the findings from this extensive study (Turner, et al, 1979; Turner, et al., 1980) that relate to the relationship between awareness and action.

Before the study respondents were asked about earthquakes specifically they were asked about the three most important problems facing the residents of Southern California. Less than 3% of them included earthquakes as one of their three concerns. However, when these respondents were eventually asked how they felt about the possibility of experiencing a damaging earthquake, over 60% acknowledged being substantially frightened. Thus, they weren't really concerned about earthquakes compared to other things, but when they thought about them specifically, many felt frightened over the prospect. Then they were asked how worried they were about one happening there. Here, just about half said they were very worried about one happening there, compared to

63% who had said they were very frightened when they thought about the consequences, should one occur. Thus it can be seen that "awareness" has a variety of dimensions. If people are told about the earthquake hazard, they may become fairly worried, at least if they perceive themselves as at risk. But getting them to think about it over and above other daily concerns is much more difficult.

Related to responses due to this awareness, these same respondents were asked what they had done for themselves with respect to earthquake risk. For this they were provided a checklist of 16 items. Over 50% of them reported having a working flashlight, battery radio or first aid kit, although most had these items for reasons other than for earthquakes. Far fewer (under 30%) had stored extra food or water; less than 20% had done specifically earthquake-related things like rearranging cupboard contents or putting good latches on cupboards. Less than 2% had ever attended a neighborhood meeting to learn about appropriate earthquake response. However, on the hopeful side for those concerned with public preparedness, over 70% of the respondents responded that there was too little news coverage of what to do when an earthquake strikes, how to prepare for an earthquake, and what government officials are doing to prepare for an earthquake. Over 80% wanted more coverage on the latter topic.

In sum, even with fairly high levels of awareness of the potential for an earthquake and of concern about consequences should an earthquake occur, few of these southern Californians had taken personal precautions specifically related to earthquake safety. When asked who they thought was responsible for doing something for particularly endangered groups, the findings clearly indicated that there was considerable reliance on the government. (Endangered groups included people in unsafe structures or unsafe locations, impaired people, and those in institutional settings).

INDIVIDUAL RESPONSE DURING EARTHQUAKES

Injuries From Earthquakes. Now I'm going to turn to a fairly new research area, dealing with what people do during the shaking. Findings from this research are useful for thinking about ways to instruct people about protecting themselves and for thinking about ways to instruct home dwellers, office occupants, and design professionals in ways to make inside environments safer with respect to earthquakes. This body of findings, often referred to as research on occupant behavior, is small, but growing related to earthquakes.

One type of research that has been done with respect to occupant behavior investigates how people get injured in earthquakes (e.g., Aroni and Durkin, 1985). We often see slides of the outsides of damaged buildings, but less often of what homes and office buildings look like inside after a good shake from an earthquake. Such pictures can give an idea of what happens to what engineers refer to as the nonstructural aspects of buildings, and the contents of buildings. Among the nonstructural aspects of buildings are things like light fixtures, plumbing, ceiling tiles, wiring, stair railings and decorative elements. Building contents include furniture, art work, knick knacks, glassware, liquor collections in homes, and desks, filing cabinets, book shelves, and machinery in offices. Most of the contents of homes and offices are not attached to anything, and all too many of the nonstructural components are not attached well enough. Items that are not well affixed have the potential to move, fall, tip, break, or empty out during an earthquake. During the period of ground shaking, building occupants bump into things, and things bump into them. Injuries include most typically bruises, scrapes, cuts, sprains and fractures. Major injuries are more typically caused when people are pinned under heavy debris. Deaths often are related to head injuries.

Minor injuries often occur when peolpe are doing the things they were taught to do. People who go to stand in doorways can be be hurt by the doors themselves, which may swing during an earthquake. Office desks may not stay put, and people are hurt as they try to get under something while being thrown off balance by the movement of the building during the period of ground shaking. Refuge zones, such as desks or tables, may also move around. In a study (Arnold, et al., 1982) of occupant behavior in an office building during the 1979 El Centro earthquake (Richter Magnitude 6.4 to 6.6) it was found that 37% of the occupants were injured during the shaking. Of the 44 injured, 30 were injured by building contents (desks, filing cabinets, shelving, etc.) and 14 by building components (in this instance, mostly by doors, since there wasn't a problem with the fixtures or ceilings falling). Also, people get pinned between objects that only minutes before were benign elements of their environment--such as a woman in Coalinga who related to me being pinned against a kitchen sink by her refrigerator during the 1983 Coalinga earthquake (Richter Magnitude 6.7). People in their homes during the Coalinga earthquake reported being injured by refrigerators, dressers, mirrors, ceiling tiles, canned goods, and machinery (Durkin, et al., 1984).

Going outside during an earthquake can be even more dangerous. In the Seattle earthquakes of 1949 and 1965 the few deaths and injuries that resulted were typically caused by falling bricks. Preliminary findings have been reported about injuries to people who were in the unreinforced masonry commercial buildings in Coalinga's business district when that earthquake struck. The relative risk of injury while exiting one of these buildings versus staying was over 3 to 1 (Durkin, 1985). The cornices and facings of masonry buildings can easily fall across doorways, catching those who are trying to run outside.

Human Behavior During Earthquakes. Research on occupant behavior also has examined what building occupants do during the shaking. Respondents to the self-administered questionnaire completed by persons who had been occupants of the 6-story Imperial County Services Building during the 1979 El Centro earthquake (Arnold, et al., 1982) were asked what they first did when the shaking started. About 36% reported they got under their desk (and for a third of these, the desk then moved away), 15% said they went and stood in a doorway, 37% said they just stayed where they were, and 8% said the first thing they did was dodge to avoid falling objects. When asked to indicate why they took that particular action, 70% said they had selected that action due to previous instructions when in school, during drills in the building, or previous experience in an earthquake.

In a study of persons in their homes during an earthquake (Richter Magnitude 7.1; Modified Mercalli Intensity 9 to 10) in the Urukawa district of Japan in 1982 (Archea and Kobayashi, 1984), people were asked to demonstrate what they had done during the 30-second period of strongest ground motion. Responses from the face-to-face interviews indicated that only 15% of the dwelling occupants remained in the same location throughout the ground shaking phase. The average distance traveled by respondents was 27 feet, and the most extreme distance was 174 feet. In the course of this travel, these occupants may have taken several different actions.

What were these people doing? About 47% moved to turn off their portable stoves. This typically was the first action, indicating the high priority of this behavior in Japan (although much less relevant to U.S. residential settings). Some 39% tried to brace free standing cabinets or bookshelves with their bodies to keep the furnishings and contents from falling. None were successful in this activity during this earthquake, although many had been in previous earthquakes of lesser intensity, so it had seemed reasonable to try it again.

About 24% of the Urukawa residents said they ran outside at some point, and a few tried to but couldn't. Only 3 of the 41 respondents reported trying to protect themselves from falling objects by getting under something. Some apparently preferred to go outside as a potentially protective action. In many of these Japanese homes there was no object to get under. However, that is true of many of the rooms in our houses as well--in my house I can think of only two objects I could get under, both tables.

Although data is beginning to accumulate on how people get injured, and what elements of buildings are particularly hazardous, there is much work to be done on applying this to what can be done to mitigate specific consequences. Home owners and business administrators can undertake many fairly easy and inexpensive means for reducing the risk of injury from buildings' contents. Guides providing general advice for how to prevent injuries and nonstructural damage are appearing (e.g., American Red Cross, 1982; Reitherman, 1985; SCEPP,a and b, n.d.). However, some actions are more appropriate for some settings than for others, and dissemination of information on what to do in particular types of buildings still is lacking.

INDIVIDUIAL BEHAVIOR FOLLOWING A DISASTER EVENT

Much research has been done on what individuals and organizations do immediately following disaster impact (e.g., Barton, 1969; Mileti, et al., 1975;). Although only a small portion of this literature refers specifically to earthquake disasters, most of it is also relevant to earthquake disasters. Since the literature is voluminous, only a few points will be reviewed here, having been selected because of the frequency with which there are misconceptions on the part of disaster response planners about these areas of concern.

One of the earliest observations in the disaster literature has stood up to numerous disasters and researchers. Panic behavior seldom is exhibited by persons during or immediately after a disaster event (Quarantelli, 1981). Instances of pure panic--i.e., uncontrolled and irrational flight away from something--have seldom been documented by disaster researchers. This is not to say that people are not frightened, for they are, but they can nonetheless engage in behaviors necessary for coping with the suddenly changed situation. For the most part individuals will have a feeling of responsibility toward someone else such as a family members, relatives or neighbors and quickly engage in behavior oriented toward reestablishing contact and providing assistance. People in caretaker or emergency occupational roles--like teachers, firefighters, policemen--typically will act take actions consistent with their role obligations, before engaging in actions related to their own families.

It appears that individuals first see to others for whom they feel some sort of responsibility. After accomplishing critical activities, like finding people, or tending to injuries, they then will begin to engage in information-seeking actions, such as listening to a radio, or going to places where information might be obtained. If conditions permit, people will want to stay near their home. And if this is not possible, they are more likely to take emergency shelter with relatives and secondly, with friends, than go to public shelters.

Typically, after disasters considerably more public shelter space is provided than is used. Public shelters are only used to any great extent when the scope of the disaster event precludes displaced families from finding shelter with those whose homes were less affected. Findings from a study of the Coalinga, California, earthquake indicate that over 50% of the families who moved out of their homes due to damage or fear, camped in their own yard after the earthquake (Bolin and Bolton, 1985). Although it is apparently the preferred alternative for victims, this might be a lot less desirable a post-earthquake solution during a drizzly winter month in Seattle, so one might assume a greater level of doubling up of families than of families staying in their yards in that instance. In Coalinga the emergency housing phase lasted an average of 3 weeks. In general, in instances of long-term dislocation because of the level of damage to the home, the typical moving pattern for a family is to some short-term emergency stay with relatives, then into governmentally provided temporary housing for individual families, and then back to one's own home. The major caution to be mentioned with respect to studies of what individuals and families do following disasters is that much of our post-disaster research has been done on fairly small communities, made up mainly of single family dwellings.

In general most people are not too emotionally debilitated after a disaster to return to their routines, which is not to say that they do not experience any distress at all. In Coalinga, about 65% of the respondent families said that someone in the household had experienced "emotional strain" as a result of the earthquake. Of these, some 28% sought counseling for this distress. The continuing aftershocks contributed to the ongoing distress felt by some. Although the psychological literature on post-disaster mental health often seems to imply that post-disaster emotional problems are typically severe and are related to the actual traumatic experience of having gone through the disaster event, sociological research reveals a different picture. Severe emotional consequences are rare, and sociologists have observed that the continuing low-grade emotional upset felt by many after a disaster may be due more to the the day-to-day hassles associated with trying to pull together resources for recovery (Quarantelli, 1979). This focus on the nature and extent of post-disaster distress suggests more attention is needed on to how resources are distributed after disasters and less on large-scale crisis intervention.

GOVERNMENTAL AWARENESS AND RESPONSE

Findings on hazard awareness among local officials indicate that they are more likely to be aware of and concerned about frequently occurring and obvious natural disasters (e.g., hurricanes, tornadoes) than of natural hazards events with low annual rates of occurrence (e.g., earthquakes) (Petak and Atkisson, 1982). Experience and education can be key factors in enhancing awareness levels of government officials and agency staff, but the message needs to be repeated in different forms and from different sources (Anderson, 1978). With respect to awareness in the State of Washington, a recent study found a fairly high level of awareness of earthquakes among the professionals and public officials who were interviewed (Drabek, et al., 1983). The researchers found that 88% of the respondents thought it was very likely that a major earthquake, causing major loss of life and property, will occur in Washington during the next 50 years. These same respondents did not think there had been substantial community preparedness efforts addressed to the earthquake hazard in the state. This suggests again the difference between knowing about the hazard, and considering it a salient concern compared to other concerns.

It is often observed that information on hazards, including the earthquake hazard is not used, even when efforts have been made to transfer it to decisionmakers (Bates, 1979; Buck, 1984; Drabek, et al., 1983). What sorts of factors interfere with the motivation or commitment of public decisionmakers to use available information for addressing a hazard when they are aware of its existence in their community? Certainly community-level economic and political factors can affect the likelihood that government agencies, especially at the local level, will take specific actions directed at preparing for an earthquake (Atkisson and Petak, 1983; Wyner and Mann, 1983:Chap. 6). Another observation that is of particular interest to those attending this workshop is that the inappropriate form of the information and the lack of consensus among the scientists about the hazard are among those factors that can inhibit the use of information by local officials. This is because the users of this information do not consider the information adequate for their purposes unless it is specific and concrete about the nature and location of the hazard. This runs counter to the values of scientists who are more comfortable with providing multiple possibilities with the uncertainties emphasized. (Szanton, 1981:64; see also, Hays, 1983:8)

The actions anticipated of public officials who have developed an awareness of the hazard are of two major kinds--planning and executing emergency preparedness and management activities, and implementing earthquake hazard mitigation activities. The final two sections of this presentation will address public preparedness planning and earthquake hazard mitigation.

PREPAREDNESS PLANNING AT THE LOCAL LEVEL

The subject of how emergency response activities are carried out in the immediate aftermath of disasters has long been of considerable interest to social science researchers (Dynes, 1969; Mileti, et al, 1975; Quarantelli, 1978). Earthquake response planning does not differ in any appreciable way from planning for other types of disasters. A major conclusion to come from the study of emergency response, however, is that disaster planning has been found to differ considerably from routine emergency response planning. Specifically, during the emergency period of a disaster response, the level of interdependence among participating organizations is altered from that of response to routine emergencies (Dynes, et al., 1972). Inadequate disaster planning is more likely a result of poor organization than of lack of resources.

Three other major points emerging from research on disaster response are that (1) good disaster planning, including earthquake response planning, is a process rather than a product, (2) good disaster response planning is based on knowledge of the hazard for that locale, and (3) effective disaster response planning takes into account what is known about public behavior during and after a disaster event.

With respect to this latter point, it has been suggested that disaster planning will be more effective if it takes into account what people are found to do in disasters, rather than expecting them to act in accordance with the plan (Quarantelli, 1982). Examples of knowledge crucial to disaster response planning include findings indicating the low likelihood of either panic or looting in the aftermath of a natural disaster in a U.S. community, people's insistence on seeing to family members and other relatives in periods of uncertainty, and families' preferences for sheltering with relatives or friends when possible after a disaster. Correction of the misperceptions disaster planners often hold about disaster behavior can help planners set more realistic priorities about needed services and facilities in a disaster (Wenger, et al., 1980).

EARTHQUAKE HAZARD MITIGATION

The final topic to be covered in this limited review of social science findings relevant to preparing for earthquakes is that of earthquake hazard mitigation. Mitigation here refers to actions taken prior to the occurrence of an earthquake event that are directed at reducing the losses likely to occur in a future earthquake. Some communities may do very little to try to reduce the consequences of the likely earthquake event, choosing to rely instead on their capability to respond to the damages and disruptions after the fact. Earthquake mitigation policy should be proactive, compared to the more traditional reactive approach of coping with the consequences of the event after it has occurred.

State and local adoption of a policy that includes earthquake hazard mitigation entails taking a long-term view of the problem. But those who make policy have very few incentives to look at the long term and they usually have enormous pressures on them to solve short-term, immediate problems. Many social, political, economic, and legal pressures and constraints have been documented in relation to efforts to implement seismic safety policies and earthquake hazard mitigation efforts (Wyner and Mann, 1982; Atkisson and Petak, 1983; Drabek, et al, 1983; Selkregg and Preuss, 1984). Deciding to attempt to implement a policy of earthquake hazard mitigation means that the decision makers have done some sort of risk assessment--that is considered the nature of the hazard and what is at risk from it--and decided that the level of risk is unacceptable. The most important feature of this process is that it is a value decision made by state or community leaders; it is not a scientific decision (Petak and Atkisson, 1982; Rossi, et al, 1982).

In the State of Washington, leaders have been somewhat successful in combining earthquake mitigation policy with other issues, and therefore accomplishing the goal of earthquake risk reduction in some limited arenas (Drabek, et al, 1983). For example, seismic safety was used along with several other considerations, in deciding about the future use of specific school structures. Concern about the Skagit Nuclear Power Plant eventually included very serious questions about seismic safety which played a role in the decision to discontinue its construction. During such controversies, concern over the hazard is increased. and it slowly becomes more difficult for community decisionmakers to ignore.

Opposition to the adoption of loss reduction measures has been found to be related to the lack of direct experience with the hazard, perceptions that the measure will lead to economic loss by some important interest group, and to lack of consensus among scientist about the hazard in that locale. Factors found to be related to successful adoption and implementation of loss reduction measures are the attitude of local governmental leadership toward the approach, the capability of local staff in developing and implementing specific measures, and the linking of the earthquake hazard with other issues confronting decision makers (Wyner and Mann, 1983).

Currently local jurisdictions have the major responsibility for adopting and enforcing loss reduction measures, should the policy decision be made that earthquake loss reduction should be pursued. In general, planning approaches at the community level either involve regulatory actions, incentives, or information aimed at altering land use and construction practices in seismically vulnerable areas. Regulatory measures either prescribe or prohibit development in seismic areas by establishing standards or restrictions, a set of sanctions for violating the regulations, and an enforcement mechanism. Incentive programs are noncoercive, and although they must be enacted, participation in an incentive program, such as tax credits for making desired use decisions, is voluntary among those eligible to participate. Informational approaches provide information about seismic hazards so as to facilitate informed decisionmaking.

When social science researchers have examined the success of efforts to put hazard reduction policies and measures in place, it is found most typically that full implementation is not accomplished. This is true even in California where the state has mandated that communities have a seismic safety element in their general plan (Wyner and Mann, 1983). Writing and adopting a seismic safety element does not ensure that the provision is ever implemented. Writing and adopting building code provisions to reduce the damage likely to be done in future earthquakes does not necessarily mean that a community also enforces the code, or that builders comply with it. In fact, there is some evidence that as building codes get better, enforcement gets worse (due to the extra resources necessary for special expertise and expanded inspection activity).

It probably isn't worth the trouble and expense to adopt a loss reduction measures if it cannot be implemented. Thinking that reduction measures are in effect when they are not may lead to some nasty surprises when and if an earthquake does occur in your community. Although there are a variety of barriers to implementing loss reduction measures this does not mean that such measures should not be considered. The final discussion in this presentation is aimed at preparing decisionmakers to identify potential stumbling blocks to the implementation of needed loss reduction measures.

When promoting loss reduction measures for a specific community, it is important to assess the potential effectiveness of a measure before adopting it. In considering if a measure is effective, it is common to ask how well the measure covers the risk--that is, how much of what is at risk would be subject to this loss reduction measure--and to ask what percentage of the total risk would be reduced if the reduction measure were fully implemented. However, it is less common to realize when assessing the potential effectiveness of a particular loss reduction measure that it is necessary to take into consideration the degree to which the loss reduction measure has been or could be implemented. In general, the implementation process entails a set of steps including the design, adoption, and enforcement of specific measures for reducing earthquake losses. Incomplete implementation or any of these stages affects the success of the measure in accomplishing its goal.

Table 1, in its first column, lists typical loss reduction (i.e. hazard mitigation) measures that can be adopted at the local level. The second column is the target group for the measure--that is, what risk-producing behavior will be affected by the measure? Are builders going to have to change their practices to meet new standards; are owners of existing buildings going to have to do something to make the structures safer; and so forth.

The column summarizing implementing actions suggests the chain of things that have to occur to put the measure in place. Any one or all of these can prove to be a weak spot in the eventual success of implementation for that measures. The last column indicates who has control over whether or not that aspect of the implementation process is carried out. For example, it is up to local officials to: decide what buildings a new code will refer to; establish the standards that must be adhered to; provide expertise and staff to enforce these standards; and to have a way in which to sanction, or punish those who do not comply. And it is up to the target group, in this case builders, to decide on the level of compliance they will meet. Performance short of compliance makes them vulnerable to sanction, but they may decide to take the risk where noncompliance serves some other interest they have, especially if they think enforcement is poor.

Table 1. Implementation Actions for Reduction Measures*

Reduction Measure	Target Group	Implementing Actions	Control
BUILDING CODE PROVISIONS	Future developers of buildings in seismic areas	Building identification, standards, enforcement, sanctions	Local officials
		Adherence to standards	Target group
HAZARDOUS BUILDING ABATEMENT PROVISIONS	Owners of existing building in seismic areas	Building identification, standards, enforcement, sanctions	Local officials
		Compliance with retrofit	Target group
ZONING PROVISIONS	Developers of property in seismic areas	Identify seismic zones, zoning revisions, plan review, sanctions	Local officials
		Compliance with zoning	Target group
SPECIAL USE or CRITICAL FACILITY PERMITS	Operators/owners of designated facilities	Requirements for each facility (negotiated), sanctions, enforcement	Local officials
		Compliance with standards	Target group
LIFELINE LOCATION or DESIGN RESTRICTIONS	Operators/owners of designated lifelines	Requirements for each lifeline (negotiated), sanctions, enforcement	Local officials
		Compliance with standards	Target group
SEISMIC AREA IMPACT REVIEW	Developers of property in seismic areas	Requirements for review, sanctions, enforcement	Local officials
		Submission of review	Target group
		Act upon review (negotiate seismic requirements)	Local officials target group
REAL ESTATE DISCLOSURE	Buyers of property in seismic areas	Designate seismic areas, disclosure requirements, sanctions, enforcement	Local officials (may be shared w/ Real Estate Board)
		Disclosure of information	Real Estate Agents
		Act upon information	Target group
PURCHASE OF DEVELOPMENT RIGHTS or TAX CREDITS	Property owners in seismic areas	Property identification, assessment, financing, negotiations with owners	Local officials (may require voter action)
		Volunteer for participation	Target group
		Future land use monitoring	Local officials
PROPERTY ACQUISITION	Property owners in seismic areas	Property identification, assessment, financing, negotiations with owners	Local officials (may require voter action)
		Volunteer for participation	Target group

*This table is based on research and analysis done for an NSF-funded project on Land Use Planning for Earthquake Mitigation, carried out by the University of Washington and Battelle Human Affairs Research Center. The project team included Patricia Bolton, Marjorie Greene, Susan Heikkala and Peter May. The Project Director was Myer Wolfe.

Various forces come into play in the extent to which various measures can be implemented. For example, zoning is likely to be undermined by the granting of variances to zoning conditions due to a reluctance to lose a large development project. Critical facility and lifeline restrictions are likely to be difficult to implement because of the inability to negotiate seismic requirements given high demand for low-cost facilities. For property acquisition programs, it is likely to be difficult to design sufficient incentives to induce participation.

In gauging the prospective implementation success of a measure or measures, the decisionmakers who will select those to try to implement will want to know whether any of the implementation considerations is sufficiently negative so as to undermine the effectiveness of the proposed measure. If so, either the measure can be rejected on the grounds that it is not feasible for that community, or it will be necessary to acknowledge where the difficulties are likely to be and be prepared to make special efforts to overcome the difficulties in implementation.

Community decisionmakers have to consider the level of risk created by the earthquake hazard, and they have to consider their other community concerns. Then they have to ask themselves at least two questions. Can they afford, politically and economically, to implement a particular reduction measure? And on the flip side of this: Can they afford, socially and legally, not to?

SUMMARY

This presentation has addressed the topics of awareness, preparedness, and mitigation with respect to earthquakes. Selected social science research findings have been used to illustrate a variety of considerations that emerge when examining the relationship between available information on the earthquake hazard and the taking of effective actions in response to this hazard. Factors related to enhancing awareness of the hazard and to motivations for action have been discussed for both individual and public decisionmakers. Research is reviewed that describes how building contents and the behavior of persons during earthquakes are related to injuries. Critical features of disaster response planning are described. The importance of considering implementation feasibility when selecting loss reduction measures is discussed.

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EARTHQUAKE EDUCATION

IS THE PUGET SOUND AREA PREPARED FOR A MAJOR EARTHQUAKE?

Linda Lawrance Noson
University of Washington
Seattle, Washington 98195

INTRODUCTION

Past earthquake education efforts within the state of Washington have primarily consisted of occasional presentations on earthquakes and earthquake safety and the distribution by state and federal agencies of information brochures. The media, also, provides sporadic coverage of local causes of earthquakes. Until recently, however, there has been no organized effort to develop a continuing on-going program to educate the public on state earthquake activity, earthquake hazards, and ways to reduce injury and damage (Drabek, Muschkatel, Killijanek, 1983).

The Seattle Earthquake Safety and Education Project (SESEP) was initiated at the University of Washington in 1983 with start-up funding provided by the Federal Emergency Management Agency (FEMA) and administered by the State Department of Emergency Management (DEM). The goals of SESEP are to develop a comprehensive earthquake safety and education program tailored for the school environment that would 1) reduce the vulnerability of school children to the life-threatening effects of earthquakes and 2) involve the larger community in earthquake preparedness activities.

The focus of SESEP on schools is to develop a program that can reach a diverse population and be integrated into existing on-going school safety and education efforts. Funding from FEMA for 1985-86 will be used to continue to develop information to help schools initiate school earthquake education programs and look for new methods to present information on causes, effects, and preparedness to the school community of staff, parents, and students.

The steps followed in the development of a school earthquake safety and education program can be used to tailor programs for other target audiences, such as, hospitals, fire stations, insurance companies and others that would benefit from earthquake safety information.

Tailored programs are important to ensure that particularly vital or vulnerable parts of the community are well prepared for an earthquake disaster. The specific needs and concerns of special interest groups are not met by hazard information aimed at the general public. The experience with schools in Seattle also suggests an increased motivation to carry out hazard reduction efforts as part of ones responsibility to a group.

Appropriate hazard reduction efforts require a realistic understanding of the potential for earthquake damage and the specific kinds of damage to be expected. Personal safety during and after ground shaking involve understanding appropriate immediate and post-earthquake response actions.

Washington state earthquake safety and education efforts, so far, have been inadequate to prepare residents for a major damaging earthquake.

PROGRAM DEVELOPMENT

Education may be defined as that body of skills and knowledge determined to be mandatory for reasonable comprehension of a specific subject area. Whether the goal is teaching the "math facts" necessary to cope with everyday math problems or teaching the "earthquake facts" necessary to cope with a major earthquake, the steps in program development are similar:

- Identify program audience
- Define reasonable and measurable program goals
- Develop specific objectives to meet program goals
- Assess program impact on learning and perception
- Evaluate teaching methods used for effectiveness and practicality
- Revise program based upon assessment to assure that desired program content is being communicated.

Disaster information is most often targeted to the individual homeowner. A brochure is the most common method of information transfer. Immediate response actions and detailed lists of needed supplies and equipment are usually outlined in the brochure. Items are not given any priority for action. The assumption appears to be that one must accomplish all parts to increase ones level of safety. Identification of no cost actions that would lessen the chance of injury during an earthquake are not separated from the many actions that require expenditure.

Transfer of such information from the home environment to school, business, or other situations becomes the responsibility of the user. Additional areas pertinent to other environments are not included.

Distribution of individual disaster information may encourage preparedness among users, but does not usually result in the development of on-going program disaster preparedness programs. Programs tailored for specific groups center on the need for cooperative planning, testing, and operation among members of the group. The Seattle Earthquake Safety and Education Project wanted to develop an on-going school earthquake preparedness program to meet the special needs of the school community of staff, parents, and students.

MOTIVATION

Preliminary results of a study by social-psychologist Dr. Karen Brattesani of what motivated individuals to participate in the Seattle Earthquake Safety and Education Project suggest that general earthquake safety brochures were the least motivating out of 12 possible factors. Among the five most motivating factors were the following:

- knowledge that their particular school building was among a set of relatively high risk school buildings
- a person at the school willing to assume a leadership role
- other program commitments
- availability of district level support and funding
- specific tasks to accomplish listed in order of priority

Barriers to school participation in developing earthquake safety programs included the following:

- Lack of support and funding from the district level often frustrated school committees in their attempt to reduce school earthquake hazards (e.g., bolt book shelves to the wall) and to obtain adequate supplies and equipment. To overcome this frustration, the importance of program elements that are entirely within the control of an individual school were emphasized (e.g., hazard identification, improved earthquake drills, program planning, parent involvement and school fund raisers can all be carried out independent of outside funding).

- Participants wanted a priority assigned to program efforts and a suggested time-line. The school project stresses the value of accomplishing actions within an order and time-frame that are realistic for the participant.

The above suggests the importance of clear, understandable information on local earthquake hazards with reference to the specific impact of an earthquake on the school community and the participants particular school. Therefore, the process developed by SESEP has been first to cover the likelihood of having a damaging earthquake that would impact the Seattle public schools.

Next, information is provided on why schools in particular need to establish on-going eathquake safety and education programs to effectively handle the problems and difficulties that will likely occur during and after ground shaking. The following is a summary of that information:

Need for school earthquake emergency planning in areas of moderate to high earthquake risk:

1. Isolation of Schools

- Communication interrupted (telephone systems overloaded or damaged)
- Transportation routes damaged or blocked
- Other priorities for emergency responders

2. Vulnerability of school population

- Children and senior citizens are subject to significantly higher rates of fatalities and
- A greater proportion of emotional and physical trauma
- Schools have a small number of adults to care for a large number of children
- Many schools have a significant disabled population

3. Schools are public facilities where attendance is mandated.

4. Disaster psychology research findings

- Uncertainty about what to do increases anxiety and lessens ability to respond appropriately
- During a disaster one has a very narrow focus of attention
- Need to develop short, brief instructions
- Instructions should be posted and regularly practiced.

After communicating the likelihood of earthquake activity that would impact the school and the need for school earthquake emergency planning, SESEP covers the elements of an on-going school earthquake safety and education program.

PROGRAM ELEMENTS

There are two primary parts to the school earthquake safety and education program: school emergency planning and student earthquake education on earthquake causes, effects, and appropriate response actions.

The FEMA "Guidebook for Developing a School Earthquake Safety Program" was field tested in Seattle at six pilot schools. Recommendation for changes were derived from staff and parent comments as well as from review by the project advisory board. The "Guidebook..." will be available from FEMA by February 1, 1986.

The "Guidebook" covers steps to the development of a school earthquake emergency plan. Those steps include the following:

- form a safety committee
- identify school earthquake hazards
- establish and evaluate drill procedures
- prepare a school emergency response plan to meet immediate care needs
- obtain necessary supplies and equipment
- inform and involve students and parents in earthquake preparedness activities

SESEP has prepared assemblies and hands-on-learning centers (with equipment developed by the California Environmental Volunteers, Palo Alto, California) to inform the student population for earthquakes causes, effects, and appropriate response actions. The student earthquake education program includes a 30 minute introductory assembly that includes: a short 15 minute slide presentation on local earthquake causes and effects and an 11 minute film, "Earthquakes Don'ts and Do's". Students especially need time for "What if" questions. A list of such questions and answers have been developed for use by teachers in the classroom. An example of the type of questions children ask is: "What about my baby sister? She can't do drop and cover." The response would be to emphasis that there are things to do to help protect the baby, such as putting the crib in a position where heavy objects are unlikely to fall inside.

The assembly content is reinforced in two, short (15 minute), hands-on learning centers following the assembly. Each class participated in two learning centers during gym time. One 15 minute center focuses on plate tectonics and the other center covers response actions at home.

The student earthquake education program stimulates interest in earthquakes, but does not provide a growing program tailored to grade level. This year a curriculum subcommittee of the project advisory board will explore incorporating the content of the earthquake education program into expanded classroom lessons. Dr. Herbert Their, Lawrence Hall of Science, Berkeley, California has developed such curriculum materials for the older student.

The key parts of developing the SESEP program involved working closely with the program users and professional evaluation of effectiveness of methods used to transfer program content which were then used to modify and enhance the program during development. Ideally such program development evaluations would be used in all phases of such projects to assist in determining 1) program content, 2) effective methods to communicate that content and 3) motivational factors for the particular target group.

STATUS OF EARTHQUAKE PREPAREDNESS IN THE STATE OF WASHINGTON

By

Larry D. McCallum
Department of Emergency Management
Olympia, Washington 98504

Introduction

The Puget Sound Earthquake Preparedness Project has concentrated on efforts which will raise the level of awareness and education to the existing earthquake hazard and develop methods and standards for incorporation into local response plans and procedures for emergency organizations. This paper will elaborate on several projects developed under our current earthquake grant and set forth some thoughts on the future scope and direction of the Puget Sound Earthquake Preparedness Planning Project.

Hazard Awareness and Public Education

It is quite clear that the level of emergency preparedness for an earthquake, in this area or in any seismically active region, directly correlates with the perception of the hazard. Research shows that seismic activities are occurring and large damaging quakes have occurred here. As with many areas of the country (including California), apathy reigns supreme and it becomes a very difficult, time-consuming task to generate interest in the existing earthquake hazard and what it means to the individual.

This, in turn, has a direct affect on the public, particularly the decision-makers, in establishing priorities for earthquake preparedness. The issue of awareness and education is complex. Researchers have shown that awareness alone may or may not lead to any meaningful educating of decisionmakers or planning to alleviate the effects of the hazard.

Another problem is how to gauge the level of awareness and education within the populace and then effectively reach those who will make a difference in mitigating the existing hazard.

Current Public Education and Awareness Programs within the Puget Sound Region

It was decided early in FFY 85 that to most effectively reach the general population and the decisionmakers with earthquake preparedness information, it would require working with those organizations already involved, such as the American Red Cross (ARC), Federal Emergency Management Agency (FEMA), local emergency managers, and safety and training divisions for business and state government agencies. The ARC and U.S. Geological Survey (USGS) slide/tape information has been used extensively throughout the Puget Sound area.

This effort has two objectives; to elevate awareness in the general population and, more importantly, to train safety and training division personnel for providing a continuing and perhaps permanent earthquake hazard awareness program for state and private entities. This program area has suffered recently because of earthquake funding cuts reducing staffing levels and requiring reprioritization of the existing work program.

An interesting follow-up to our awareness campaign would be to assess its success by determining how much information is used to develop plans and adapt hazard reduction measures at home or in the office. What have decisionmakers done with the information? How many corporations here in Seattle have taken earthquake planning into account?

Washington Earthquake Hazard Information Project

There seems to be a lack of knowledge on the characteristics of seismicity and earthquakes which occur in Puget Sound. To offset this gap in awareness, the state along with the University of Washington have been compiling an earthquake hazards brochure to give the public general background information on earthquake cause and effect, seismic monitoring, fault zones, and other information to contrast the Puget Sound region with other seismically active areas. In addition, the brochure will have some information on home and business protection.

Earthquake Awareness Week

The state sponsors an earthquake awareness week each year in early April. During this period, news releases are made and local emergency offices present earthquake safety education programs to schools throughout the state. Both the ARC and FEMA participate.

General Information Networking

Since the Mexico City earthquake, interest in seismicity and preparedness within the Puget Sound region has increased dramatically. FEMA and state brochures on earthquake preparedness have been sent to countless numbers of concerned citizens and to local emergency management organizations to be disseminated during group presentations. The brochures are of excellent quality and are definitely an asset in efforts to increase awareness and education.

Earthquake Preparedness Planning in the Puget Sound Basin

Planning for the response to a major earthquake event is predicated on the existence of general emergency planning at the local level. In other words, Standing Operating Procedures (SOP's) as well as specific data on vulnerability of critical facilities and utilities must be couched within the framework and annex structure of an existing plan before it will do some good. Many muncipalities in this area currently do not have emergency management response plans. On the other hand, there are some jurisdictions in Puget Sound with excellent plans. The process of upgrading existing plans and developing new ones is slow because of reduced funding of emergency management programs.

Development of Pre-Hospital Medical Protocols

An early focus of the Puget Sound Earthquake Preparedness Program was to work with local Emergency Medical Services (EMS) organizations to determine some of the major medical response problems which would be encountered in the event of a major earthquake. These problems were identified and during this last year

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standards or specific procedures were developed for pre-hospital medical treatment including triage protocols, lists of critical/vital hospital equipment and supplies, protective measures for hospitals, and guidelines for pre-determining alternate treatment facilities.

These standards will be introduced into local emergency management organizations as budgets and time permit for incorporation into existing emergency plans to achieve both earthquake hazard reduction and mitigation within the medical community emergency response system.

Washington First Responder Audio-Visual Training Package

Research, including the 1975 USGS Study, has shown that the post earthquake environment will be a major test of all levels of emergency management, particularly the first responders. Research findings on early work elements of the project demonstrated the need for local first responders to obtain additional skills to assist in urban search and rescue, pre-hospital medical treatment, the use of volunteers within the disaster scene, and many other specific functions.

We submitted a proposal under our earthquake grant, retained a consultant and are currently developing a Washington First Response Audio-Visual Training Program, which will assist many sectors of the first responder community after a major earthquake or other incidents. The program, modeled after the California Plan for Life tape series, will be introduced when completed as part of the training curriculum in existing Washington agency training programs. It is also envisioned the material will be made available through local emergency management networks.

Pilot Computer-Assisted Seismic Damage Assessment System

A major problem in developing emergency response planning for any disaster, including earthquakes, is the inability to determine damage scenarios (extent of damage) which can occur in a specific jurisdiction. In an attempt to resolve these problems, the earthquake planning program has been funding a special pilot project, in cooperation with the Western Washington University

School of Geography, to develop software and demonstrate the feasibility of using a microcomputer to generate earthquake intensity maps depicting potential damage from magnitude and epicenter data using western Whatcom County as the study area. There have been promising results from the project.

The software has been completed and maps can be generated for areas within the study area. During the design of the software, a major objective of the researchers was to maintain flexibility for use of the software in other Puget Sound areas and to permit the addition of variables, data, and tasks for use in a larger project mode.

A real plus of this project has been the close coordination of design of the system, including the user-friendly format, with Whatcom County Department of Emergency Services.

After the system is perfected, location and capability of first response needs could be determined in relation to potential earthquake damage areas. Knowledge of this type will assist in pre-planning locations of emergency vehicles and could influence land use codes by restricting development in areas of potential hazard. Although the results are preliminary, the applications are very promising. It is our hope funding will be available to develop these applications for the entire Puget Sound study area.

The Future: Formation of a Washington State Seismic Safety Council

The direction this state takes in elevating the level of earthquake preparedness is in its own hands. The state of Washington, to my knowledge, has never supported (funded) earthquake planning or determined that earthquake preparedness planning is a priority for state government. FEMA funds support all our projects including raising the level of awareness and education.

This becomes a problem when federal funds become limited. Projects and programs are not implemented. The real difficulty lies in defining future goals and objectives of earthquake preparedness programs specifically for Washington and not based on national perception of Washington needs. In order to begin to resolve these difficulties, a major task in 1986 is to form a state level seismic safety council with expertise in seismic research, planning and architecture, legal and policy application, and emergency management.

The group will be comprised of approximately 12 persons whose purpose will be to identify problems and make recommendations for strengthening earthquake safety by policy improvement in the areas of hazard reduction and mitigation. Their goal is to present to the Governor by September 30, 1986 prioritized recommendations detailing what should be done to mitigate and reduce earthquake hazards state-wide. The work of this council will be essential in obtaining future state support for earthquake preparedness planning in Puget Sound or other areas. The work is important and will be intensive, but with the help of all of us who have a part to play, we will succeed.

FEDERAL EARTHQUAKE RESPONSE PLANNING IN THE PUGET SOUND AREA

by

Richard A. Buck
Federal Emergency Management Agency
Seattle, Washington

INTRODUCTION

In 1975 the U.S. Geological Survey completed an earthquake hazard vulnerability analysis for the six counties in the Puget Sound Area under contract to the Federal Disaster Assistance Administration (predecessor of the Federal Emergency Management Agency-FEMA). I was contract monitor for the study. The counties were Snohomish, King(Seattle), Pierce(Tacoma), Thurston, Mason and Kitsap. The purpose of the analysis was to give emergency planners and responders a profile of the likely damages and problems after a great earthquake in the Puget Sound Area. The profile was based on a maximum credible earthquake of 7.5 magnitude. It assumes two epicenters and develops separate damage profiles for each. One epicenter is near Seattle; the other near Tacoma—both close to historic epicenters of large earthquakes in the area.

Both damage profiles reveal serious earthquake problems for disaster responders in the Puget Sound Area. The overall impact on people and facilities, however, is considerably less than shown by similar studies for the San Francisco and Los Angeles areas. Table 1 compares the results of the studies done for west coast population centers in terms of injuries requiring hospitalization and homeless people. With 8,000 serious injuries, the Puget Sound Area problem is considerably less than that faced in Los Angeles and San Francisco. This point is made because it has important implications for the way disaster preparedness is approached in the States of Washington and California. Once the study was completed, the Federal Disaster Assistance Administration sought to initiate

TABLE 1.

Seriously Injured and Homeless After a Great Earthquake

	Los Angeles	San Francisco	Puget Sound	Alaska
Injured	82,900	40,400	8,000	176
Homeless	182,000	57,500	23,500	2,000

preparedness efforts at the local, State and Federal levels, starting with State and local governments. The logic of the approach was to build preparedness from the level with the most direct role in emergency response. The Federal preparedness effort was to begin later—addressing the deficiencies in State/Local capability. The method for encouraging a State and local effort was two-fold. The first approach was merely to inform officials of the results of the study. The second was to offer funding ($250,000 in matching money) to entice the State Department of Emergency Services into a State and local earthquake preparedness program. The first thrust was pursued vigorously. Our staff presented the results to the county commissioners and officials in cities in the six counties, and to State agency personnel. A sound-slide show was produced capsulizing the essence of the study in 12 minutes. The information was well received. Officials were interested. The news media was interested. But little action followed. The second thrust (i.e., the grant) did not materialize because of a breakdown in negotiations between the Federal Disaster Assistance Administration and the Department of Emergency Services. Our conclusion after six months of effort was that not much was going to happen in State and local earthquake preparedness. However, we believed that the Federal Disaster Assistance Administration had an obligation to insure that the Federal governmnent achieved some measure of preparedness to respond to State and local requests for assistance after a major earthquake, regardless of the State and local interest in earthquake preparedness. Therefore, we proceeded with a modest Federal earthquake preparedness effort—moving ahead of the State and local governments. This reenacted what had previously happened in the San Francisco Bay Area, where the draft Federal plan was completed years before the State plan.

PLANNING CONCEPT

The Federal Earthquake Response Plan for the Puget Sound Area is based on three fundamental premises: first, governmental disaster response, as well as normal governmental activity, operates in a laissez faire mode; second, improvements in response capability can only occur incrementally; third, a major earthquake in the Puget Sound Area would not be so devastating that the routine methods of Federal disaster response would fail.

Laissez faire is a term borrowed from economics to depict a system that operates without much central direction and, indeed, consists of competing elements. The conventional wisdom is that government operates in a hierarchial fashion—orders flow from a unified head to subordinate units, which dutifully carry them out. Organizations do not work that way. Instead, superimposed on the hierarchial structures are a series of informal networks. A unit in Organization A deals directly with a unit in Organization B to get a job done without involving the heads of the two organizations; in fact, the units may be competing with other units in their own organizations for resources, and may form alliances with the outsiders to overcome resistence within their own organizations. Organizations operate the same way in disasters. Disaster plans which attempt to impose strong centralized authority are doomed to failure. In fact, after an earthquake the loss of telephone service will make centralization even more difficult.

A disaster may even increase competition between units for scarce resources. The challenge of disaster management is to identify the most important units in the disaster response and support their demands for resources over others.

The second premise is that organizational change (including improvements in disaster response capability) will occur only incrementally. Successful organizational change does not normally happen in a revolutionary fashion. Attempts at comprehensive disaster planning, therefore, are not likely to succeed. Improvements in response capability must occur in increments—with time for each new increment to become institutionalized. This is an anathema to some planners—

who see that any change in an organization necessitates change throughout the organization. Logically this is true. In the real world, the usual way to change an organization is to change a part. This introduces instabilities in other parts of the organization, which eventually lead to incremental changes throughout the organization. It is best to let these changes occur at the organization's natural pace.

The third premise of our preparedness program is that a Puget Sound Area earthquake would not be a national catastrophe. A great earthquake in the Puget Sound Area would be a serious disaster for the people in the area to be sure. But it would not dramatically impact the economy or response capability of the nation. It would be greater in impact, but not qualitatively different, from the 25 to 50 major disasters declared by the President in the nation every year. This is in contrast to a great earthquake in Los Angeles or San Francisco—which would exceed the capabilities of the Federal government's normal disaster assistance program.

CONTENT OF THE FEDERAL RESPONSE PLAN

On these premises, the Federal Disaster Assistance Administration launched its earthquake preparedness effort for the Federal government in the Puget Sound Area in 1976, and completed the Federal earthquake plan nine months later. The plan assumes that the normal disaster relief mechanisms will be used to handle the disaster, and that Federal agencies will operate in the way they normally handle their business. The plan is designed to deal with some extraordinary operational problems that a great earthquake would bring, which are as follows:

1. Loss of telephone service and difficulty of surface travel. The normal means of communication between Federal agencies and State government would be lost. The plan sets up an emergency operating center at the Federal Regional Center in Bothell. Key agencies would automatically send representatives to the site after a

great earthquake. They would get there by whatever means are at their disposal. Fort Lewis would automatically dispatch two helicopters to the Federal Regional Center, with one landing at the GSA Center in Auburn to pickup our communications coordinator and any other Federal representatives who reach that location. The helicopters would then be stationed at the Federal Regional Center to do reconnaissance and perform transportation missions. A disaster radio frequency was established which ties together FEMA, the State, 6th Army and Fort Lewis. Separate radio networks with other agencies would be established using existing equipment. The use of FEMA's facility in Bothell was predicated on its ability to withstand shock (it was constructed with some thought to blast protection in a nuclear war), its radio capabilities and its independence of local utility service (it has auxiliary power and a water supply). In the unlikely event that the earthquake is epicentered near the Regional Center, the backup facility would be the headquarters building at Fort Lewis.

2. The Need for Federal Agencies to do Emergency Work: I noted earlier that the Federal government is involved in 25 to 50 declared disasters every year. Only occasionally is there a need for Federal agencies to directly do emergency work. Usually the lifesaving and property protection work has been completed by State and local governments, and the private sector before there is a disaster declaration. Sometimes there is a need for Federal agencies to directly be involved. In the Mt. St. Helens disaster, the Federal military services did search and rescue around the mountain. But we do not get much experience with this type of operation. After a great earthquake, Federal agencies would supplement State/local resources by directly providing medical teams, performing debris clearance and demolition of unsafe buildings, transporting relief supplies and providing expert personnel. The plan identifies these emergency functions and which agencies have the capabilities

to perform them. Table 2 comes from the plan. The plan does not make emergency assignments. The assignmnents would be made at the time of the disaster after a request for assistance from the State or local governments. Table 2 gives agencies an idea of what they might be asked to do after a great earthquake; and gives them a chance to make some preparations.

The Federal earthquake response plan was tested in 1977 in an exercise in which the U.S. Army at Fort Lewis deployed to the Seattle area with troops and equipment, and the other Federal agencies manned the Federal Regional Center in an emergency mode. The City of Seattle furnished players to facilitate the Federal play, but did not play the exercise itself. The plan has not been tested since, but it has been the subject of interagency review meetings periodically and has been revised several times since 1977.

STATE OF GOVERNMENTAL PREPAREDNESS

How prepared are governments in the Puget Sound Area to respond to a great earthquake?

There has not been much specific preparation for earthquakes. Because an earthquake would disrupt communications and access to damage areas, we can expect a poorer response from all levels of government than to other disasters, such as floods and oil spills. The quality of response will depend mainly on general disaster preparedness and the overall capability of the governmental unit. The Washington Department of Emergency Management has had a grant under the National Earthquake Hazards Reduction Act for the last three years to upgrade earthquake response capability. For the last two years, the area of concentration has been disaster medical response at the local level. There has been progress in awareness of the disaster medical problem among emergency medical service providers, as well as the development of guidance in triage and hospital

TABLE 2.

SUMMARY OF AGENCY PRIMARY AND SUPPORT FUNCTIONS

CATEGORIES OF FUNCTIONS/AGENCIES	ARC	BPA	BUREC	COE	DOD	DOE	EEPA	EPA	FAA	FBI	FDA	FEMA	FHWA	FNS	GSA	HHS	IHS	NCS	PHS	ROFEC	USCG	USFS
1. Support/Technical Assistance			S	P	P,S							P			P			S			S	S
2. Medical	P				P,S						P				S				S		S	S
3. Public Health						P		P,S								S			P,S		S	
4. Handling Deceased					P					S					S							
5. Heavy Rescue				S	P																	
6. Food & Shelter	P				S						P,S			S	S							
7. Emergency Sewage Disposal				P,S	S			P,S							P		S					
8. Potable Water				P,S	P			S							S		S					
9. Electricity		S			P		P								S						S	
10. Transportation				P	P,S				P				S		P						S	S
11. Bldg. Safety/ Debris Clearance				P	S										S					P		
12. Fire Protection					S																S	P
13. Welfare Inquiries	P																					
14. Damage Reconnaissance					P																S	S

P = Primary Role   S = Support Role

preparedness for earthquakes. It will take many years of work to achieve significant improvements in disaster medical response capability. The first required steps have been made, but continued progress will require funding of an on-going medical preparedness program.

The State of Washington has shown itself capable of responding well to small disasters in recent years, such as localized flooding and drought. The State response to the Mt. St. Helens disaster was poor, but the emergency management program has improved greatly in the years since the first Mt. St. Helens eruption. There are obvious deficiencies in State capability of dealing with a catastrophic event. There is no definite plan for State assistance to local government in a mass casualty situation. This deficiency has been recognized for some years, but not corrected. A bright spot at the State level is the Washington National Guard, which has shown great concern for improving its ability to respond after an earthquake. Last year it held a week-long earthquake seminar, followed by an earthquake command post exercise.

The Federal government has not had an on-going effort to better prepare Federal agencies for earthquake response in the Puget Sound area. There have been periodic preparedness initiatives, including updating the Puget Sound Federal Earthquake Response Plan and the Ft. Lewis response plan, seminars to inform Federal agency staffs about the latest developments in earthquake research, development of a public information SOP and various improvements in radio systems. The biggest deficiency is in radio backup to the telephone system among Federal agencies. We expect to continue to upgrade radio systems; actual accomplishment will depend on agency budgets in the coming years.

There is a national earthquake response plan being developed, which has gone through several drafts. I see it mainly as something needed for a big California earthquake. To the extent that it upgrades agency disaster response capabilities nationwide, it will contribute to better response to disasters, all disasters.

CONCLUSION

My comments about a great Puget Sound earthquake not being a national catastrophe were not intended to convey a feeling of complacence. It would be a terrible disaster. Government agencies in the Puget Sound Area should continue to maintain and improve their response capability. This preparedness should not be exclusively focused on earthquakes; governments should be prepared to deal with a diversity of disasters. A great earthquake is a good type of disaster to plan against because it would place the greatest demands against all response functions and at the same time cause the great degradation to response capability. General response capability should be improved at all levels of government. However, the greatest payoff in terms of saving lives in an earthquake will come from reducing the man-caused hazards: the vulnerable buildings, and systems. My years in the disaster relief business have given me the opportunity to observe many major disasters around the country. Few of them were really natural disasters. Mainly they were caused by the way humans build their structures and systems and where they place them. Nature is not malevolent. But until humans learn to respect nature we will have disasters, and we will need an ability to respond to them.

BUILDING CODES - CURRENT PRACTICE AND POSSIBLE CHANGES THEIR IMPACT ON BUILDING PERFORMANCE IN PUGET SOUND

By

Bruce Olsen
Consulting Engineer
Seattle, Washington 98101

Introduction

Codes governing seismic design have developed out of many years of continuous research and debate, combined with information gathered through observation of the effect of many earthquakes. Modern codes were not initiated until the early 1950's, but have been in a state of continuous modification since that time. In spite of changing codes, building performance has not always lived up to the expectations of the structural design profession. Nevertheless, increased confidence has developed with regard to structural safety of buildings designed within current code guidelines. There have been many modifications of the code over the past fifteen years, but these may be overshadowed by recent and ongoing studies which are leading to markedly different guidelines.

Background

The Uniform Building Code was officially adopted by the State of Washington more than fifteen years ago, although it was used by local adoption or reference over a much longer period. Combined with this has been reference to the Recommended Lateral Force Requirement and Commentary published by the Seismology Committee of the Structural Engineers Association of California - a publication commonly referred to as the "Blue Book". Continuous liaison over this period between the Structural Engineers Associations of Washington and California has served to limit conflicts in philosophy and to avoid problems in the transfer of material directed at highly seismic conditions from being applied through introduction into the UBC to areas of lesser seismicity.

Current Practice

The Uniform Building Code was adopted by the State of Washington as a minimum requirement. Local jurisdictions have been permitted to modify this code and some have done so, although not in the seismic portions.

This code provides regulation of design for new structures, basically of normal proportions and found in the average construction inventory. No specific regulation is contained in UBC with regard to existing structures. Local ordinances have been passed to deal with the problem of making old unreinforced masonry buildings acceptable where they have been remodelled. Changes in other existing buildings have been required based on costs of modernization, but no useable guidelines exist. In ordinary design, structural engineers have followed the UBC requirements, subject to differences in interpretation between individuals and offices. A more important factor is that of recognising the code requirements for the minimum that they should be and designing to higher levels to assure satisfactory performance.

While much research has been performed, and many theoretical analyses performed, the earthquake problem is surrounded by uncertainties and the present code, applied to the preponderant majority of buildings, is governed by rules established largely by observation and engineering judgement. Thus, the formula by which the forces are established which are assigned to a given building consists of a combination of five coefficients applied to the dead weight of the building. Eash coefficient contains elements of evaluation derived as much from experience and observation as from theoretical development. Generally each has been arrived at only after hot debate followed by compromise. This is also true of those aspects where design requirements have impacted specific materials. Each step, however, has lead to improvement in detailing and use of materials.

Possible Changes

Seismic design requirements presently contained in the Uniform Building Code are derived primarily from the SEAOC "Blue Book". This document was first published in 1958, as a very small document outlining rather minimal requirements. Subsequently the Blue Book was reviewed and republished periodically. Twelve years after initial publication, the SEAOC decided that the Blue Book should be reviewed by an ad hoc committee for the purpose of evaluating the manual and to determine those steps and directions that should be taken in the future. One of the recommendations of the ad hoc committee was that a complete reconsideration of the Blue Book be undertaken, with a new start to develop a document embodying new concepts, recognizing the valuable material that had been developed in the original.

Since the activity envisioned was beyond the scope of volunteer effort, which had been the basis of the Blue Book development, it was necessary to seek a source of funding. This was found in the National Science Foundation, which, together with the National Bureau of Standards provided the backing for a major project. The scope was broadened by develop a set of guidelines which were not provincial, but could be applied nationally, and a group of more than eighty engineers, seismologists, model code representatives and others were engaged to develop this new document.The resultant material is not presented as a code, but as a resource document which contains material that can be selectively used by different authorities or in different regions. It may attract the attention and use of federal agencies and could result is different design procedures between federal and private practice, unless model codes follow the same system.

Significance

To compare systems, we look at the current methods by which values are set for the forces and input energy to be absorbed by a given structure. This is done by the determination of what is called Base Shear, which corresponds to force input at the base, which must be overcome by the dissipation of energy in the structure. Under UBC we apply a Zone Factor which recognized the regional seismicity as compared to other geographic regions. To this we add consideration of relative importance, or essential nature of the building, a factor related to structural type, one related to period, and one related to soil conditions at the site. The Importance factor causes an increase in Base Shear, or the equivalent of a larger input force. By comparison, the document presently being represented by the Building Seismic Safety Council does not contain such a factor. With the philosophy that all buildings receive the same earthquake impulse

The design forces remain the same for all structures, but buildings in different uses are assigned to categories, which in turn have varying controls on the detailing to assure that greater toughness is inherent in buildings of greater importance.

Concurrent with the ATC/BSSC document, SEAOC has been undertaking an independent revision of the Blue Book. In this revision, some of the BSSC material has been adopted, however, the Importance Factor has been retained, and thus the requirement that essential facilities be designed for a higher level of energy input. This creates a conflict on philosophy as well as end product between the two documents.

Under the BSSC proposal, a seismicity map is included, through which the relation between regions is established. Using the UBC code zoning procedure, a differential of 1.0 to 0.75 has existed. By the new map this changes to a relation of 1.0 to 0.5. If adopted, this could leave Puget Sound relieved of much of the force presently imposed, although later studies do not bear out the differential. At the same time, the revision to the Blue Book retains the old relationship between the zones with which it deals.

There are other activities which have been continuing which may have an impact on some aspects of design. The problem of unreinforced masonry, both old and new, has always been with us, and for several years a joint venture of engineers has been working on this. From this a new Methodology for Mitigation of Hazard in Unreinforced Masonry Buildings was developed and published by Agbabian-Barnes-Kariotis in January of 1984.

Not yet developed is material dealing with earthquake hazards in existing buildings. A workshop held as a joint venture by ATC-BSSC-EERI earlier this year has resulted in a report to FEMA termed "An action plan for reducing earthquake hazards in existing buildings" and points to research and guideline development for many other existing buildings which are in the construction inventory, and which may require structural modification to justify their continued use or occupancy.

Outside the field of building construction there has been continued activity related to seismic safety. Under the management of ATC many guidelines have been prepared dealing with not only building matters, but with highway bridges as well.

Summary

The Uniform Building Code has come to be the guide document to which most commonreference is made in seismic design in Puget Sound. Changes proposed by the BSSC are philosophically more rational, but will require an education for local practitioners. It also contains some elements which might not be presently acceptable to local engineers. The SEAOC revision of the Blue Book will come closest to the existing code, both in procedure and results. This will probably be suggested for incorporation in the UBC, and engineers in Washington must decide whether such a change should be supported or opposed.
Regardless of our choice, Puget Sound will experience future earthquakes and the measure of future damage is dependent on both the level of input force and the development of good detailing procedure.

ON STATE AND LOCAL SEISMIC SAFETY ADVISORY BOARDS

BY

Karl V. Steinbrugge
El Cerrito, California

With the growing public awareness of the hazards and risks associated with earthquakes, political decision makers have increasingly asked the design professionals, scientists, contractors, and others for their views on earthquake hazard reduction. California has had the fortune, or misfortune, to have had a number of very damaging earthquakes and, as one result, has turned to seismic advisory bodies.

Not all advisory boards succeed on a long term basis for a variety of reasons, and this has been true for California as well as elsewhere. As first chairman of California's Seismic Safety Commission and also chairman of its predecessor Advisory Board to California Legislature's Joint Committee on Seismic Safety, perhaps I can share with you some of our experience. This experience also includes advisory boards to local government such as first chairman of the Board of Consultants on Safety of Fills, San Francisco Bay Conservation and Development Commission.

I have also observed or worked with seismic safety advisory groups in Nevada, Utah, and Alaska. When such groups are established, the political decision makers more often than not do not continue them for any long period of time. It is my to intent emphasize the general principles which have worked for California as well as elsewhere, but my examples are restricted to California.

Immediate Post-Earthquake Advisory Groups:

California is no exception to having experienced problems. The great San Francisco earthquake of 1906 found the public, government, and academia totally unprepared for the event as well as for response after the event. A State Earthquake Investigation Commission was established, and its published report was a monumental two volume plus atlas study. The Commission died in due course. Professor Andrew C. Lawson writing five years after the event wrote these comments:

"....In the present state of public opinion in California for example, it is practically impossible to secure state aid for the study of earthquakes. The commercial spirit of the people fears that any discussion of earthquakes for the same reason as it taboos any mention of an occurrence of the plague in the city of San Francisco. It believes that such discussion will advertise California as an earthquake region and so hurt business...... " (Bull. Seism. Soc. Am., 1:3, 1911).

These kinds of pressures still exist. Tourism, need to create new employment by bringing in new industries, "high cost of earthquake-resistive construction", etc. are considered by some to be valid bases for counterpressures on the needs for adequate seismic safety.

Before counterpressures begin, damaging earthquakes immediately bring out editorials and public expressions for action to "improve building codes", "require better inspection", and public expressions of indignation on seismic hazards. Unless an adequate advisory group is quickly established and one which has access to important political decision makers, little may be accomplished in long term mitigation efforts due, in part, to these subsequent counterpressures.

While the public is most receptive to advisory groups immediately after the event, experience suggests these groups have not been as successful as they might have been. Reasons have been manifold. One has been naivete in real world public policy. Another has been influenced by "tunnel vision" because the group was not sufficiently multidisciplinary. Yet another has been a perception that a short-term "quick-fix" was the goal without having had the time to consider long-term mitigation.

Between-Events Advisory Groups:

Between events and without the pressures of "quick-fix" solutions, a more carefully planned approach can be taken, and this is the focus of the balance of this paper.

In general, seismic safety has no well organized constituency in the form of broad based public groups with knowledgeable spokespersons. The usual case is a professional group or a scientific society speaking from their particular viewpoint. Case histories show that earthquake hazard reduction measures, including advisory boards as well as earthquake building codes, are accepted by the public when the researchers, the design professionals, and the construction industry believe in the hazard, make a good and reasonable case, and take their case to the public in a convincing manner. It has often been noted that public decision-makers (city council persons, state legislators, etc.) take little or no action when the experts are divided in their opinions, and the building industry are experts in costs and construction.

With the continuing and growing public awareness in the western states of the earthquake hazard, there are an increasing number of situations where advisory boards or commissions can and should be formed. A great asset is a multidisciplinary composition of the group. It may be instructive to examine California's solution to the composition of its Seismic Safety Commission after its predecessor advisory group deliberated on this for a period of time:

A. Four members appointed from established organizations in the fields of architecture and planning, fire protection, public utilities, and electrical engineering and mechanical engineering.

B. Four members appointed from established organizations in the fields of structural engineering, soils engineering, geology and seismology.

C. Four members appointed from nominees submitted by the League of California Cities and County Supervisors Association of California.

D. Three members appointed from established organizations in the fields of insurance, social service, and emergency services.

E. One member shall be appointed from the Senate by the Senate Rules Committee, and one member shall be appointed from the Assembly by the Speaker of the Assembly.

Clearly, the composition of the Commission is not dominated by academia, bureaucrats, local politicians, or other groups. Experience has shown that the interactions among these disciplines have been most productive in resulting in good legislation, good advice to the Executive Branch of State Government, and assistance to local government as well as helpful in public awareness. Some kind of a similar mix of disciplines is most strongly recommended for any seismic safety commission or other group.

The Commission's role is advisory, <u>not</u> operational. This is vital so that the bureaucracy does not see the Commission as a threat. The Commission can, and has, recommended budget and program changes -- sometimes against stated agency positions (but not necessarily real position). Care was taken to avoid issues from becoming politically polarized.

The potential impact of the Commission's advice depends upon to whom it is given. Since the impact of a great earthquake requires leadership at the very top of government, the commission must have access to these top leaders. It will be noted in "E", above, that two members of the California Legislature (or their alternates) are members of the Commission, thereby giving the Commission access to the Legislature.

The Commission is independent in that it reports directly to the legislature and to the executive branch. As such, it receives no directives on policy. (It will be noted that no state agency representatives were included as members of the Commission; this was in order to avoid agency influence on an otherwise independent body.) On the other hand, it can and has recommended agency policy. If deemed necessary, it has used its access to the Legislature to recommend legislation. Counterbalancing this is the fact that the Commission has no organized public support and its recommendations must stand on their own integrity. Thus, the vital importance in the choice of competent commissioners who as a group have a well-developed balance among their various disciplines and the real world. Commissioners should view themselfs as representing the public, with their discipline being a special addition to the Commission.

Counterpart to legislative access is the need for access to the executive branch. As first chairman, I and the Commission's executive Director, Robert Olson, personally met with all agency heads having significant roles in earthquake. These contacts were strongly maintained during the Commission's formative years. Continuing strength of these contacts will over time, of course, vary with the personalities involved.

The Commission has no legal "clout". It has no legal power to stop anything or to start anything. But years ago it was explained to me by a knowledgeable staffer high in the executive branch of government that "power is the perception of power". For example, after careful examination of one issue, the Commission forced reexamination of a powerful agency's construction project by threatening to take legal action due to the hazard that the construction possibly posed to several thousand persons. The authority to take this action was not established. However, with the Commission's multidisciplinary background and the nationally recognized technical expertise of several commissioners, the Commission was successful. There are risks in this -- if the Commission is not scientifically, technically, and morally sound, the backlash could be disasterous.

Presently, California's Seismic Safety Commission is a well-balanced mix of disciplines, with a good staff, and enjoys the confidence of the legislature, executive branch, and the public. Its future can only be assured by the continuing high quality of newly appointed commissioners. The Commission's effectiveness lies in its independence, its non-operational role, and willingness to take carefully reasoned and balanced leadership in new policies without replacing the responsibilities of operational agencies.

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APPENDIX A

PARTICIPANTS AT
WORKSHOP ON "EARTHQUAKE HAZARDS IN THE PUGET SOUND, WASHINGTON, AREA"
October 29-30, 1985
Hilton Hotel
Seattle, Washington

John Adams
Pacific Geosciences Center
P.O. Box 6000
Sidney, B.C.
Canada

Ted Algermissen
U.S. Geological Survey
MS 966, P.O. Box 25046
Denver Federal Center
Denver, Colorado 80225

Garney Arcand
Deputy Chief of Police
Belevue Police Department
11511 Main Street
Belevue, Washington 98009-9013

Brian F. Atwater
U.S. Geological Survey
Branch of Western Regional Geology
c/o Deprtment of Geological Sciences
University of Washington
Seattle, Washington 98103

Harold E. Bade
Chief Deputy
Thurston County Sheriff's Office
2000 Lakeridge Drive SW
Olympia, Washington 98502

Torrangco Barker
Geophysicist
S-Cubed
P.O. Box 1620
La Jolla, California 92037

Leon Beratan
Nuclear Regulatory Commission
Chief, Earth Sciences Branch SS1130
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Eddie N. Bernard
Director, Pacific Marine Env.
Laboratory, NOAA
7600 Sand Point Way N.E., Bldg. 3
BIN C15700
Seattle, Washington 98115-0070

Patricia Bolton
Battelle Human Affairs Research Center
4000 N.E. 41st Street
Seattle, Washington 98105

John R. Booker
Geophysics Program
University of Washington
Seattle, Washington 98195

Derek Booth
Geologist
U.S. Geological Survey
University of Washington, AK-60
Seattle, Washington 98195

Robert Brelin
Building System Technology
216 1st Avenue South, #402
Seattle, Washington 98104

Jane Buchannon-Banks
5400 MacArthur Boulevard
Vancouver, Washington 98661

Jane Bullock
Federal Emergency Management Agency
500 C Street, S.W.
Washington, D.C. 20472

Padraic Burke
President
Building Systems Technology
216 First Avenue, South #402
Seattle, Washington 98104

Don Caldwell
Golder Associates
4104 149th Avenue, NE
Redmond, WA 98052

Raymond L. Chalker
Chalker Engineers Inc.
950 South Fawcett, Suite 301
Tacoma, Washington 98402

Sallie Chaney
American Red Cross
Seattle-King County Chapter
1900 25th Avenue S.
P.O. Box 24286
Seattle, Washington 98124

Darrel S. Cowan
Professor of Geological Sciences
University of Washington, AJ-20
Seattle, Washington 98195

Robert Crosson
University of Washington
Graduate Program In Geophysics
AK-50
Seattle, Washington 98195

Bruce Davidson
Transportation Planner & Engineer
Urban Regional Research & FEMA Reservist
2129 Woodcrest Drive
Olympia, Washington 98501

Veronica Frakes
Department of Emergency Management
1820 Jefferson Street
Port Townsend, Washington 98368

Cynthia Frankel
Disaster Planner
Fairchild Industries
Puyallup, Washington

David E. Frinell
Deputy Sheriff and Emergency Services
Coordinator for County
Thurston County Sheriff's Office
2000 Lakeridge Drive SW
Olympia, Washington 98502

John F. Gibbons
Sr. Geologist
Dames and Moore
500 Sansome Street
San Francisco, California 94111

Paula Gori
U.S. Geological Survey
905 National Center
Reston, Virginia 22092

Jim Granger
Assistant Manager, Building Operations
Seattle City Light
1015 Third Avenue
Seattle, Washington 98104-1198

Paul Grant
Shannon and Wilson, Inc.
1150 N. 38th Street
Seattle, Washington 98103

Carol Guthrie
Registered Nurse
American Red Cross
13357-30 N.E.
Seattle, Washington 98125

David Hadley
Sr. Vice President
Sierra Geophysics
15446 Bel-Red Road
Redmond, Washington 98052

William E. Hancock
Geologist
U.S. Army Corps of Engineers
Seattle District Office
P.O. Box C-3755
Seattle, Washington 98124

Neil M. Hawkins
Chairman, Civil Engineering
University of Washington
201 More Hall, FX-10
Seattle, Washington 98105

Walter Hays
U.S. Geological Survey
905 National Center
Reston, Virginia 22092

Tom Heaton
U.S. Geological Survey
Seismological Laboratory 252-21
California Institute of Technology
Pasadena, California 91125

Darrell Herd
U.S. Geological Survey
905 National Center
Reston, Virginia 22092

Don Hickman
Senior Engineer
Factory Mutual Engineer Assistant
12807 NE 136th Street
Kirkland, Washington 98034

Jerry Higgins
Assistant Professor
Geological Engineering Section
Washington State University
Pullman, Washington 99164-2902

John F. Hodgins
Federal Emergency Management Agency
Bothell, Washington

Eugene Hoerquf
Catographer
Western Washington University
Bellingham, Washington 98225

Steven M. Ihnen
Sierra Geophysics, Inc.
15446 Bel-Red Road
Redmond, Washington 98052

Wallace W. Ip
Commercial Plans Examiner
King County Building Dept.
450 King County Admin. Bldg.
Seattle, Washington 98104

Bob Johnson
Fire Chief for City of Aburn
1101 D. N.E.
Aburn, Washington 98002

Gary Johnson
Acting Chief, Natural Hazards Division
Federal Emergency Managment Agency
500 C Street, S.W.
Washington, D.C. 20472

Tim Johnson
Lieutenant
Bellevue Ponce Training
1838-116th NE
Bellevue, Washington 98004

Myrtle A. Jones
Hydrologist
U.S. Geological Survey
1201 Pacific Avenue
Tacoma, Washington 98402

Hiroo Kanamori
California Institute of Technology
Department of Geological & Planetary Science
Pasadena, California 91125

William A. Kiel
Washington Public Power
P.O. Box 968
Richland, Washington 99352

Edna King
Public Affairs Officer, Western Region
U.S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025

Thomas Kinsman
Department of Construction & Land Use
City of Seattle
503 Municipal Building
Seattle, Washington 98005

Thomas V. Kraft, C.F.P.S
Sr. Fire Protection and Utilties Specialist
CIGNA Loss Central Services
720 Olive Wy, Suite 1300
Seattle, Washington 98101

Steven L. Kramer
Assistant Professor
University of Washington
132-F More Hall, FX-10
Seattle, Washington 98195

Ronald G. Kruml
American Red Cross
Seattle-King County Chapter
1900 25th Avenue South
P.O. Box 24286
Seattle, Washington 98124

Kenneth R. Lajoie
U.S. Geological Survey
345 Middlefield Road, MS 977
Menlo Park, California 94025

Charles A. Langston
Department of Geophysics
Pennsylvania State University
440 Deike Building
University Park, Pennsylvania 16802

Raymond Lasmanis
State Geologist
Geology & Earth Resources Division
Department of Natural Resources
Olympia, Washington 98504

John Lewis
American Red Cross
Seattle-King County Chapter
1900 25th Avenue S.
P.O. Box 24286
Seattle, Washington 98124

Brian Lewis
University of Washington
Graduate Program In Geophysics
AK-50
Seattle, Washington 98195

E. V. Leyendecker
Leader, Earthquake Hazards Reduction Group
Structures Division
Center for Building Technology, NEL
National Bureau of Standards
Washington, D.C. 20234

Ruth S. Ludwin
Research Scientist
University of Washington
AK-50 Geophysics Program
University of Washington
Seattle, Washington 98195

Stephen Malone
University of Washington
Graduate Program in Geophysics
AK-50
Seattle, Washington 98195

Carole Martens
Seattle Earthquake Safety and Education
Project
Geophysics Program, AK-50
University of Washington
Seattle, Washington 98195

Peter May
Political Science and Public Affairs
DO-30
University of Washington
Seattle, Washington 98195

Larry McCallum
Washington State Department of
Emergency Management
4220 E. Martin Way
Olympia, Washington 98504

Russell L. McClilntick
Department of Emergency Services
123 Fifth Avenue
Kirkland, Washington 98033

Merle McNeil
Mason County Emergency Services
Mason County Courthouse
Shelton, Washington 98584

Raymond P. Miller
Senior Vice President
Sahnnon & Wilson, Inc.
1105 N. 38th Street
P.O. Box C 30313
Seattle, Washington 98119

Gary Norris
Training Director and Member of Emergency
Operating Committee
City of Bellevue Fire Department
1838 116th
Bellevue, Washington

Linda Noson
University of Washington
Graduate Program In Geophysics
AK-50
Seattle, Washington 98195

Bruce C. Olsen
Consulting Engineer
1411 4th Ave. Bldg., Suite #1420
Seattle, Washington 98101

Thomas J. Owens
Assistant Professor of Geology
University of Missouri
101 Geology Building
Columbia, Missouri 65211

Frank A. Packard
Hydrologist
U.S. Geological Survey
1201 Pacific Avenue
Tacoma, Washington

Betty A. Pearson
Kitsap County Courthouse
614 Division Street
Port Orchard, Washington 98366

Charles A. Pearson
City of Tacoma Public Works Department
Building Division
Suite 345 Tacoma Municipal Building
747 Market Street
Tacoma, Washington 98402

Elaine Peterson
Building Planning, Design and Construction
Seattle School District No. 1
Facilities Building
810 Dexter Avenue North
Seattle, Washington 98109

Larry Pettit
SARECO Insurance Company
SARECO Plaza
Seattle, Washington 89185

Jane Preuss
616 1st Avenue
Suite 200
Seattle, Washington 98104

Anthony Qamar
Senior Research Associate
University of Washington
Geophysics AK-50
Seattle, Washington 98195

Norman Rasmussen
Rockwell
1100 Jadwin Avenue, Rm 332
Richland, Washington 99352

Albert Rogers
U.S. Geological Survey
Denver Federal Center
Box 20546, MS 966
Denver, Colorado 80225

Gary Rogers
Pacific Geosciences Center
Earth Physics Branch
P.O. Box 6000
Sidney, B.C. Canada

Robert Rothman
Geosciences Branch
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Jim Savage
U.S. Geological Survey
345 Middlefield Road, MS 977
Menlo Park, California 94025

David Schwartz
U.S. Geological Survey
345 Middlefield Road
Menlo Park, Califorrnia 94025

Stewart Smith
1616 North Fort Meyer Drive
Suite 1440
Arlington, D.C. 22209

William Spence
U.S. Geological Survey
Branch of Global Seismology, MS 967
Denver Federal Center
Denver, Colorado 22050

Karl Steinbrugge
Consulting Engineer
6851 Cutting Boulevard
El Cerrito, California 94530

Dennis R. Stettler
Vice President
Hart-Crowser & Associates
1910 Fariview Avenue East
Seattle, Washington 98102

William M. Stockham, Manager
King County Office of Emergency Services
Department of Public Safety
King County Courthouse, Room EA-46
516 Third Avenue
Seattle, Washington 98104

Thomas A. Terich
Professor of Geography & Regional Planning
Western Washington University
Bellingham, Washington 98225

Gerald W. Thorsen
Geologist, Geology Division
Wash. State Dept. Natural Resources
Dept. Natural Resources, PY-12
Olympia, Washington 98504

Alex Tula
Geologist
Hart Crowser & Associates
1910 Fairview Avenue, E.
Seattle, Washington 98102

Peter Vogel
Education Specialist
Federal Emergency Management Agency
Emergency Management Institute
Emmitsburg, Maryland 21727

Charles L. Vogel
Seattle City Light
1015 Third Avenue, Rm 809
Seattle, Washington 98104

Hank Waldron
Shannon and Wilson, Inc.
1150 N. 38th Street
Seattle, Washington 98103

Craig Weaver
University of Washington
Department of Geological Sciences
Seattle, Washington 98195

Robert Webb
Building Operations Management
Seattle City Leight
1015 3rd Avenue
Seattle, Washington 98103

Frank V. Westerlund
Remote Sensing Applications Laboratory
Department of Urban Planning
University of Washington, MS JO-40
Seattle, Washington 98195

GLOSSARY OF TERMS USED IN EARTHQUAKE HAZARDS ASSESSMENTS

Accelerogram. The record from an accelerometer showing acceleration as a function of time. The peak acceleration is the largest value of acceleration on the accelerogram.

Acceptable Risk. A probability of occurrences of social or economic consequences due to earthquakes that is sufficiently low (for example in comparison to other natural or manmade risks) as to be judged by appropriate authorities to represent a realistic basis for determining design requirements for engineered structures, or for taking certain social or economic actions.

Active fault. A fault is active if, because of its present tectonic setting, it can undergo movement from time to time in the immediate geologic future. This active state exists independently of the geologists' ability to recognize it. Geologists have used a number of characteristics to identify active faults, such as historic seismicity or surface faulting, geologically recent displacement inferred from topography or stratigraphy, or physical connection with an active fault. However, not enough is known of the behavior of faults to assure identification of all active faults by such characteristics. Selection of the criteria used to identify active faults for a particular purpose must be influenced by the consequences of fault movement on the engineering structures involved.

Asthenosphere. The worldwide layer below the lithosphere which is marked by low seismic wave velocities. It is a soft layer, probably partially molten.

Attenuation law. A description of the average behavior of one or more characteristics of earthquake ground motion as a function of distance from the source of energy.

Attenuation. A decrease in seismic signal strength with distance which depends not only on geometrical spreading, but also may be related to the physical characteristics of the transmitting medium that cause absorption and scattering.

b-value. A parameter indicating the relative frequency of earthquakes of different sizes derived from historical seismicity data.

Capable fault. A fault along which future surface displacement is possible, especially during the lifetime of the engineering project under consideration.

Convection. A mechanism of heat transfer through a liquid in which hot material from the bottom rises because of its lesser density, while cool surface materials sinks.

Convergence Zone. A band along which moving plates collide and area is lost either by shortening and crustal thickening or subduction and destruction of crust. The site of volcanism, earthquakes, trenches, and mountain building.

Design earthquake. A specification of the ground motion at a site based on integrated studies of historic seismicity and structural geology used for the earthquake-resistant design of a structure.

Design spectra. Spectra used in earthquake-resistant design which correlate with design earthquake ground motion values. Design spectra typically are smooth curves that take into account features peculiar to a geographic region and a particular site.

Design time history. One of a family of time histories used in earthquake-resistant design which produces a response spectrum enveloping the smooth design spectrum, for a selected value of damping.

Duration. A qualitative or quantitative description of the length of time during which ground motion at a site exhibits certain characteristics such as being equal to or exceeding a specified level of acceleration such as 0.05g.

Earthquake hazards. The probability that natural events accompanying an earthquake such as ground shaking, ground failure, surface faulting, tectonic deformation, and inundation, which may cause damage and loss of life, will occur at a site during a specified exposure time. See earthquake risk.

Earthquake risk. The probability that social or economic consequences of earthquakes, expressed in dollars or casualties, will equal or exceed specified values at a site during a specified exposure time.

Earthquake waves. Elastic waves (P, S, Love, Rayleigh) propagating in the Earth, set in motion by faulting of a portion of the Earth.

Effective peak acceleration. The peak ground acceleration after the ground-motion record has been filtered to remove the very high frequencies that have little or no influence upon structural response.

Elastic rebound theory. A theory of fault movement and earthquake generation that holds that faults remain lock while strain energy accumulates in the rock, and then suddenly slip and release this energy.

Epicenter. The point on the Earth's surface vertically above the point where the first fault rupture and the first earthquake motion occur.

Exceedance probability. The probability (for example, 10 percent) over some period of time that an event will generate a level of ground shaking greater than some specified level.

Exposure time. The period of time (for example, 50 years) that a structure is exposed to the earthquake threat. The exposure time is sometimes related to the design lifetime of the structure and is used in seismic risk calculations.

Fault. A fracture or fracture zone in the Earth along which displacement of the two sides relative to one another has occurred parallel to the fracture. See Active and Capable faults.

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Focal depth. The vertical distance between the hypocenter and the Earth's surface in an earthquake.

Ground motion. A general term including all aspects of motion; for example, particle acceleration, velocity, or displacement; stress and strain; duration; and spectral content generated by a nuclear explosion, an earthquake, or another energy source.

Intensity. A numerical index describing the effects of an earthquake on the Earth's surface, on man, and on structures built by him. The scale in common use in the United States today is the Modified Mercalli scale of 1931 with intensity values indicated by Roman numerals from I to XII. The narrative descriptions of each intensity value are summarized below.

I. Not felt--or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body of striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink or clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practially all, outdoors by many or most; outdoors direction estimated. Awakened many or most. Frightened few--slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes and glassware to some extent. Cracked windows--in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors and shutters abruptly. Pendulum clocks stopped, started or ran fast, or slow. Move small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees and bushes shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees and bushes shaken slightly to moderately. Liquid set in strong motion. Small bells rang--church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Move furnishings of moderately heavy kind.

VII. Frightened all--general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows and furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general--alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly--branches and trunks broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse, racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls, cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

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X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changes level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipelines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures, remained standing. Destroyed large well-built bridges by the wrecking of supporting piers or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipelines buried in each completely out of service.

XII. Damage total--practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.

Liquefaction. Temporary transformation of unconsolidated materials into a fluid mass.

Lithosophere. The outer, rigid shell of the earth, situated above the asthenosphere containing the crust, continents, and plates.

Magnitude. A quantity characteristic of the total energy released by an earthquake, as contrasted to intensity that describes its effects at a particular place. Professor C. F. Richter devised the logarithmic scale for local magnitude (M_L) in 1935. Magnitude is expressed in terms of the motion that would be measured by a standard type of seismograph located 100 km from the epicenter of an earthquake. Several other magnitude scales in addition to M_L are in use; for example, body-wave magnitude (m_b) and surface-wave magnitude (M_s), which utilize body waves and surface waves, and local magnitude (M_L). The scale is open ended, but the largest known earthquake have had M_s magnitudes near 8.9.

Mantle. The main bulk of earth between the crust and core, ranging from depths of about 40 to 2900 kilometers.

Mid-oceanridge. Characteristic type of plate boundary occurring in a divergence zone, a site where two plates are being pulled apart and new oceanic lithosphere is being created.

Plate tectonics. The theory and study of plate formation, movement, interaction, and destruction.

Plate. One of the dozen or more segments of the lithosphere that are internally rigid and move independently over the interior, meeting in convergence zones and separating in divergence zones.

Region. A geographical area, surrounding and including the construction site, which is sufficiently large to contain all the geologic features related to the evaluation of earthquake hazards at the site.

Response spectrum. The peak response of a series of simple harmonic oscillators having different natural periods when subjected mathematically to a particular earthquake ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variations of the peak spectral acceleration, displacement, and velocity of the oscillators as a function of vibration period and damping.

Return period. For ground shaking, return period denotes the average period of time or recurrence interval between events causing ground shaking that exceeds a particular level at a site; the reciprocal of annual probability of exceedance. A return period of 475 years means that, on the average, a particular level of ground motion will be exceeded once in 475 years.

Risk. See earthquake risk.

Rock. Any solid rock either at the surface or underlying soil having a shear-wave velocity 2,500 ft/sec (765 m/s) at small (0.0001 percent) strains.

Sea-floor spreading. The mechanism by which new sea floor crust is created at ridges in divergence zones and adjacent plates are moved apart to make room.

Seismic Microzoning. The division of a region into geographic areas having a similar relative response to a particular earthquake hazard (for example, ground shaking, surface fault rupture, etc.). Microzoning requires an integrated study of: 1) the frequency of earthquake occurrence in the region, 2) the source parameters and mechanics of faulting for historical and recent earthquakes affecting the region, 3) the filtering characteristics of the crust and mantle constituting the regional paths along which the seismic waves travel, and 4) the filtering characteristics of the near-surface column of rock and soil.

Seismic zone. A generally large area within which seismic design requirements for structures are uniform.

Seismotectonic province. A geographic area characterized by similarity of geological structure and earthquake characteristics. The tectonic processes causing earthquakes have been identified in a seismotectonic province.

Source. The source of energy release causing an earthquake. The source is characterized by one or more variables, for example, magnitude stress drop, seismic moment. Regions can be divided into areas having spatially homogeneous source characteristics.

Strain. A quantity describing the exact deformation of each point in a body. Roughly the change in a dimension or volume divided by the original dimension or volume.

Stress. A quantity describing the forces acting on each part of a body in units of force per unit area.

Strong motion. Ground motion of sufficient amplitude to be of engineering interest in the evaluation of damage due to earthquakes or in earthquake-resistant design of structures.

Subduction zone. A dipping planar zone descending away from a trench and defined by high seismicity, interpreted as the shear zone between a sinking oceanic plate and an overriding plate.

Transform fault. A strike-slip fault connecting the ends of an offset in a mid-ocean ridge. Some pairs of plates slide past each other along transform faults.

Trench. A long and narrow deep trough in the sea floor; interpreted as marking the line along which a plate bends down into a subduction zone.

Triple junction. A point that is common to three plates and which must be the meeting place of three boundary features, such as convergence zones, divergence zones, or transform faults.

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APPENDIX C

STRONG MOTION ACCELEROGRAPH STATIONS IN OREGON AND WASHINGTON (APRIL 1986)
(SOURCE: RICHARD MALEY, U.S. GEOLOGICAL SURVEY, MENLO PARK, CALIFORNIA)

STATION	INSTRUMENT	COORDINATES	OWNER*	COMMENTS
OREGON				
Applegate Dam				
Upper Tower	SMA-4532	42.088°N	COE	Moderate
Lower Tower	SMA-4531	123.119°W		Instrumentation
Crest	SMA-4533			
Downstream	SMA-4534			
Right Abutment	SMA-4535			
Blue River Dam				
Center Crest	SMA-861	44.17°N	COE	Moderate
Upper Tower	SMA-951	122.33°W		Instrumentation
Lower Tower	SMA-862			
Toe	SMA-940			
Right Abutment	SMA-949			
Bonneville Dam				
Lower Gallery	SMA-5209	47.648°N	COE	Moderate
Power House Gallery	SMA-4536	121.943°W		Instrumentation
Power House Balcony	SMA-4537			
Cougar Dam				
Left Crest	SMA-858	44.13°N	COE	Moderate
Center Crest	SMA-859	122.24°W		Instrumentation
Toe	SMA-943			
Left Abutment	SMA-942			
Lower Tower	SMA-948			
Upper Tower	SMA-952			
Dalles Lock and Dam				
Four accelerographs scheduled for installation FY86			COE	Moderate Instrumentation
John Day Lock and Dam				
Four accelerographs scheduled for installation FY86			COE	Moderate Instrumentation
Detroit Dam				
Right Abutment	SMA-950	44.72°N	COE	Moderate
Upper Gallery	SMA-954	122.25°W		Instrumentation
Lower Gallery	SMA-955			
Green Peter Dam				
Lower Gallery	RFT-535	44.48°N	COE	Moderate
Upper Gallery	TTA-1017	122.53°W		Instrumentation
Downstream	SMA-944			
Hill Creek Dam				
Center Crest	SMA-856	43.71°N	COE	Moderate
Toe	SMA-946	122.42°W		Instrumentation
Right Abutment	SMA-947			

Lookout Point Dam				
Center Crest	SMA-860	43.92°N	COE	Moderate
Left Crest	SMA-863	122.75°W		Instrumentation
Lower Spillway	SMA-857			
Upper Spillway	SMA-953			
Toe	SMA-941			
Right Abutment	SMA-945			
Lost Creek Dam				
Upper Tower	TTA-1015	42.671°N	COE	Moderate
Lower Tower	TTA-1006	122.672°W		Instrumentation
Center Crest	TTA-1007			
Left Crest	TTA-1014			
Right Crest	RFT-499			
Downstream	TTA-1021			
Portland				
State University	RFT-158	45.52°N	USGS	Basement
Chramer Hall		122.68°W		
Portland				
V.A. Hospital	SMA-774	45.52°N	VA	Ground Level
Steam Plant		122.68°W		
Scoggins Dam				
Right Abutment	RFT-603	45.50°N	USBR	Ground Level
		122.68°W		
Willow Creek Dam				
Crest	SMA-4976	45.476°N	COE	Moderate
Downstream, Rock	SMA-4975	123.196°W		Instrumentation
Grouting Gallery	SMA-4974			
WASHINGTON				
Anacortes	SMA-3910	48.47°N	USGS	Ground Level
		122.65°W		
Bellevue				
190/136th Place SE		47.62°N	WSDOT/	Extensively
Hwy Overcrossing		122.19°W	USGS	Instrumented
Structure Array	CRA-130			Structure
Recorder Building	SMA-304			15 Channels
Bellingham				
190/Bakerview Road		47.580°N	WSDOT/	Extensively
Hwy Overcrossing		122.484°W	USGS	Instrumented
Structure Array	CRA-129			Structure
Recorder Building	SMA-3346			15 Channels
Blaine				
City Maintenance Yard	SMA-167	48.996°N	USGS	Ground Level
		122.742°W		

Chief Joseph Dam				
Downstream	SMA-1253	48.00°N	COE	Moderate
Lower Gallery	SMA-1249	119.63°W		Instrumentation
Crest	SMA-1252			
Everett				
Court House	SMA-305	47.98°N	USGS	Ground Level
		122.21°W		
Grand Coulee Dam				
Lower Gallery	SMA-1899	47.96°N	USBR	Minimal
Upper Gallery	SMA-1899	118.98°W		Instrumentation
Gig Harbor				
Fire Station	SMA-125	47.333°N	USGS	Ground Level
		122.602°W		
Howard A. Hanson Dam				
Crest	SMA-3348	47.282°N	COE	Moderate
Left Abutment	SMA-3345	121.791°W		Instrumentation
Toe	SMA-3349			
Issaquah				
190/Sunset Way		47.532°N	WSDOT/	Extensively
Hwy Overcrossing		122.021°W	USGS	Instrumented
Structure Array	CRA-100			Structure
Recorder House	SMA-1222			15 Channels
Lower Granite Dam				
Center Crest	SMA-500	46.666°N	COE	Moderate
Right Crest	SMA-3112	117.431°W		Instrumentation
Left Abutment	SMA-3111			
Lower Gallery	SMA-2714			
Downstream	SMA-622			
McCord Air Force Base				
Passenger Terminal	SMA-639	47.15°N	USGS	Ground Level
		122.48°W		
Mount St. Helens				
Spirit Lake				
Downhole System	CRA-283	46.27°N	USGS	Downhole Sensors
Rock Site	SMA-5121	122.16°W		Acceleration &
				Pore Pressure
				15 Channels
Castle Creek				
Downhole System	CRA-282	46.27°N	USGS	Downhole Sensors
		122.16°W		Acceleration &
				Pore Pressure
				12 Channels
Mud Mountain				
Crest	SMA-1234	47.14°N	COE	Moderate
Right Abutment	SMA-1251	121.93°W		Instrumentation
Toe	SMA-1248			

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