UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY, [Reports - Open file series]

A Study of Earthquake Losses in the Puget Sound, Washington, Area

Open-File Report 75-375

1975

UNITED STATES DEPARTMENT OF THE INTERIOR
U.S GEOLOGICAL SURVEY

A Study of Earthquake Losses in the Puget Sound, Washington, Area

By

U.S. Geological Survey

Reports Open-File series Report 75-375
1975

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards and nomenclature.

A STUDY OF EARTHQUAKE LOSSES IN THE PUGET SOUND, WASHINGTON, AREA

Contributors to the geological and seismological portions of this report are

Margaret G. Hopper, U.S. Geological Survey
Charley J. Langer, U.S. Geological Survey
William J. Spence, U.S. Geological Survey
A. M. Rogers, U.S. Geological Survey
S. T. Algermissen, U.S. Geological Survey

Contributors to the engineering analysis portions of this report are

Bruce C. Olsen, Olsen, Ratti, and Fossatti, Consulting Engineers
Henry J. Lagorio, Architect
Karl V. Steinbrugge, Structural Engineer

Other persons making substantial contributions to this report are John V. Christiansen, Skilling, Helle, Christiansen and Robertson; Henry J. Degenkolb, H. J. Degenkolb and Associates; Alfred A. Kelly, Kelly, Pittalko, Fritz and Forssen; Raymond P. Miller, Shannon and Wilson; David E. McAllister, Fire Protection Engineer; Donal R. Mullineaux, U.S. Geological Survey; Karen M. Spencer, U.S. Geological Survey; Josephine P. Troxel, Olsen, Ratti and Fossatti, Consulting Engineers; Howard Waldron, Shannon and Wilson; and Stanley D. Wilson, Shannon and Wilson. The staff of the Seattle office of the Federal Disaster Assistance Administration, Region X, supplied information and gave useful advice throughout the preparation of this report. The assistance of Richard A. Buck, Disaster Programs Officer, and Stephanie I. Pulakis, Disaster Programs Specialist, was of particular help.

PREFACE

The purpose of this report is to provide the Federal Disaster Assistance Administration and the State of Washington with a rational basis for planning earthquake disaster relief and recovery operations in the Puget Sound Basin. The maps, tables, and other data in this report have been prepared for this particular purpose only. Application of the material in this report to other types of analyses should be undertaken with considerable care, and due attention should be given to the limitations and restrictions placed on the data and conclusions stated in this report.

CONTENTS

Page

Page

ILLUSTRATIONS

Page

Page

TABLES

Page

SUMMARY

General review

The Puget Sound Basin has a history of frequent seismic activity, including two recent damaging events. The greatest extent of urban development and the most densely populated area generally correspond to the area where the greatest energy release has been experienced.

For this study two earthquakes have been simulated, each having magnitude 7.5, a reasonable maximum value for this area. Analysis of the events indicate that under the worst condition as many as 2,200 people would die, and 8,700 additional persons would suffer injuries requiring hospitalization or immediate medical treatment. Such casualties would occur under the worst conditions of exposure, as during the rush hours, but could be approximately as great at any time during the working day. It is possible that as many as 23,500 people would be homeless or would require temporary shelter pending reestablishment or relocation. Conditions of exposure would be altered during the nighttime, causing a drastic reduction in casulaty potentials to a level of about 5-10 percent of the daytime losses. Thus, the time of greatest concern is during the normal working day, and the areas of concern are the highly urbanized sections of the Puget Sound Basin.

This study is intended to inform those agencies serving the region of potential hazard to people, structures, and lifeline functions, in such a way that the administrators of emergency services can proceed with confidence in planning response to earthquake disaster. Figure 1 shows the extent of the study area and the location of the epicenters of the postulated earthquakes. A comparison of the two isoseismal maps as they apply to each county, in tables 1 through 6, emphasizes the marked change in intensity at a site as the simulated earthquake is moved from a close to a distant location. The Modified Mercalli Intensity scale is defined on page 284.

The report is concerned not only with human casualties and displacement, but also with impairment or destruction of essential facilities critical to the continuing normal functioning of the area. This includes

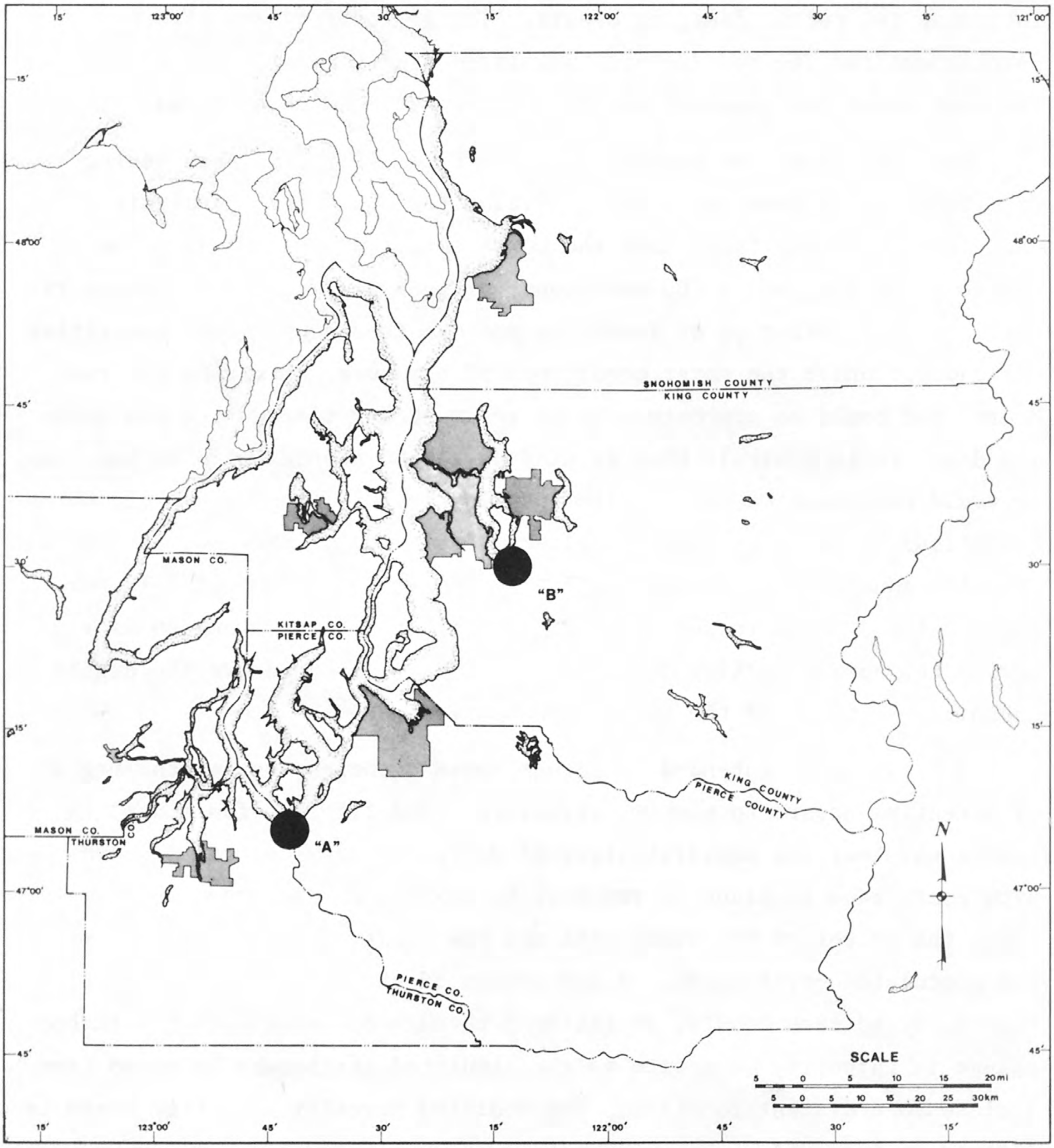


Figure 1.--Epicenters of the two earthquakes simulated in this study.

hospitals and medical personnel, police and fire department equipment and personnel, communications, and utilities.

The total damage profile was developed with careful consideration of conditions of the seismicity, geological history, population density and distribution, and physical status of structural and lifeline installations throughout the region. There is a potential for broad fluctuation in the casualty figures resulting from the chance positioning of people at the time of the occurrence of the earthquake. An example is that of the Lafayette Elementary School in West Seattle, where, in the 1949 earthquake, a large brick gable over the entry collapsed directly onto an area normally used for assembly of pupils. Such assembly regularly occurred at 11:55 a.m. The earthquake occurred at 11:57 a.m., but fortunately during the spring vacation.

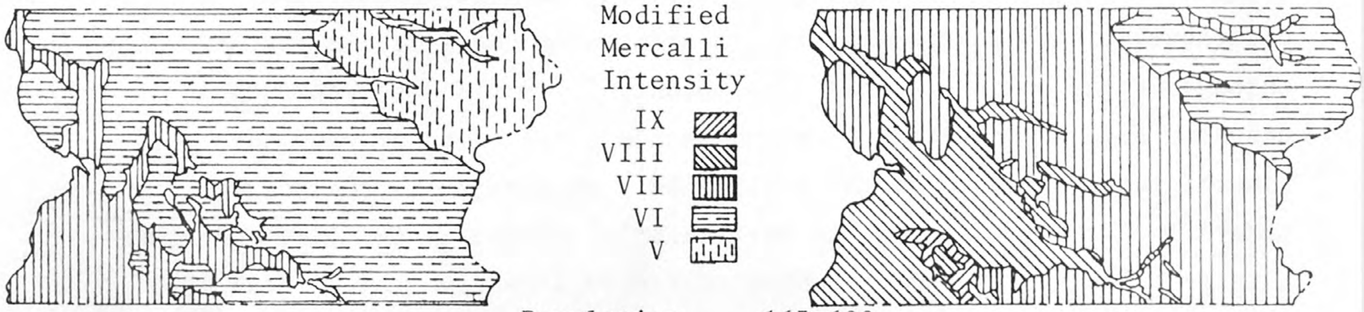
Following a large earthquake, effective remedial steps to maintain or to return to operation the essential public services will depend upon the prompt and informed actions of public agencies. Response planning should include not only consideration of disaster problems within a particular jurisdiction but also sharing of assistance with neighboring jurisdictions. Moderate response requirements experienced in one area can free resources to aid communities in more heavily damaged portions of the affected area.

The damage profile is quite different among the six counties within the study. The remainder of the summary is devoted to a brief general assessment of possible problems in each of the counties. A detailed development and presentation of each of the problems is covered in the text of the report.

TABLE 1.--ANTICIPATED DAMAGE PATTERNS FROM EARTHQUAKE DISASTER

SNOHOMISH COUNTY

Postulated earthquake "A" | Postulated earthquake "B"



Population 165,600
Area in mi^2 2,098

Vital needs	Earthquake "A" Minimal	Earthquake "A" Minor	Earthquake "A" Major	Earthquake "B" Minimal	Earthquake "B" Minor	Earthquake "B" Major
Communications----------		●				●
Fire--------------------		●				●
Police------------------		●				●
Electric power----------	●					●
Water-------------------			●			●
Access roadways---------		●				●
Medical:						
Manpower--------------	●				●	
Hospitals-------------		●				●
Ambulances------------	●				●	
Blood bank------------		●				●
Supplies--------------	●				●	
Food supplies-----------		●			●	
Schools (as shelters)---	●				●	

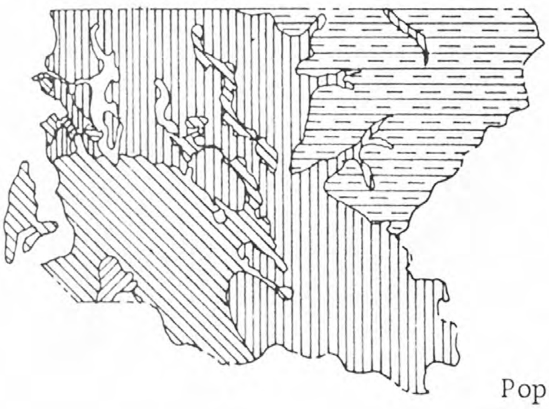
Degree of impairment

Estimated losses	Earthquake "A"	Earthquake "B"
Deaths--------------------	90	100
Serious injuries----------	360	400
Homeless------------------	830	1,450

TABLE 2.--ANTICIPATED DAMAGE PATTERNS FROM EARTHQUAKE DISASTER

KING COUNTY

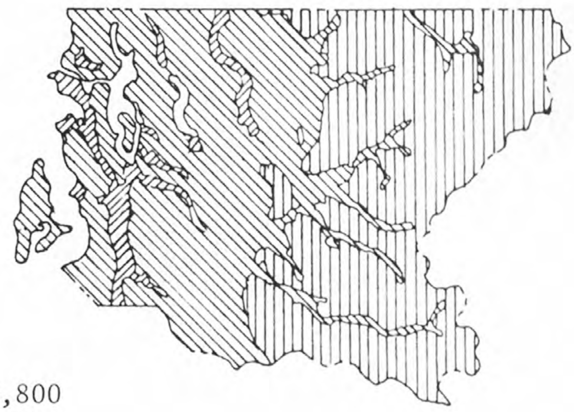
Postulated earthquake "A"



Modified Mercalli Intensity

IX
VIII
VII
VI
V

Postulated earthquake "B"



Population 1,143,800
Area in mi^2 2,128

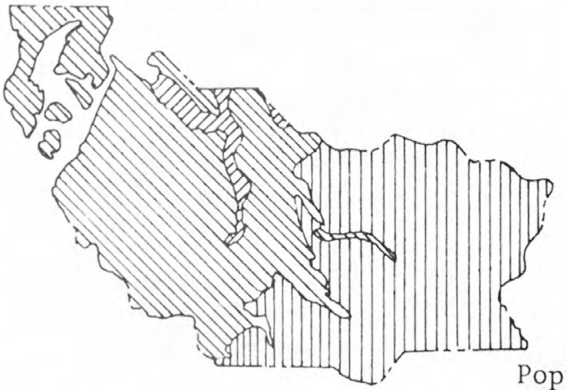
Vital needs	Degree of impairment: Earthquake "A" Minimal	Earthquake "A" Minor	Earthquake "A" Major	Earthquake "B" Minimal	Earthquake "B" Minor	Earthquake "B" Major
Communications----------		●				●
Fire--------------------		●				●
Police------------------		●				●
Electric power----------			●			●
Water-------------------		●				●
Access roadways---------			●			●
Medical:						
Manpower--------------			●			●
Hospitals-------------			●			●
Ambulances------------		●				●
Blood bank------------		●				●
Supplies--------------		●			●	
Food supplies-----------	●				●	
Schools (as shelters)---		●				●

	Estimated losses: Earthquake "A"	Earthquake "B"
Deaths--------------------	1,500	1,650
Serious injuries----------	6,000	6,600
Homeless------------------	7,130	18,630

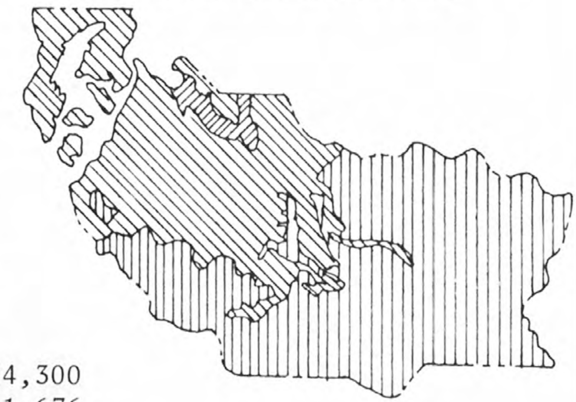
TABLE 3.--ANTICIPATED DAMAGE PATTERNS FROM EARTHQUAKE DISASTER

PIERCE COUNTY

Postulated earthquake "A"



Postulated earthquake "B"



Population 404,300
Area in mi^2 1,676

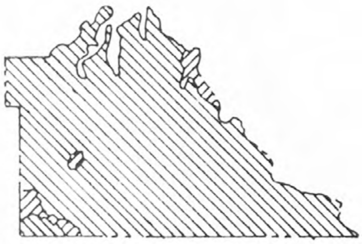
Vital needs	Degree of impairment					
	Earthquake "A"			Earthquake "B"		
	Minimal	Minor	Major	Minimal	Minor	Major
Communications----------		●				●
Fire--------------------			●			●
Police------------------		●			●	
Electric power----------			●		●	
Water-------------------			●			●
Access roadways---------		●				●
Medical:						
Manpower--------------		●			●	
Hospitals-------------			●			●
Ambulances------------		●			●	
Blood bank------------			●			●
Supplies--------------		●			●	
Food supplies-----------			●			●
Schools (as shelters)---			●			●

	Estimated losses	
	Earthquake "A"	Earthquake "B"
Deaths--------------------	320	320
Serious injuries----------	1,280	1,280
Homeless------------------	8,010	2,490

TABLE 4.--ANTICIPATED DAMAGE PATTERNS FROM EARTHQUAKE DISASTER

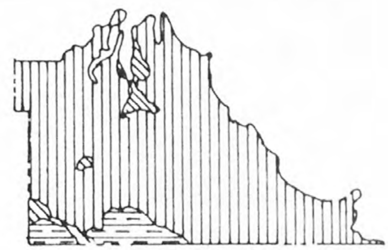
THURSTON COUNTY

Postulated earthquake "A"



Modified Mercalli Intensity
IX
VIII
VII
VI
V

Postulated earthquake "B"



Population	81,300
Area in mi^2	714

Vital needs	Degree of impairment: Earthquake "A" Minimal	Minor	Major	Earthquake "B" Minimal	Minor	Major
Communications----------			●		●	
Fire--------------------			●		●	
Police------------------			●		●	
Electric power----------			●		●	
Water-------------------			●	●		
Access roadways---------		●			●	
Medical:						
Manpower--------------		●			●	
Hospitals-------------		●			●	
Ambulances------------			●			●
Blood bank------------			●			●
Supplies--------------			●			●
Food supplies-----------			●		●	
Schools (as shelters)---			●		●	

	Estimated losses: Earthquake "A"	Earthquake "B"
Deaths--------------------	70	70
Serious injuries----------	280	280
Homeless------------------	410	350

TABLE 5.--ANTICIPATED DAMAGE PATTERNS FROM EARTHQUAKE DISASTER

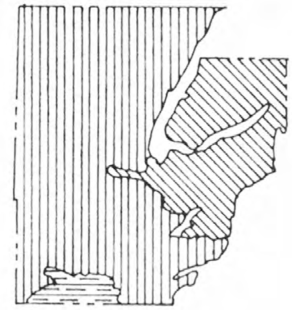
MASON COUNTY

Postulated earthquake "A"

Modified Mercalli Intensity

IX
VIII
VII
VI
V

Postulated earthquake "B"



Population 21,500
Area in mi^2 962

Vital needs	Degree of impairment: Earthquake "A" Minimal	Earthquake "A" Minor	Earthquake "A" Major	Earthquake "B" Minimal	Earthquake "B" Minor	Earthquake "B" Major
Communications----------		●			●	
Fire--------------------		●			●	
Police------------------		●			●	
Electric power----------	●			●		
Water-------------------	●			●		
Access roadways---------		●		●		
Medical:						
Manpower--------------	●			●		
Hospitals-------------		●			●	
Ambulances------------		●			●	
Blood bank------------		●			●	
Supplies--------------		●		●		
Food supplies-----------		●		●		
Schools (as shelters)---		●		●		

	Estimated losses: Earthquake "A"	Earthquake "B"
Deaths--------------------	10	10
Serious injuries----------	40	40
Homeless------------------	190	88

TABLE 6.--ANTICIPATED DAMAGE PATTERNS FROM EARTHQUAKE DISASTER

KITSAP COUNTY

Postulated earthquake "A"		Postulated earthquake "B"
	Modified Mercalli Intensity IX VIII VII VI V	

Population	103,100
Area in mi^2	393

Vital needs	Earthquake "A" Minimal	Earthquake "A" Minor	Earthquake "A" Major	Earthquake "B" Minimal	Earthquake "B" Minor	Earthquake "B" Major
	Degree of impairment					
Communications		●			●	
Fire		●			●	
Police		●			●	
Electric power	●			●		
Water	●			●		
Access roadways		●			●	
Medical:						
Manpower	●			●		
Hospitals		●			●	
Ambulances		●			●	
Blood bank		●			●	
Supplies		●			●	
Food supplies		●			●	
Schools (as shelters)		●			●	

	Estimated losses Earthquake "A"	Estimated losses Earthquake "B"
Deaths	40	40
Serious injuries	160	160
Homeless	520	540

Conclusions

Snohomish County

The maximum number of estimated deaths in Snohomish County that might be caused by the postulated earthquakes is 100; the maximum number of serious injuries requiring hospitalization could be as many as 400. Care of the injured may be hampered by damage to highways and hospitals, but it appears that there will be sufficient medical personnel and medical supplies. Serious problems could exist in restoring communications and other utilities. Temporary housing may be required for 1,450 people for an indeterminate length of time.

Power transmission lines, petroleum and gas pipelines, highway arterials, and railroad lines serving other portions of the Puget Sound Basin pass through Snohomish County. All of these facilities can be affected by a major earthquake at water crossings and in poor-soil areas, and interdiction will have an impact not only on Snohomish County but will also critically affect the needs of other communities in the region.

King County

The level of possible damage in King County is high because of the concentration of population in the metropolitan area surrounding Seattle, and it becomes markedly higher as the epicenter of an earthquake is moved nearer the city. High, too, are the estimates of deaths, injuries, and persons made homeless.

High density of population means a concentration of the region's lifelines--telephone, television and radio centers; wholesale food, drug, medical and hospital supplies; a complicated freeway system; numerous bridges; and the state's major airport. Damages to these vital needs affect not only the urban and rural needs of King County but have great impact on the functioning of the entire region and on Kitsap County in particular.

Pierce County

The population density of Pierce County is less than half that of King County, but the county's location near the epicenter of both postulated earthquakes creates major concerns in each case. Structures housing communication centers, high-rise buildings, city bridges, water and power utilities will all feel this impact.

More than 300 deaths and nearly 1,300 serious injuries will tax medical personnel, hospitals, ambulance services, and the county's blood bank. Collapses of residences built in slide-prone and poor-soil areas increase the estimate of homeless people to 8,000 in the event of a major earthquake located in the Nisqually River delta.

Thurston County

Past experience helps to establish damage patterns that are expected to occur in Thurston County. An MMI IX impact in Olympia will be major for all lifelines and will adversely affect a great many structures. Olympia is especially vulnerable in the case of a disaster of high energy and sudden onset, because a convening of the legislature swells the normal population and makes unusual demands on the community's lifelines, demands that have not been taken into consideration in disaster planning.

Deaths to 70 people and four times as many injuries will be a concern for Thurston County's one hospital. The county presently depends upon the Puget Sound Blood Center in Seattle for emergency supplies and upon wholesale suppliers in King and Pierce Counties for medical and food supplies. In turn, the county might be called upon to aid Mason County if lifelines there became overloaded.

Mason County

Mason County will experience little variance in damages or losses caused by an earthquake at an epicenter on the Nisqually River delta or by one occurring south-southeast of Seattle. If the postulated epicenter is located between Olympia and Tacoma, nearly 200 persons might become homeless because of some presumed geologic hazards. This situation would create a greater concern for temporary shelters and food supplies.

Medical personnel and services appear to be sufficient for the moderate demands of 10 seriously injured people, but supplies of blood, drugs, and hospital supplies will only be available from sources outside the county.

Kitsap County

In many respects the lifelines in Kitsap County are located in an area isolated from the region by water crossings. The county is very dependent upon ferries and bridges for transport of all supplies from wholesale establishments in Pierce and King County. In the event of a major earthquake, the impact of 40 estimated deaths and 160 seriously injured persons will be mitigated somewhat by the resources of U.S. Naval facilities established in the county in several areas. It would still be necessary to call upon the resources of blood banks in Seattle or Tacoma.

INTRODUCTION

This report is a counterpart to "A Study of Earthquake Losses in the San Francisco Bay Area," 1972, and "A Study of Earthquake Losses in the Los Angeles, California Area," 1973. The methodologies used in the aforementioned reports have also been used in this Puget Sound Basin study, except that some of them have been expanded to provide greater detail or better accuracy, or have been revised to accommodate new situations. The supporting details for some of the methodologies described in the preceding studies have not been repeated in this report.

Purpose and scope of the study

Statement of the problem

The problem is to determine the earthquake damage to critical facilities in the Seattle area that would result from severe earthquakes that may reasonably be expected to occur in the Puget Sound Basin. For purposes of this study, the Puget Sound area is taken to mean the following six counties surrounding the south portion of Puget Sound: Snohomish, King, Pierce, Thurston, Mason, and Kitsap. Special attention is given to potential damage in the heavily populated central part of this area, which includes Seattle, Tacoma, and Olympia (fig. 2). In certain cases potential damage to special facilities outside the Puget Sound Basin is discussed.

Two earthquakes that might occur in the Puget Sound area were simulated: (1) a shock of magnitude 7.5 near the epicenter of the April 13, 1949, earthquake between Tacoma and Olympia, and (2) a shock of magnitude 7.5 close to the epicenter of the April 29, 1965, earthquake near Seattle. The rationale for the selection of these two earthquakes is given in a later section.

Project design

The project was divided into two separate areas of work:

1. Construction of isoseismal maps, and
2. Estimation of casualties and damage for each of the two postulated earthquakes.

The first phase of the project was done by the U.S. Geological Survey using techniques developed for earlier studies of the San Francisco and Los Angeles areas (Algermissen and others, 1972; Algermissen and others, 1973). This part of the work included the following:

1. Selection of the earthquakes to be simulated,
2. Collection of data on historical, damaging earthquakes in the Puget Sound area,
3. Derivation of relationships among important parameters (magnitude, intensity, distance),
4. Estimation of the distribution of intensity, or degree of shaking, for each of the postulated earthquakes, and
5. Preparation of maps showing the estimated intensities.

The second, or damage-assessment, phase of the project was carried out by consultants in the Seattle area. In this part of the work, the intensity maps produced by the Geological Survey were used by the local Seattle consultants, along with their extensive knowledge of the region, its people, and its institutions, to estimate the extent of damage and loss of life that might be caused by the postulated earthquakes. This phase includes estimates of

1. Probable casualties and homeless,
2. Damage to structures that might cause major loss of life,
3. Damage to facilities critical to the recovery of the area after the shock, and
4. Damage to transportation, communication, utility, and debris-clearance systems.

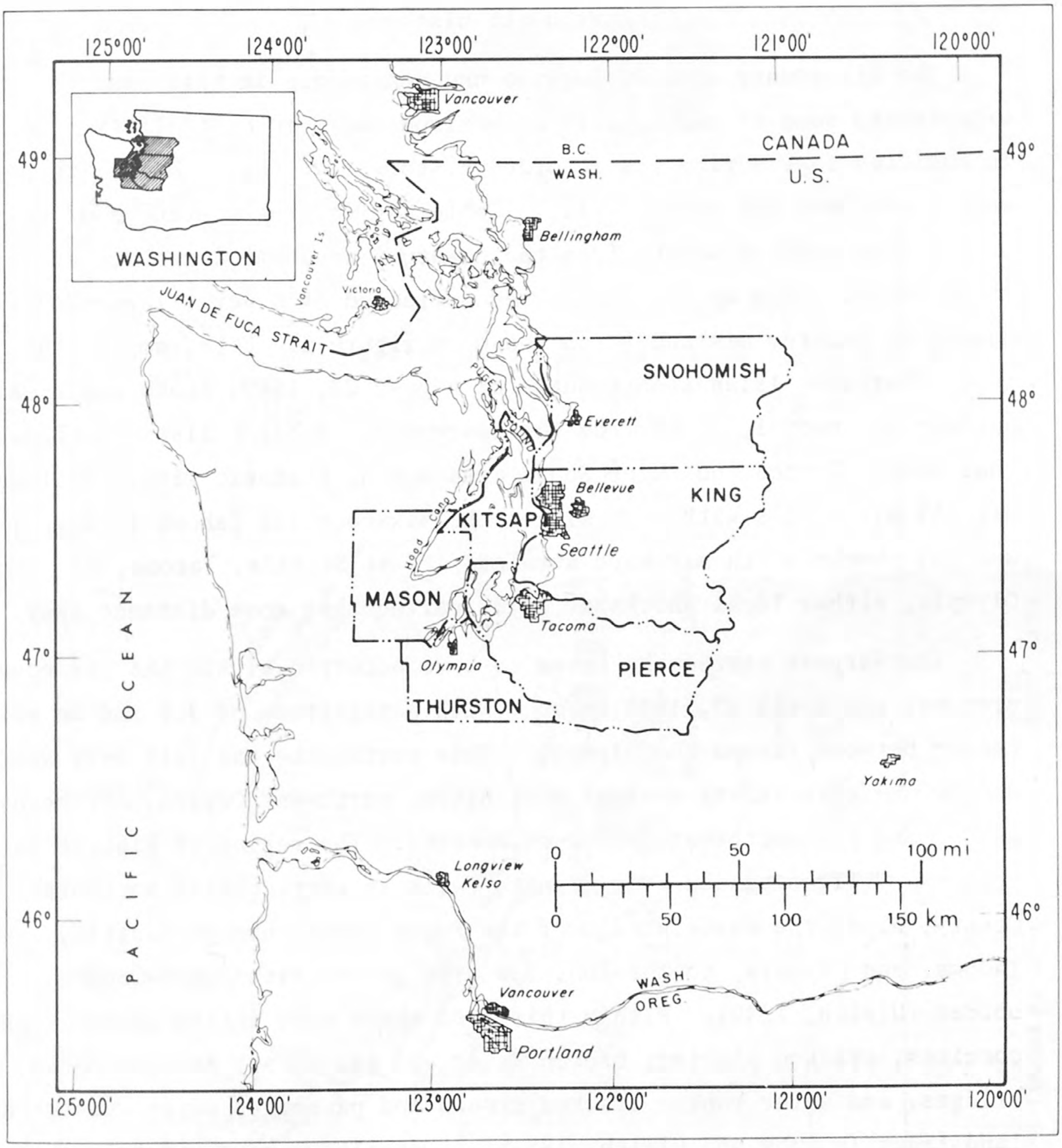


Figure 2.--Map of Puget Sound region. Area of study includes the six counties: Snohomish, King, Pierce, Thurston, Mason, and Kitsap.

Earthquake history

The six-county area of Puget Sound considered in this study has experienced some 67 earthquakes of maximum Modified Mercalli (M.M.)[1] intensities $I_o \geq V$ during its recorded history. Of these shocks, three were $I_o = VII$ and two were $I_o = VIII$. Table 7 gives the distances of each of the five largest shocks from the downtown areas of Seattle, Tacoma, and Olympia. This area has also been affected by several larger earthquakes at greater distances, as shown in figure 3. For example, the Queen Charlotte Islands earthquake of August 22, 1949, broke water mains in Seattle, over 1,000 km from the epicenter. Table 8 lists earthquakes that have affected the Puget Sound area during historic time. Included are (1) all shocks with $I_o \geq V$ within the six counties (shown in fig. 4), and (2) shocks which may have attained $I \geq V$ at Seattle, Tacoma, or Olympia, either local shocks or major earthquakes some distance away.

The largest earthquake known to have occurred within the six-county area was the April 13, 1949, shock, with a magnitude of 7.1 and an epicenter between Tacoma and Olympia. This earthquake was felt over some 390,000 km^2, including most of Washington, northwest Oregon, northern Idaho, and the northwest corner of Montana. The region of highest intensity, VIII, extended from Granite Falls in west-central Snohomish County, along the eastern edge of the Puget Sound through Seattle, Tacoma, and Olympia, to the Longview area on the Washington-Oregon border (Ulrich, 1949). Within this area there were fallen chimneys and cornices; cracked plaster; broken water and gas mains; damaged docks, bridges, and water tanks; cracked ground and pavement; water spouts; and landslides (Murphy and Ulrich, 1951b). Detailed reports on this earthquake were obtained from 1949 intensity-survey data provided by the University of Washington.

---

[1]This refers to the Modified Mercalli (M.M.) intensity scale (Wood and Neumann, 1931), which is reproduced in abbreviated form at the end of this report.

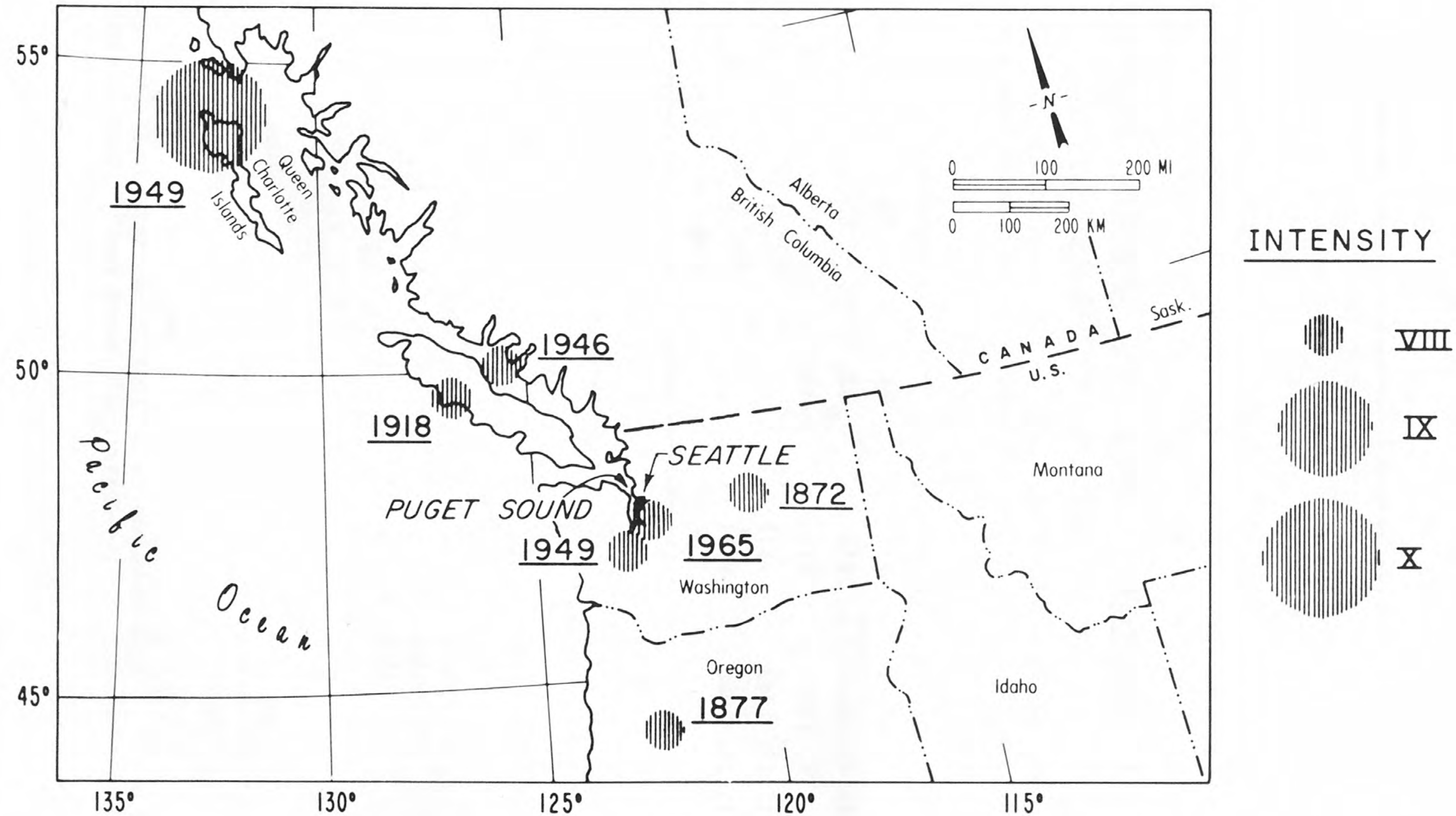


Figure 3.--Principal earthquakes affecting Puget Sound area during historical times.

Table 7.--Epicentral distances of large Puget Sound earthquakes from major metropolitan areas

		Distance from major cities (in km)		
Date	I_o	Seattle	Tacoma	Olympia
Nov. 13, 1939	VII	68	43	19
April 29, 1945	VII	52	55	98
Feb. 15, 1946	VII	55	37	29
April 13, 1949	VIII	62	27	16
April 29, 1965	VIII	24	20	61

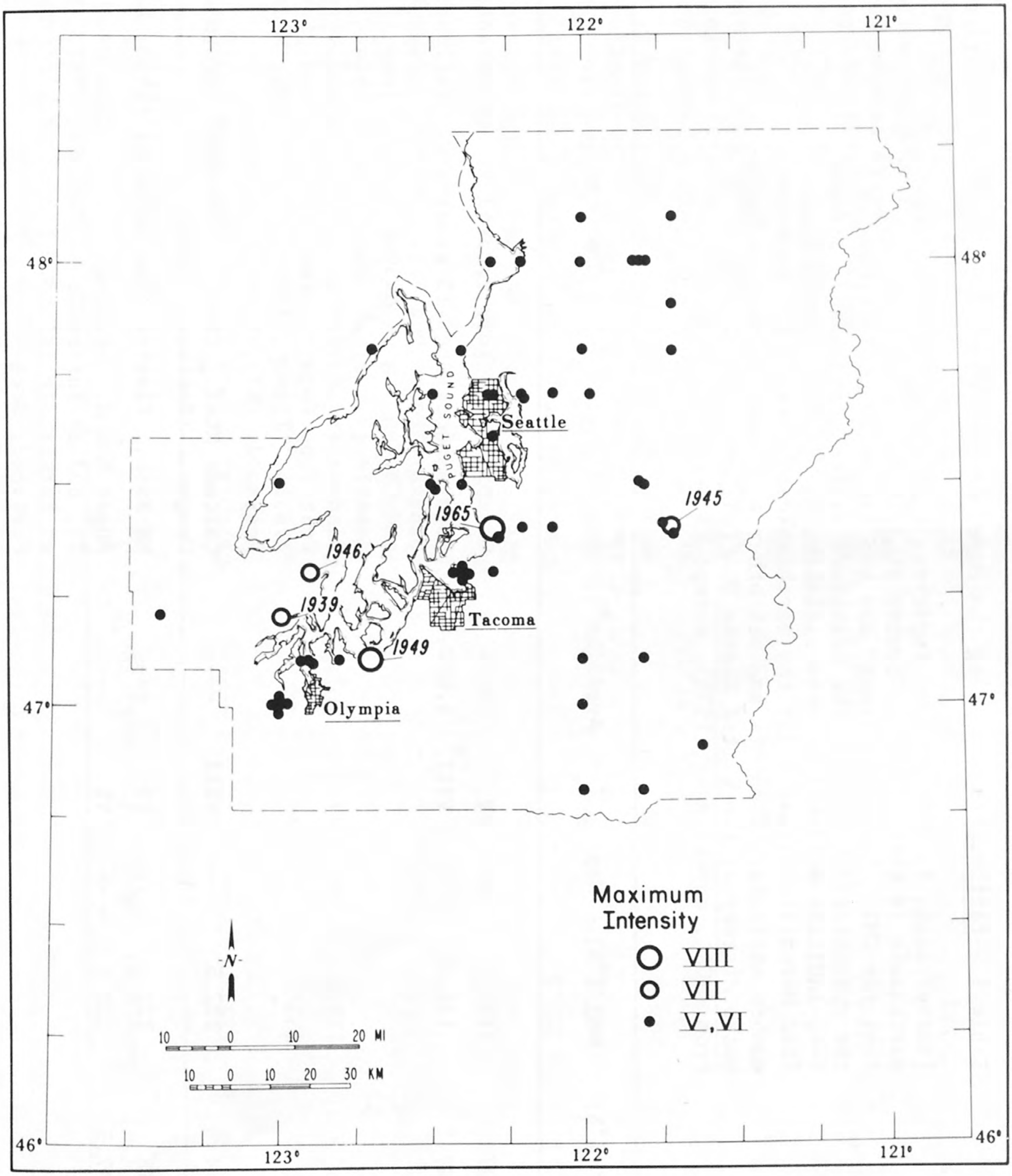


Figure 4.--Epicenters of historical earthquakes with $I_o \geq$ V M.M. within the six-county Puget Sound study area.

Table 8.--Earthquakes affecting the Puget Sound area, 1859-1973

[Number sign, #, next to year indicates that the epicenter of the earthquake is within the six-county study area. Date given is that for GMT. "Lat" and "Long" are the latitude and longitude of the epicenter. "Mag." is the magnitude of the earthquake. Leaders, ---, indicate information not available. I_o is the maximum Modified Mercalli intensity for the earthquake; brackets, [], indicate number assigned. Comments and all other information are from Earthquake History of the United States (Coffman and von Hake, 1973) or from (NOAA, unpub. data, 1970), except as noted]

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1859	Apr. 2	47	123	---	V	----	Olympia. Crockery rattled. Many awakened.
1872	Dec. 15	47.7	120.0	---	VIII+	1,000,000	Severe shock Dec. 15 at Olympia, followed by many others through Dec. 16. Strongest near Wenatchee and Chelan; threw dishes from shelves in Seattle [V]; slight damage at Olympia. Cracked windows and ceilings in Victoria and Olympia [V]. Felt from Eugene, Oreg. to B.C. and probably Alaska. (Stepp, 1971; Holden, 1898; Milne, 1956; Rockwood, 1873, Bechtel, 1975).
1877	Oct. 12	44	122.5	---	VIII	----	Cascade Mtns., Oreg. Chimneys thrown down in Oregon. (Rockwood, 1878).
#1880	Aug. 22	48	122	---	VI	----	NW Wash. Plaster cracked in Victoria, B.C.
#1880	Dec. 13	47.5	122.5	---	VI	----	Puget Sound. Strongest shocks from Dec. 7 to Dec. 29, and at intervals to Mar. 14, 1881. Strongest at Bainbridge Island. Felt from Victoria, B.C. to Portland, Oreg. Four shocks in succession at Olympia.

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1885	Oct. 9	47	123	---	V	----	Olympia. A moderate shock. (Townley and Allen, 1939).
#1885	Dec. 9	47.5	122.5	---	V	----	Woke sleepers in Olympia.
1891	Nov. 29	48.0	123.5	---	VI	10,400	Elevator jammed in Seattle. Lake Washington was lashed into a foam, and the water rolled onto the beach 0.5 m above highest water mark and 2.5 m above present stage. [V]. People rushed from buildings at Port Townsend. (Bradford, 1935).
#1892	Apr. 17	47	123	---	VI	----	Near Olympia. Felt sharply at Tacoma and Portland, Oreg. where people rushed into the street.
1893	Mar. 7	45.8	119.3	---	VII	----	Umatilla, Oreg. Some building damage.
#1903	Mar. 14	47.7	122.2	---	V	25,900	Sharp at Tacoma, Olympia, and Seattle. Many ran into the streets in Olympia. In Seattle dishes were thrown to the floor (Townley and Allen, 1939).
1904	Mar. 17	48.5	122.8	---	[VII]	52,000	Seattle, Victoria, and Olympic peninsula. In Seattle bottles were thrown from shelves, chairs moved, and people were thrown from their feet (Townley and Allen, 1939).
#1906	June 1	--	---	---	V	----	Seattle (Rasmussen, 1967).
1909	Jan. 11	49.0	122.7	---	VII	64,700	NW Wash. Walls cracked at Blaine; plaster thrown down at Bellingham. Sidewalks twisted and piers damaged at Anacortes. Felt at Olympia and Aberdeen.
#1913	July 29	47	122	---	V	3,900	Mt. Rainier, Wash. Strongest at Ashford and LaGrande. Caused no alarm. Felt at Tacoma. (Townley and Allen, 1939).

(Table continues)

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1913	Dec. 25	47.7	122.5	---	V	20,700	Two shocks, second one stronger, felt at Seattle and Edmonds.
#1914	Sep. 5	47	123	---	V	2,600	Olympia, Auburn, Tacoma, Puyallup, and Sumner. (Bradford, 1935).
#1916	Jan. 2	47.3	122.3	---	V	31,000	Tacoma, Seattle, Olympia, and Silverton.
#1917	Mar. 28	46.8	122.0	---	V	----	Ashford, Pierce County (Rasmussen, 1967; Townley and Allen, 1939).
#1917	June 9	46.8	122.0	---	V	----	Longmire, and Pierce and Lewis Counties (Townley and Allen, 1939).
#1917	Nov. 12	46.8	121.8	---	VI	2,600	Mt. Rainier. Rockslides.
#1917	Nov. 14	46.8	121.8	---	V	----	Longmire, Pierce County. (Townley and Allen, 1939).
1918	Dec. 6	49.8	126.5	7.0	[VIII]	----	NW Wash. Severe in Victoria, B.C. Felt in Seattle. (Gutenberg and Richter, 1954)(Townley and Allen, 1939).
1920	Jan. 24	49.0	122.7	---	VII	----	NW Wash., Straits of Georgia. Walls cracked at Bellingham and Anacortes. Some houses damaged on Vancouver Island.
#1928	Feb. 2	47.8	121.7	---	VI	----	Startup. Plaster cracked, people alarmed.
#1931	Dec. 31	47.5	123.0	---	VI	25,900	Wall cracked at Lilliwaup. Articles thrown from shelves at a number of locations.

(Table continues)

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1932	Jan. 5	48.0	121.8	---	V	3,900	Sultan and Monroe.
#1932	July 18	48.0	121.8	---	VI	36,300	Tolt River and Sultan. Widely felt. Near epicenter, very difficult to stand. Some building damage in Everett. (Bradford and Waters, 1934).
#1932	Aug. 6	47.7	122.3	---	VI	1,300	Seattle. Strong local shock. A few chimneys demolished; others badly damaged.
#1932	Aug. 7	48.0	121.8	---	V	18,100	Near Sultan. Moderate. (Rasmussen, 1967).
#1938	Jan. 6	47.8	122.4	---	V	----	Kingston, Port Orchard, and Seattle. Many awakened. Some frightened.
#1939	Nov. 13	47.2	123.0	5.8	VII	155,000	Olympia. Chimneys fell at Auburn, Brooklyn, Centralia, Elma, Oakville, and Tacoma. Felt over 155,000 km^2 in the United States. (Algermissen and Harding, 1965; Coombs and Barksdale, 1942).
#1940	Oct. 27	47.2	123.4	---	V	31,100	Strongest at Port Angeles, Port Townsend, and Everett. V at Seattle.
#1944	Mar. 31	47	123	---	V	6,500	Sharp shock at Grapeview, Olympia, Orting, Shelton, and Tacoma.
#1944	Sep. 18	--	---	---	[V]	----	Many awakened in Tacoma and Olympia. (Bodle, 1946).
#1945	Jan. 28	--	---	---	VI	----	Stanwood. Felt by many. Some plaster fell (Rasmussen, 1967; Bodle and Murphy, 1947).
#1945	Apr. 29	47.4	121.7	---	VII	129,000	Plaster, windows, and chimneys cracked in North Bend area. Large rock slides on Mount Si. Felt in most of Washington and small portions of Idaho and Oregon. V at Tacoma. (Bodle and Murphy, 1947).

(Table continues)

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1945	Apr. 30	47.4	121.7	---	VI	----	Aftershock. Light damage at North Bend.
#1945	May 1	47.4	121.7	---	V	----	Aftershock. Felt widely in west-central Washington.
#1946	Feb. 15	47.3	122.9	6.3	VII	181,000	Caused damage at Bremerton, Burton, Olympia, Seattle, and Tacoma. Several people killed. $250,000 damage in Seattle. Also felt in SW B.C. and NW Oregon. 25 km deep or more. (Bodle and Murphy, 1948; Barksdale and Coombs, 1946; Rasmussen and others, 1974).
#1946	Feb. 15	47.1	122.9	---	VI	----	Felt at Eatonville, Clear Lake, Randle, Gig Harbor, Olympia, and Stampede Pass. (Bodle and Murphy, 1948).
#1946	Feb. 23	47.1	122.9	---	VI	----	Olympia. Small objects moved and loosened plaster fell. (Bodle and Murphy, 1948).
#1946	Mar. 20	47.7	122.2	---	V	----	Issaquah and Kirkland. Felt by many. (Bodle and Murphy, 1948).
1946	June 23	49.9	125.3	7.3	VIII	259,000	Georgia Strait, B.C. One of the strongest shocks on record for Puget Sound area. Heavy damage in epicentral region. Felt strongly at Olympia, Seattle, Tacoma, Raymond, and Bellingham. Damage on upper floors of tall buildings in Seattle. [VI] (Stepp, 1971; Gutenberg and Richter, 1954; Bodle and Murphy, 1948).
#1947	Jan. 12	47.5	121.8	---	V	----	Strongest at Bothell and Snoqualmie Falls. (Murphy, 1950; Stepp, 1971).
#1947	Apr. 2	47.1	122.9	---	V	----	Olympia. Felt most in downtown Olympia and Quilcene. (Murphy, 1950).

(Table continues)

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1948	Aug. 3	47.5	121.8	---	V	----	Snoqualmie Falls. Awakened many. (Murphy and Ulrich, 1951a)
#1948	Sep. 24	48.0	122.2	---	V	----	Felt throughout Puget Sound area.
#1949	Apr. 13	47.1	122.7	7.1	VIII	388,000	Nearly all large buildings in Olympia damaged. Heavy property damage over a wide area of Washington and Oregon. Toppled chimneys, cracked walls, and fallen plaster in many places. 70 km deep (Nuttli, 1952; Ulrich, 1949; U.S. Army Corps of Engineers, 1949).
1949	Aug. 22	54.2	133.0	8.1	[X]	[3,300,000]	Queen Charlotte Islands. Felt from Portland, Oreg. to S. Alaska. Two-foot tsunami at Ketchikan, Alaska. Broke water mains in Seattle, [VI], sloshed water from swimming pools in Tacoma. (Note: Milne derives felt area of 2,220,000 mi^2 (=5,750,000 km^2) using epicenter-to-Jasper distance as radius of a circle. Epicenter to Jasper is 1,025 km, giving 3,300,000 km^2.) (Coulomb, 1952; Murphy and Ulrich, 1951b; Milne, 1956).
1950	Apr. 14	48.0	122.5	---	VI	18,000	Port Townsend-Langley area. V at Tacoma. IV at Seattle (Murphy and Ulrich, 1952).
#1950	Dec. 3	48.0	122.3	---	V	----	Mukilteo. Several sharp tremors. Dishes broken.
#1952	Aug. 6	47.4	122.2	---	V	----	Seattle. Plaster fell.
#1954	Mar. 16	47.1	121.8	----	V	7,800	Near Mt. Rainier. Intensity V in parts of King and Pierce Counties.
#1954	May 5	47.3	122.4	---	V	3,900	Felt sharply at Tacoma, Lakewood, and North Bend.

(Table continues)

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1954	May 15	47.4	122.3	---	VI	44,000	Slight damage at Belfair, Lake Stevens, North Bend, Seattle, and Skykomish. 15 km deep. (Stepp, 1971).
#1955	Mar. 26	48.1	122.0	---	VI	22,000	A house foundation cracked near Everett. Many awakened. Hartford, Monroe, Preston, and Sultan.
#1955	Nov. 3	48.1	121.7	---	V	----	Felt throughout Snohomish County. 50 km deep (Stepp, 1971).
#1956	Jan. 7	47.3	122.4	---	V	6,500	Intensity V at Burley, Dash Point, Dieringer, and Retsil. 50 km deep. (Stepp, 1971).
#1957	Jan. 26	48.3	122.4	---	VI	38,800	Plaster fell at Clear Lake. V at numerous towns. 60 km deep. (Stepp, 1971).
#1957	Feb. 11	47.5	121.7	---	VI	10,400	North Bend and Snoqualmie. V at Issaquah, IV at Seattle (Rasmussen, 1967; Brazee and Cloud, 1959).
#1957	May 4	47.3	122.4	---	V	5,200	Dash Point. V at Algona, Auburn, Buckley, Des Moines, Redondo, Sumner, and Zenith. 40 km deep (Stepp, 1971).
#1959	Oct. 14	47.8	122.0	---	V	7,300	Felt by all at Monroe, Sultan, and Pinehurst.
#1960	Jan. 7	46.7	122.7	---	V	9,100	Felt principally in Lewis, Pierce, and Thurston Counties. V at Olympia. (Talley and Cloud, 1962).
#1960	Apr. 11	47.6	122.3	---	VI	1,600	Concrete and wood walls slightly damaged and plaster cracked in Seattle.
#1960	Sep. 10	47.7	123.2	---	VI	36,300	Concrete basement floor and wall cracked at Bremerton. Considerable plaster cracking at Seattle [VI].
#1962	Dec. 31	47.1	122.0	---	VI	33,700	West of Mt. Rainier. Cracks in plaster, chimneys, and walls. Broken dishes. Twisted columns. 33 km deep. (Stepp, 1971).

(Table continues)

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1963	Jan. 24	47.4	122.1	---	VI	14,200	Plaster and walls cracked at Maple Valley and Tacoma. Furniture moved; objects fell. 17 km deep. (Stepp, 1971).
#1964	Jul. 30	47.7	122.1	3.5	V	3,900	Near Seattle. Strongest at Edison and La Conner. (Stepp, 1971).
#1964	Oct. 15	47.7	122.0	4.0	V	2,300	Near Seattle. Felt principally in King and Snohomish Counties. Felt strongly at Bellevue, Preston, and Medina. 33 km deep.
#1965	Apr. 29	47.4	122.3	6.5	VIII	337,000	Seattle. Extensive chimney damage in West Seattle. Seven killed. Damage $12.5 million. Relatively large intensity VII area. 59 km deep. (Algermissen and Harding, 1965).
#1965	Oct. 23	47.7	122.4	4.8	VI	----	Felt at Bremerton, Everett, Olympia, Tacoma, Seattle, and Waterman. 63 km deep. (von Hake and Cloud, 1967; Stepp, 1971; Bulletin of the International Seismological Centre, 1965).
#1967	Mar. 7	47.8	122.7	4.2	V	19,400	Sharp, felt throughout Puget Sound area. V at Seattle and many other places. 35 km deep. (Stepp, 1971; von Hake and Cloud, 1969).
#1969	Oct. 9	46.9	121.6	4.4	V	----	Intensity V at Elbe and Packwood. 33 km deep. (Stepp, 1971).
#1969	Nov. 1	47.9	121.7	4.1	V	----	NW Washington. Intensity V at Baring, Duvall, Edmonds, Gold Bar, Grotto, Index, Lake Stevens, Skykomish, Startup, and Sultan. 5 km deep. (Stepp, 1971).
#1970	Feb. 10	47.7	122.3	3.9	V	3,900	Principally felt at Puget Sound Region. V at Bothell and Richmond Beach. 33 km deep. (Coffman and von Hake, 1972).

(Table continues)

Table 8 (cont'd)

Year	Date	Lat (°N)	Long (°W)	Mag.	I_o	Area (km^2)	Comments
#1970	Oct.24	47.3	122.4	4.2	V	5,980	NW Washington. Strongest at Elbe, Milton, and Puyallup. 25 km deep. (Coffman and von Hake, 1972).
#1973	June 9	47.6	121.8	3.5	V	----	Strongest at Snoqualmie and Carnation. (Coffman and von Hake, in press).

The only other earthquake known to have caused intensity-VIII damage in the Puget Sound area was the April 29, 1965, shock, having a magnitude of 6.5 and centered between Seattle and Tacoma. Although this earthquake did not have the widespread area of intensity-VIII damage that the 1949 earthquake exhibited, reports of this degree of damage were scattered from Seattle and Issaquah on the north to Dash Point near Tacoma on the south. The relatively large region of intensity-VII damage included most of the area surrounding Puget Sound, from Everett to Olympia and from the east side of the Hood Canal to Snoqualmie (von Hake and Cloud, 1967). Again, much information was obtained from an intensity survey conducted right after the earthquake by the University of Washington (Norman Rasmussen, written commun., 1974). Intensities were assigned in this study.

Three earthquakes of maximum intensity VII occurred within the study area in historical times: November 13, 1939; April 29, 1945; and February 15, 1946. The last was the largest of these, approaching the 1965 shock in intensity. This earthquake, usually assigned a magnitude of 5 3/4, is now thought to have been more nearly 6.3 (Rasmussen and others, 1974). Its felt area extended over at least 181,000 km^2 (Bodle and Murphy, 1948) and has been estimated to be as large as 583,000 km^2, including area in Canada and at sea (Barksdale and Coombs, 1946). The region of maximum intensity extended over much of the same area that was intensity VII in the 1965 shock and, as later, included damage in Seattle, Tacoma, and Olympia (Bodle and Murphy, 1948).

The 1939 earthquake occurred about 13 km southwest of the 1946 epicenter, only 19 km from Olympia. Although somewhat smaller than the 1946 shock, this earthquake was felt over 155,000 km^2 in the United States (Bodle, 1941), and its total felt area has been estimated to be as high as 549,000 km^2 (Coombs and Barksdale, 1942). Maximum intensity of VII was reported at Olympia and Tacoma and at several other scattered places from Centralia to Auburn (Bodle, 1941).

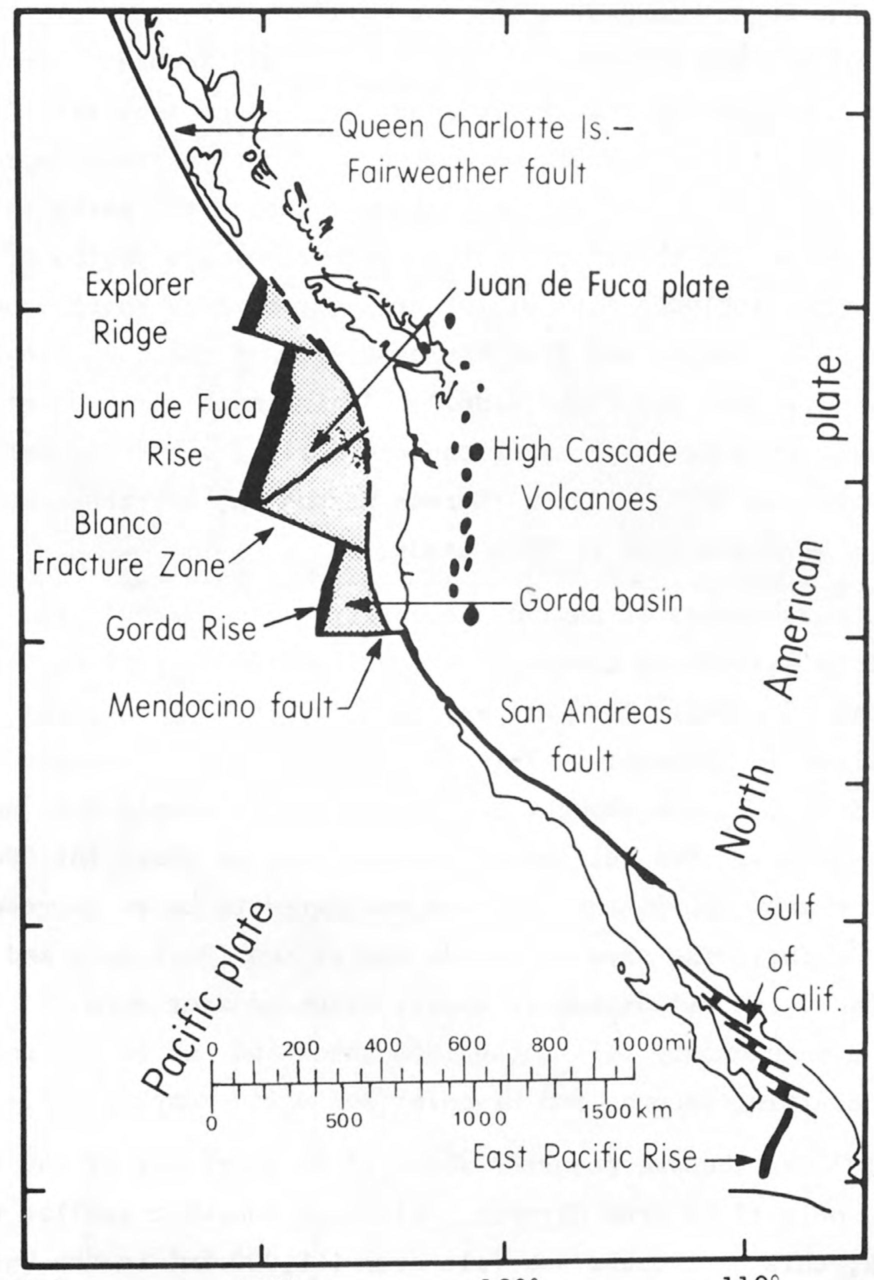


Figure 5.--Location of some tectonic elements in the northeast Pacific and western North America. Shaded area represents the Juan de Fuca plate (Silver, 1971b).

The epicenter of the 1945 shock was not on the edge of Puget Sound itself, as were the four epicenters of the earthquakes just discussed. Rather it was about 45 km east of the Sound and of the 1965 location. This earthquake is thought to have originated along the Mount Si Fault, which extends north-south through North Bend and Sultan, and it did some damage (intensity VII) in North Bend, Palmer, and Stampede Pass. The earthquake was felt over 129,000 km^2, mostly in Washington (Bodle and Murphy, 1947). A similar but smaller shock, the Tolt River earthquake of July 18, 1932, is also believed to have occurred along the Mount Si Fault and may have locally reached intensities as high as VII in its mostly uninhabitated epicentral region. Its felt area has been estimated from 36,000 km^2 (Coffman and von Hake, 1973) to 181,000 km^2 (Bradford and Waters, 1934).

Seismicity and tectonic setting of the Puget Sound region

The primary cause of the seismicity of the entire western United States is the motion differential between the North American and Pacific plates. Figure 5 schematically illustrates the primary tectonic elements that are considered in this discussion. In general the San Andreas fault and the Queen Charlotte Islands-Fairweather fault can be considered as related transform faults connecting the east Pacific rise (where oceanic crust is generated)(shown on fig. 5) and the Aleutian trench (where oceanic crust is consumed)(north of the area shown on fig. 5). This large fault system would represent a line of pure slip between the North American and Pacific plates, provided that these plates behaved in a rigid manner (McKenzie and Parker, 1967). An exception to rigid-plate motion exists for the shaded zone of figure 5, where plate segments are being internally deformed. It is the detailed analysis of this deformation and the interaction of these subplates with the North American plate that leads to an improved understanding of the seismicity of northern California, Oregon, and Washington.

A definite association of seismic activity with the Puget Sound depression exists (Crosson, 1972). This depression and its extension, the Willamette Valley, are shown in figure 6. The Puget Sound region is the only zone in the contiguous United States where large subcrustal earthquakes are known to occur. This fact makes the seismic zoning of the Puget Sound region a unique problem.

A recent study of earthquake activity in the Puget Sound region for the period June 18, 1970-July 3, 1971 indicates that most of the regional seismicity is crustal (Crosson, 1972). The earthquakes in Crosson's study for which reliable depths were determined are shown in the depth histogram of figure 7. There is evidence, however, that four of the five earthquakes of table 7 were subcrustal, perhaps in the depth range 50-70 km. The 1949 and 1965 earthquakes are the largest Puget Sound-region earthquakes to have occurred in the recent historical record and these were 70 and 59 km in focal depth. Based on the observation that these two deep earthquakes were characterized by an extremely low level of aftershock activity, and noting that the 1939 and 1946 earthquakes also exhibited low aftershock activity, Algermissen and Harding (1965) concluded that the 1939 and 1946 shocks were also subcrustal. Such a lack of aftershock activity is characteristic of subcrustal earthquakes. Figure 8 shows the probability of an earthquake of magnitude 6.0 being followed by 20 aftershocks having magnitudes of 3.0 or greater as a function of the focal depth of the main shock (from Mogi, 1963). This curve is based on activity in and near Japan. Page (1968) noted that, on a worldwide scale, well-defined aftershock sequences occur only within the Earth's crust. The physical basis for the lack of aftershock activity for subcrustal earthquakes appears to be related to the small source dimensions of deep earthquakes and to the high hydrostatic pressure that exists at these depths, which has the effect of quickly arresting any rupture process (Wyss and Molnar, 1972).

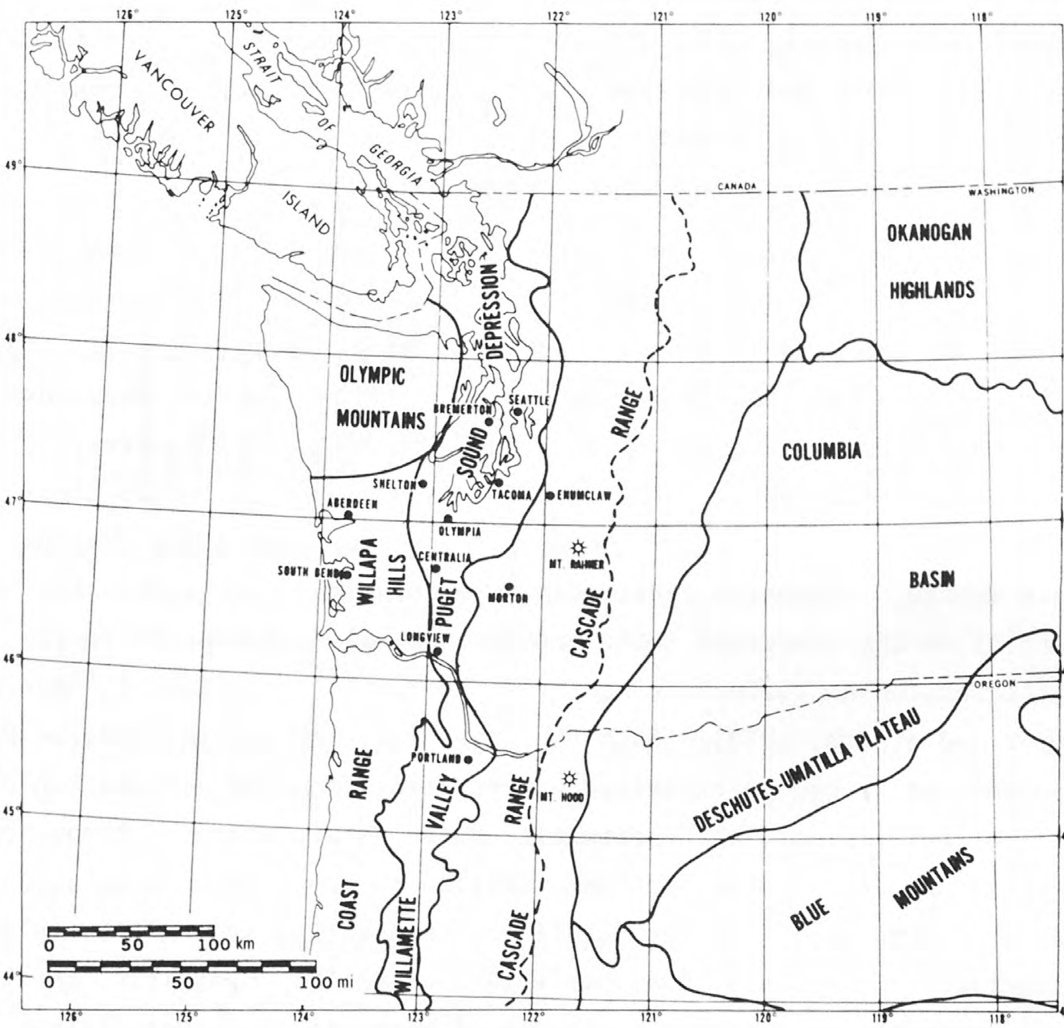


Figure 6.--Physiographic divisions of the northwestern United States (Stepp, 1971).

The only remaining large Puget Sound-area earthquake of table 8 (April 29, 1945) has been discussed in the preceding section. It occurred approximately 45 km due east of the subcrustal 1965 earthquakes, and available data indicate that it was a crustal event, occurring in association with the north-south trending Mount Si fault. This earthquake was followed by several moderately strong aftershocks.

Focal mechanisms have been determined for the 1949 earthquake (Nuttli, 1952; Hodgson and Storey, 1954), for the 1965 earthquake (Algermissen and Harding, 1965), and for composite sets of small, shallow Puget Sound earthquakes (Crosson, 1972). All of these determinations share a common feature in that the axis of maximum compressive stress is oriented approximately N35°W. This important result clearly ties the subcrustal earthquake activity to the predominating shallow stress system. Composite focal-mechanism solutions for earthquakes occurring on the Mendocino fault and in the region of Cape Mendocino are interpreted as reflecting active north-south compression in that region (Seeber and others, 1970). Both the Cape Mendocino and the shallow Puget Sound seismicity can be explained as resulting from the deformation of a large volume of crust: both seismicity patterns are diffused throughout the crust and have little apparent relation to known major faults. A study of the tectonics of the Pacific northwest (Silver, 1971b) implies a direction of maximum compressive stress of N35°W. Similarly, in situ stress measurements by the U.S. Bureau of Mines in the Coeur d'Alene district of Idaho result in a mean value of excess maximum horizontal compressive stress of 200 psi in a N16°W direction (B. Brady, written commun., 1973). This trend of compressive stress in the northwestern United States breaks down in the vicinity of the Rocky Mountain trench, located just east of northern Idaho, where Sbar and others (1972) found active west-northwest extension. These results on the stress system in the northwestern United States are explainable using the arguments of plate tectonics theory. A review is now presented of the evolution of the oceanic spreading center off the Pacific northwest and the relation of this to oceanic and continental seismicity in this region. This review will show that the immediate Puget Sound region presents unique problems in seismic zoning.

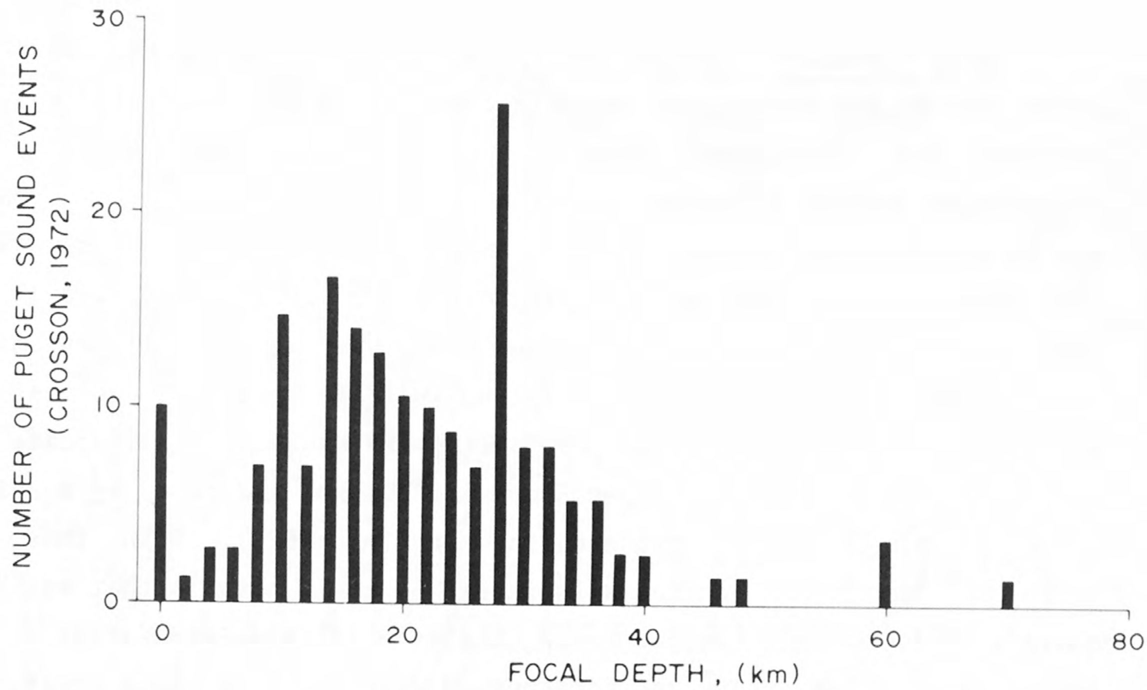


Figure 7.--Depth histogram of Puget Sound region earthquakes for the period June 18, 1970 - July 3, 1971 (adapted from Crosson, 1972).

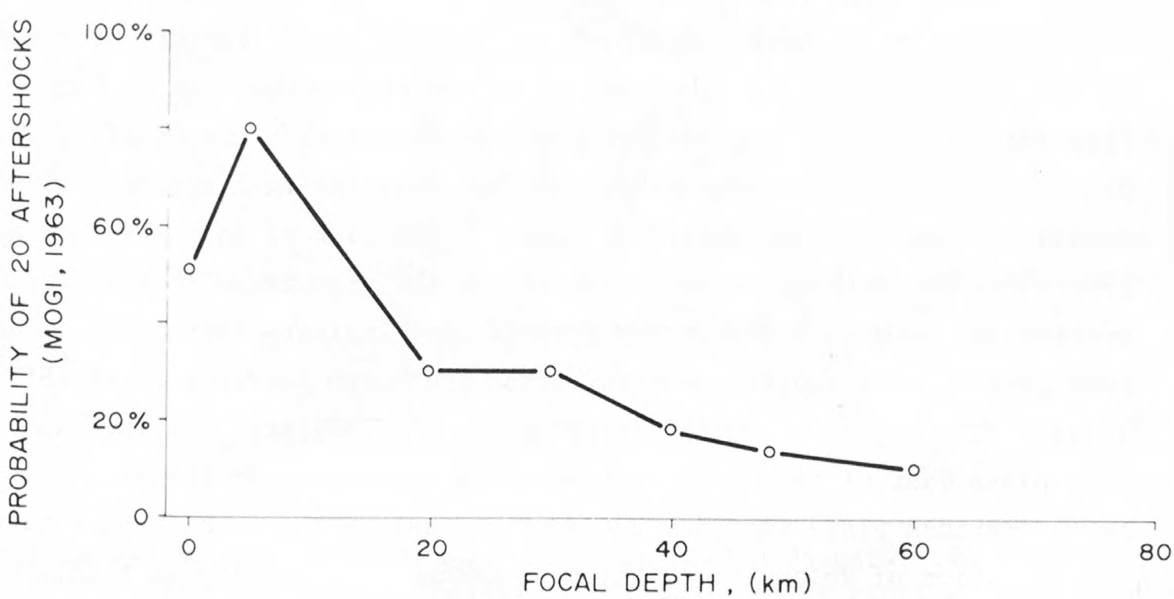


Figure 8.--Probability of a magnitude 6.0 or larger earthquake being followed by 20 or more aftershocks of magnitude 3.0 or larger, as a function of main shock focal depth. Curve is empirically derived from earthquakes which have occurred in and near Japan (Mogi, 1963).

Figure 9 presents the seismicity ($m_b \geq 5.0$) of the northwestern United States and the adjoining Pacific Ocean for the interval January 1963-May 1973. This is the largest time interval for which there exists high-quality computer-determined earthquake locations. The base map is adapted from Atwater (1970). Bathymetric contours are shown at 200, 1000, and 2000 fathoms. The approximately vertical stippled lines indicate mapped magnetic anomalies and show their ages in millions of years; double lines with inner stippling indicate spreading centers; solid lines indicate active mapped faults; and dashed lines indicate inferred faults. The 1965 Puget Sound earthquake, indicated by a solid circle, is the largest of these earthquakes ($m_b = 6.5$). Using this seismicity map in conjunction with figure 5, it is notable that earthquake activity is high on the Queen Charlotte Islands-Fairweather fault, the Explorer ridge and the unnamed fracture zone south of it, the Blanco fracture zone, the Gorda rise, and the Mendocino fault (the Mendocino fracture zone is inactive west of the Gorda rise; Tobin and Sykes, 1968), while earthquake activity is low in the Juan de Fuca rise and on the San Andreas fault segment due south of the Mendocino fault. Plate tectonics theory using rigid plate motions would predict normal faulting associated with the rises, right-lateral faulting on the three indicated fracture zones, and an active oceanic trench feature near the Washington-Oregon coast. The lack of seismicity on the Juan de Fuca rise and the northern San Andreas fault indicates that the Pacific, Juan de Fuca, and North American plates are not behaving in a strictly rigid manner but are being internally deformed. The lack of an active oceanic trench off the Washington-Oregon coast and the associated lack of active continental volcanism and active Benioff zone indicate that the Juan de Fuca plate is not rapidly underthrusting the North American plate (Silver, 1971a). The magnetic anomaly patterns clearly indicate that the Juan de Fuca plate east of the Gorda rise has more actively underthrust the North American plate than has the section east of the Juan de Fuca rise. The cessation of volcanism in the high Cascades within the last 10,000 years, coupled with the foregoing, indicates that today the Juan de Fuca plate may be bonded to the North American plate. Such a bonding between the North American and Juan de Fuca plates has previously been suggested by Bolt, Lomnitz, and McEvilly (1968), Atwater (1970), and Crosson (1972).

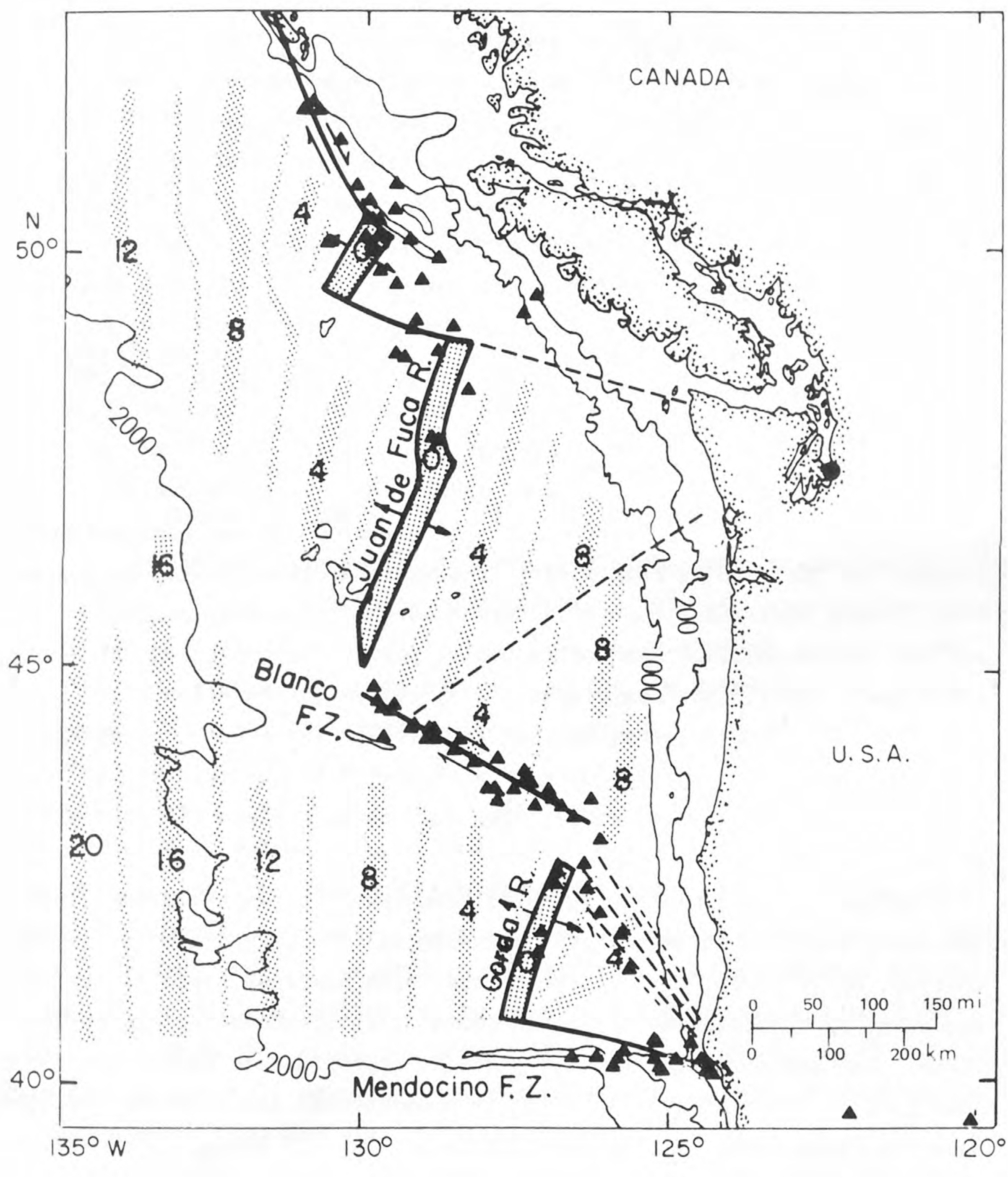


Figure 9.--Seismicity of the Juan de Fuca plate, January, 1963 - May, 1973, magnitude > 5.0. Individual earthquakes are represented by solid triangles. Sea-floor ages in millions of years are taken from Atwater (1970). Bathymetric contours of 200, 1000, and 2000 fathoms are from McManus (1967). Solid circle is the 1965 Puget Sound earthquake. Solid lines represent known faults; dashed lines represent inferred faults.

The Juan de Fuca and Gorda spreading centers are regarded as passive features that either are remnants of active spreading centers or represent weak structural lineaments that have become plate boundaries (Atwater, 1970; Silver, 1971b). This is unlike the spreading centers associated with midoceanic rises. The latter may be active tectonic features that actually provide the driving force for plate motions. Oceanic plates, such as the Pacific or Juan de Fuca plates, are more dense than continental plates, such as the North American plate, and thus when an oceanic plate collides with a continental plate it tends to underthrust it. Evidence of a subducted portion of the Juan de Fuca plate has been inferred from studies of P-wave travel-time residuals (McKenzie and Julian, 1971; Crosson, 1972). Because the magnetic anomalies of the eastern Pacific Ocean become older as one goes westward (except for the Juan de Fuca plate), the North American plate appears to have already overridden much of a former oceanic spreading center and the eastern half of the corresponding magnetic-anomaly set (Atwater and Menard, 1970). The overridden plate, called the Farallon plate (after the Farallon Islands, off San Francisco), is largely responsible for the voluminous Cenozoic volcanic activity of the western United States (Lipman and others, 1971). The Juan de Fuca plate is a remnant of the Farallon plate.

Because oceanic plate originates from upwelling mantle material at spreading centers, it becomes thicker with distance (age) from spreading centers, as it cools. The motion of the North American plate is nearly due west, as indicated by the north-south orientation of the mid-Atlantic ridge. The motion of the Pacific plate is approximately northwest, as indicated by the direction in which it underthrusts the Aleutian arc, the Kamchatka peninsula, and Japan (McKenzie and Parker, 1967). Thus the relative motion of these two major plates is for the Pacific plate to move northwest relative to the North American plate, resulting in the zone of megashear that comprises the Queen Charlotte Islands-Fairweather fault and the San Andreas fault. The Juan de Fuca plate seems to be a minor plate, passively caught between the active plate motions of the

North American and Pacific plates. This condition is responsible for the northwest compression observed at Cape Mendocino, in the Puget Sound region, and in the Coeur d'Alene region. While the Mendocino fault is thought to have a right-lateral strike-slip motion component (Tobin and Sykes, 1968; Bolt and others, 1968), the predominating tectonics is for the Mendocino fault to be underthrust from the south (Seeber and others, 1970). Focal-mechanism solutions for earthquakes occurring in the Juan de Fuca plate east of the Gorda Rise indicate that right-lateral faulting is occurring across this block, connecting the San Andreas fault with the Blanco fracture zone (Tobin and Sykes, 1968; Bolt and others, 1968). Other than the 1965 Puget Sound earthquake, the only three earthquakes in the area of figure 9 that have magnitudes greater than or equal to 6.0 lie in this portion of the Gorda block.

We can now discuss the tectonic evolution and present-day seismicity associated with the Juan de Fuca plate. Figure 10 (adapted from Crosson, 1972) summarizes the tectonic evolution of this plate, beginning at 10 m.y.b.p. (million years before present). Off the Pacific northwest at 10 m.y.b.p., the Farallon plate was actively underthrusting the North American plate. The longer arrows indicate probable direction of plate motions while the shorter arrows indicate the direction of spreading. The sense of motion associated with certain faults is also indicated. The hachured line indicates probable sediment-filled trench location. About 5 m.y.b.p., the north end of the Juan de Fuca Rise began to split off to form the present Explorer Ridge; this was in response to a tendency for the Juan de Fuca plate to be rotated clockwise due to the force system previously described. The eastward extension of this left-lateral offset is continuous with the Calawah River fault zone at the north end of the Olympic Peninsula (Stewart, 1969). Crosson (1972) discussed evidence suggesting a major crustal transition from the Olympic peninsula to Vancouver Island. North-south compression is suggested from thrust faulting in the north Olympic Peninsula (McWilliams, 1970). Crosson hypothesized that the indicated left-lateral fault must absorb considerable north-south compression. This zone appears to approximate the present-day northern boundary of the Juan de Fuca plate. P-wave first motion data indicate that the small transform fault which connects the Explorer Ridge and the Juan de Fuca Rise is now a right-lateral transform fault (W. Spence and S. T. Harding, unpub. data, 1975).

Figure 10c shows a major left-lateral offset trending northeast through the Juan de Fuca plate. Silver (1971b) has constructed vector diagrams of the block motions during the development of this offset, which began about 2 1/2 m.y.b.p. and which has a total offset of 70 km. This major left-lateral fault is now inactive, as indicated by the lack of seismicity there and also by the undeformed sediments. These sediments date to about 500,000 years and lie over this fault (Silver, 1971b). This fault is consistent with the tendency for the blocks of the Juan de Fuca plate to be rotated clockwise.

Much evidence indicates that this process is in a final stage and that a new mode of deformation of the Juan de Fuca plate is beginning. The previously cited evidence that the Juan de Fuca plate is now bonded to the North American plate imposes a new set of boundary conditions for stresses acting on this system. With this boundary fixed, the subblocks of the Juan de Fuca are no longer free to rotate. Thus the Queen Charlotte Islands-Fairweather and San Andreas megashear will seek a least-energy linkage by attempting to cut across the Juan de Fuca plate. While the new faulting east of the Gorda rise is parallel to this megashear, the connecting Blanco fracture zone is at least 25° counterclockwise to the pure slip direction. The Blanco fracture-zone orientation and the lack of seismicity in the Juan de Fuca plate are evidence that the middle and upper portion of the Juan de Fuca plate is experiencing high horizontal compression in a direction of N35°W. Given the measured stress directions at Cape Mendocino, the Puget Sound region, and Coeur d'Alene, it appears that much of the northwestern United States is being stressed due to the lack of earthquake activity (destressing) within the portion of the Juan de Fuca plate under discussion. Studies of focal mechanisms for earthquakes immediately north of the Juan de Fuca Rise and a finite element modeling of the stress field in or around the Juan de Fuca plate are now in progress (W. Spence and S. T. Harding unpub. data, 1975). A valuable test of these results could be provided by extensive measurements of in situ stress in the northwestern United States.

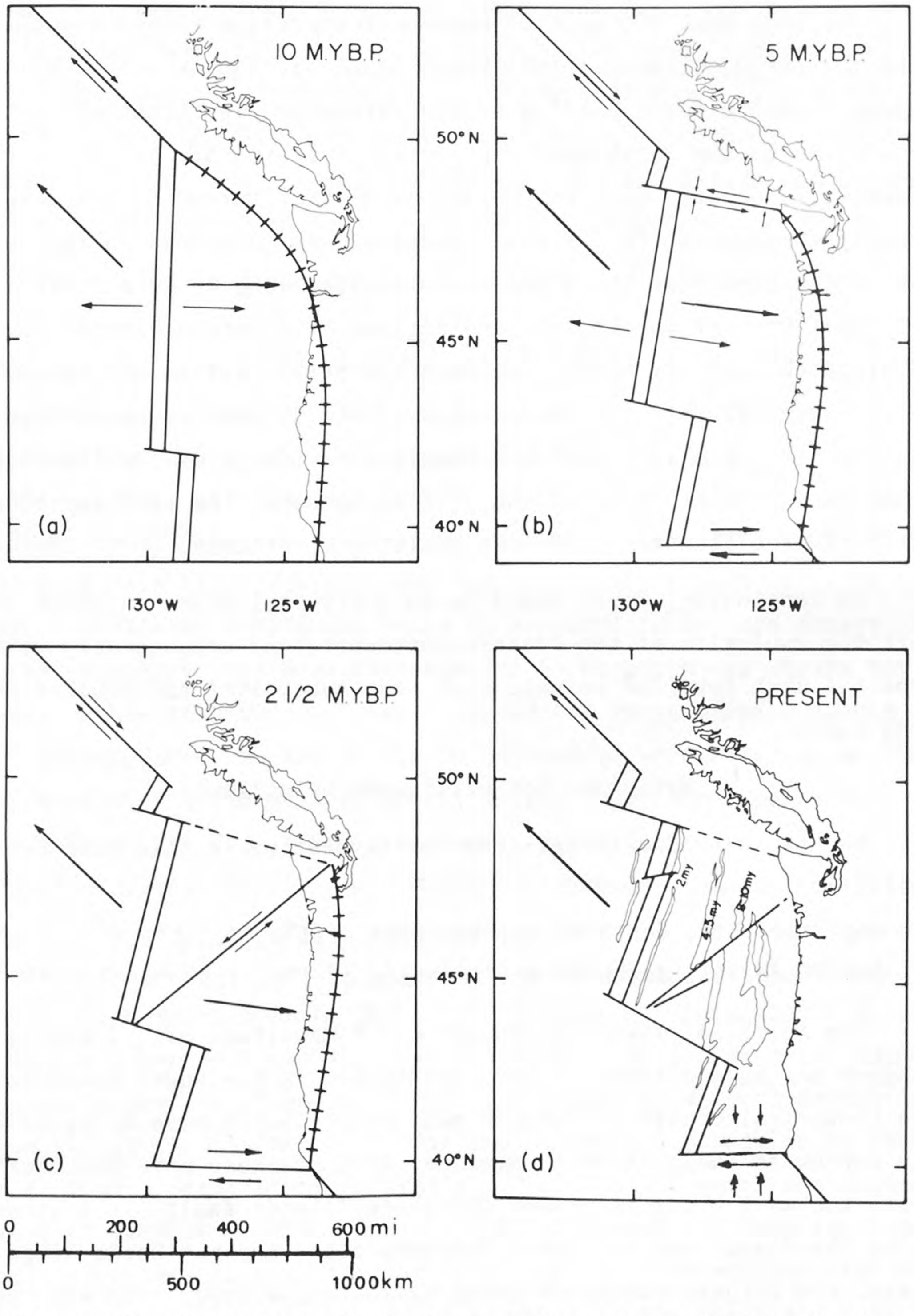


Figure 10.--Evolution of the Juan de Fuca plate during the last 10 m.y. (Crosson, 1972). Long arrows indicate direction of gross plate motion, double lines represent spreading centers, hachured line represents a trench resulting from subduction of Juan de Fuca (Farallon) plate. The sense of motion associated with certain faults is also indicated.

The fact that the axis of maximum compressive stress associated with the large subcrustal 1965 Puget Sound earthquake is N32°W is strong evidence for a bonding of the formerly underthrusting Juan de Fuca plate to the North American plate. Only in this way could the stresses associated with the megashear be transferred to the deep portion of the Juan de Fuca plate. Moreover, as indicated in figure 10, the northern edge of the formerly subducting Juan de Fuca plate is very nearly under the Puget Sound region. The interaction of these complicated boundary conditions with the stress system already discussed would cause a highly contorted stress field at depth beneath Puget Sound. Thus, while the axis of maximum compressive stress of the 1949 Puget Sound is similar to that of the 1965 earthquake, the 1949 earthquake exhibits significantly different faulting directions.

In conclusion, Puget Sound is uniquely positioned in terms of the tectonic evolution of the Pacific northwest, and consequently we must expect a high level of seismic risk from subcrustal earthquakes occurring there.

Rationale for earthquake selection

The two earthquakes selected for simulation in this study were as follows:

1. magnitude 7.5, depth 50 km, location 47.1°N, 122.7°W.
2. magnitude 7.5, depth 50 km, location 47.5°N, 122.2°W.

The April 13, 1949, earthquake had a magnitude of 7.1 and is the largest earthquake known to have originated in the Puget Sound Basin in the historical record. Although many other shocks have occurred off the northwest coast of North America, most of these have been farther north and west along the Queen Charlotte Islands fault, or southwest, along the Blanco and Mendocino fracture zones and the Gorda Ridge. Of these, the largest magnitude event close to the study area was the June 23, 1946, earthquake in the Strait of Georgia, British Columbia, some 380 km northwest of Seattle. This earthquake had a magnitude of 7.3 (Gutenberg and Richter, 1954) and was the largest known shock within 500 km of Seattle. Two earthquakes within this range, December 16, 1872, in the Wenatchee-Chelan area, and October 12, 1877, in the Oregon Cascades, may have been nearly as large. Rasmussen, Millard, and Smith (1974) have estimated the magnitude of the 1872 shock as possibly 7.5. Thus, on the basis of the historical record of earthquake occurrence, a magnitude of 7.5 appears to be reasonable for the largest earthquake that might be likely to occur in the Puget Sound area.

The choice of depth for the hypothetical earthquakes was somewhat more arbitrary. It was assumed that the chosen depth should be of the same order as that of the largest known earthquakes in the area. Depths have been estimated, however, for only a few of the Puget Sound earthquakes. The 1949 Olympia earthquake has been assigned a depth of 70 km (Nuttli, 1952), and the 1965 Seattle shock, 59 km (Algermissen and Harding, 1965. The earthquakes for which I_0 is equal to V or VI within the study area have been assigned depths ranging from 5 to 55 km. Because a shallower earthquake would be expected to do more damage close to the epicenter, the more conservative 50 km depth was chosen for this study, rather than the 60-70 km depth of the largest known shocks.

Locations of the two events to be studied were selected so that they were within the pattern of the larger Puget Sound epicenters and so that most of the damage would be concentrated in the heavily populated area from Seattle to Olympia. Given the distribution of the five largest shocks in the Puget Sound area, it must be assumed that any future earthquake is equally likely to occur at any point around the southern end of the sound. Thus the epicenter of the actual 1949 earthquake was chosen for the first shock to be studied. As this lies between Tacoma and Olympia, it may be expected to do more damage in those cities than in Seattle. For the second earthquake to be studied, a site nearer Seattle was desirable. The 1965 epicenter was deemed too far south to display much separation of the effects of the two hypothetical earthquakes and too far from Seattle to do maximum credible damage in Seattle and in the built-up areas to the north and east. Thus a point just east of down-town Seattle, near the southern end of Lake Washington, was chosen.

Frequency of occurrence of damaging earthquakes

For information on the earthquake recurrence rates for the Puget Sound region, a larger sample of events is needed than is available from the six-county study area. The area chosen includes most of Washington and the northern half of Oregon. The distribution of epicenters within this area is shown in figure 11. Stepp (1971) listed a total of 744 earthquakes in this area, spanning a 100-year time interval from 1870 through 1969. Because epicenters are plotted to the nearest 1/10th degree, more than one earthquake may be represented by a single symbol on the map in locations where more than one earthquake occurred.

Figure 12 shows a plot of the common logarithm of the expected number of events per year, log N, as a function of maximum intensity I_o for the 100-year sample. In the derivation of the coefficients for the line

$$\log (N/yr) = 2.84-0.52\ I_o ,$$

the point for the intensity IV shocks has been excluded, as the correction for completeness was not sufficient to establish a uniform rate. (See Stepp, 1973.) (Attempting to fit a data set having incomplete estimates would result in the underestimation of the rates of small earthquakes and the overestimation of the rates of large earthquakes by the least squares line.)

Another approach to the derivation of earthquake recurrence rates is the extreme-value statistical method, commonly used to estimate return periods for floods. The data for this analysis (Stepp, 1971) are the maximum earthquake intensities I_j for each of the 100 years. Because the true annual maxima were not reported for many of the early years, only the last 50 years of the sample are used in Stepp's analysis. These $\overline{I}_j$ are arranged in order from smallest to largest, and an ordered probability $P(\overline{I}_j)$ is calculated for each of the n ordered annual maxima $\overline{I}_j$, using

$$P(\overline{I}_j) = \frac{j-0.44}{n+0.12} ,$$

a formula taken from Gringorten (1963). Table 9 (adapted from Stepp, 1971), shows these values.

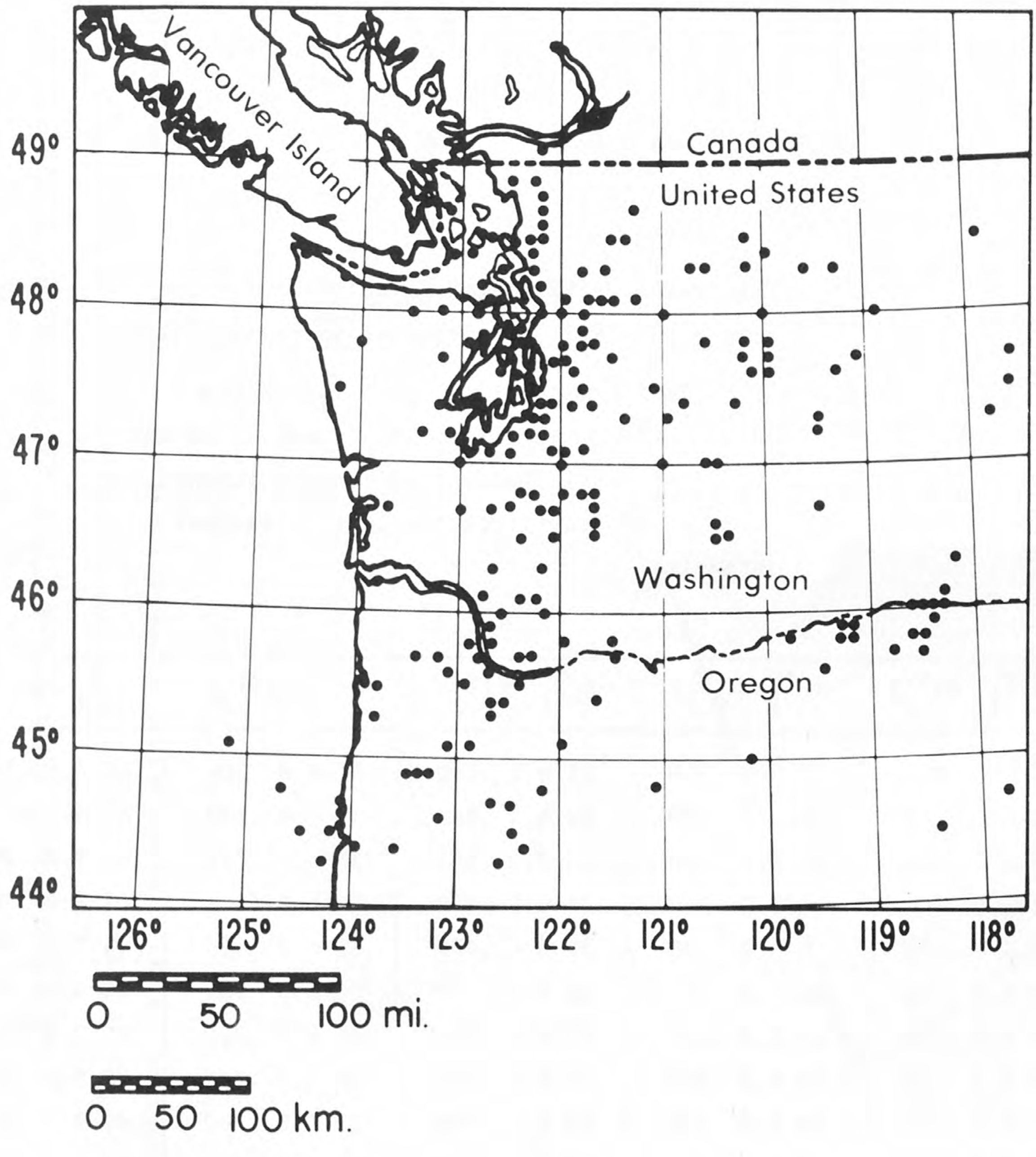


Figure 11.--Geographic distribution of earthquake epicenters in the vicinity of the Puget Sound, 1870 through 1969. A symbol may represent more than one earthquake. Adapted from Stepp (1971).

Table 9.--Yearly intensity maxima (1920-1969) for the Puget Sound area, in order of increasing size

[Adapted from Stepp, 1971. $P(\overline{I}_j)$ is the calculated probability of $\overline{I}_j$, where $\overline{I}_j$ is the jth of 50 maximum annual earthquake intensities, arranged in order from smallest to largest intensity]

j	$\overline{I}_j$	$P(\overline{I}_j)$	j	$\overline{I}_j$	$P(\overline{I}_j)$	j	$\overline{I}_j$	$P(\overline{I}_j)$	j	$\overline{I}_j$	$P(\overline{I}_j)$	j	$\overline{I}_j$	$P(\overline{I}_j)$
1	0.0	.011	11	5.0	.210	21	6.0	.410	31	6.0	.609	41	6.0	.809
2	4.0	.031	12	5.0	.230	22	6.0	.430	32	6.0	.629	42	6.0	.829
3	4.0	.051	13	5.0	.250	23	6.0	.450	33	6.0	.649	43	7.0	.849
4	5.0	.071	14	5.0	.270	24	6.0	.470	34	6.0	.669	44	7.0	.869
5	5.0	.090	15	5.0	.290	25	6.0	.490	35	6.0	.689	45	7.0	.889
6	5.0	.110	16	5.0	.310	26	6.0	.509	36	6.0	.709	46	7.0	.909
7	5.0	.130	17	5.0	.330	27	6.0	.529	37	6.0	.729	47	7.0	.928
8	5.0	.150	18	5.0	.350	28	6.0	.549	38	6.0	.749	48	8.0	.948
9	5.0	.170	19	5.0	.370	29	6.0	.569	39	6.0	.769	49	8.0	.968
10	5.0	.190	20	6.0	.390	30	6.0	.589	40	6.0	.789	50	8.0	.988

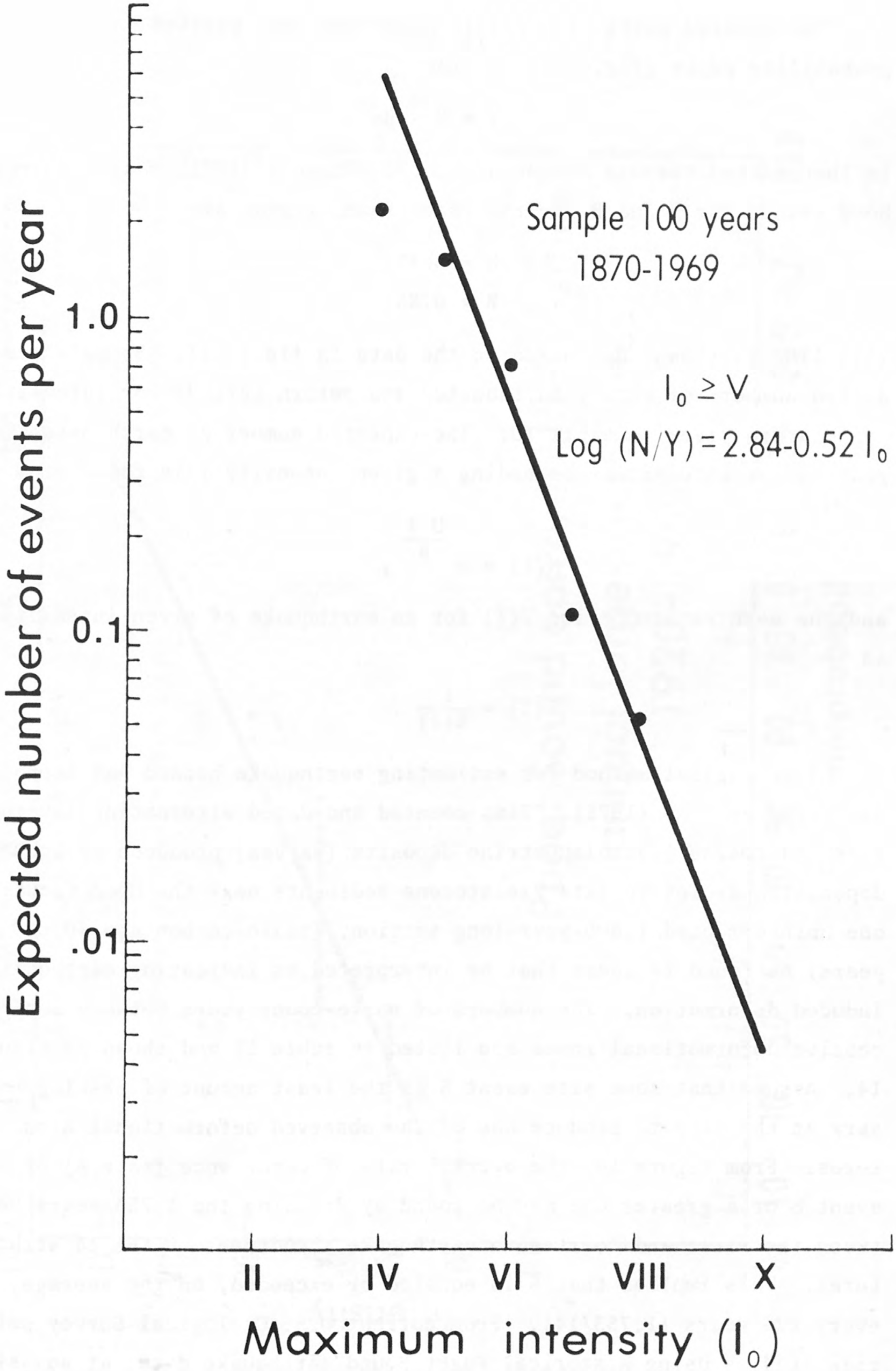


Figure 12.--Least squares fit of log (N/yr) = a + b I_0 for 100-year sample corrected for incompleteness. Adapted from Stepp (1973).

The ordered pairs $(\overline{I}_j, P(\overline{I}_j))$ have then been plotted on extreme probability paper (fig. 13). A line

$$I = U - Bx$$

is then fitted through the data points. Stepp's (1971) maximum likelihood values for U and B for the Puget Sound region are

$$U = 5.33$$
$$B = 0.85.$$

This line is shown superposed on the data in figure 13. Stepp's predicted numbers of yearly earthquakes and return periods for intensities IV to X are given in table 10. The expected number of earthquakes in a year having intensities exceeding a given intensity I is found from

$$N(I) = e^{\frac{U-I}{B}} ,$$

and the mean return period T(I) for an earthquake of given intensity I is

$$T(I) = \frac{1}{N(I)} .$$

A geological method for estimating earthquake hazard has been developed by Sims (1975). Sims counted and dated alternating layers of fine and coarse glaciolacustrine deposits (varves) produced by annual deposition cycles in late Pleistocene sediments near the Hood Canal. In one uninterrupted 1,800-year-long section, (radio-carbon age 40,000 years) he found 14 zones that he interpreted as indicating earthquake-induced deformation. The numbers of varve-count years between successive deformational zones are listed in table 11 and shown in figure 14. Assume that some site event S is the least amount of shaking necessary at the site to produce one of the observed deformational structures. From figure 14, the overall rate of occurrence (rate A) of the event S or a greater one may be found by dividing the 1,753 years between the first and fourteenth earthquake structures by the 14 structures. This implies that S is equaled or exceeded, on the average, every 125 years (1,753/14). From current U.S. Geological Survey seismic risk studies using historical Puget Sound earthquake data, at any site

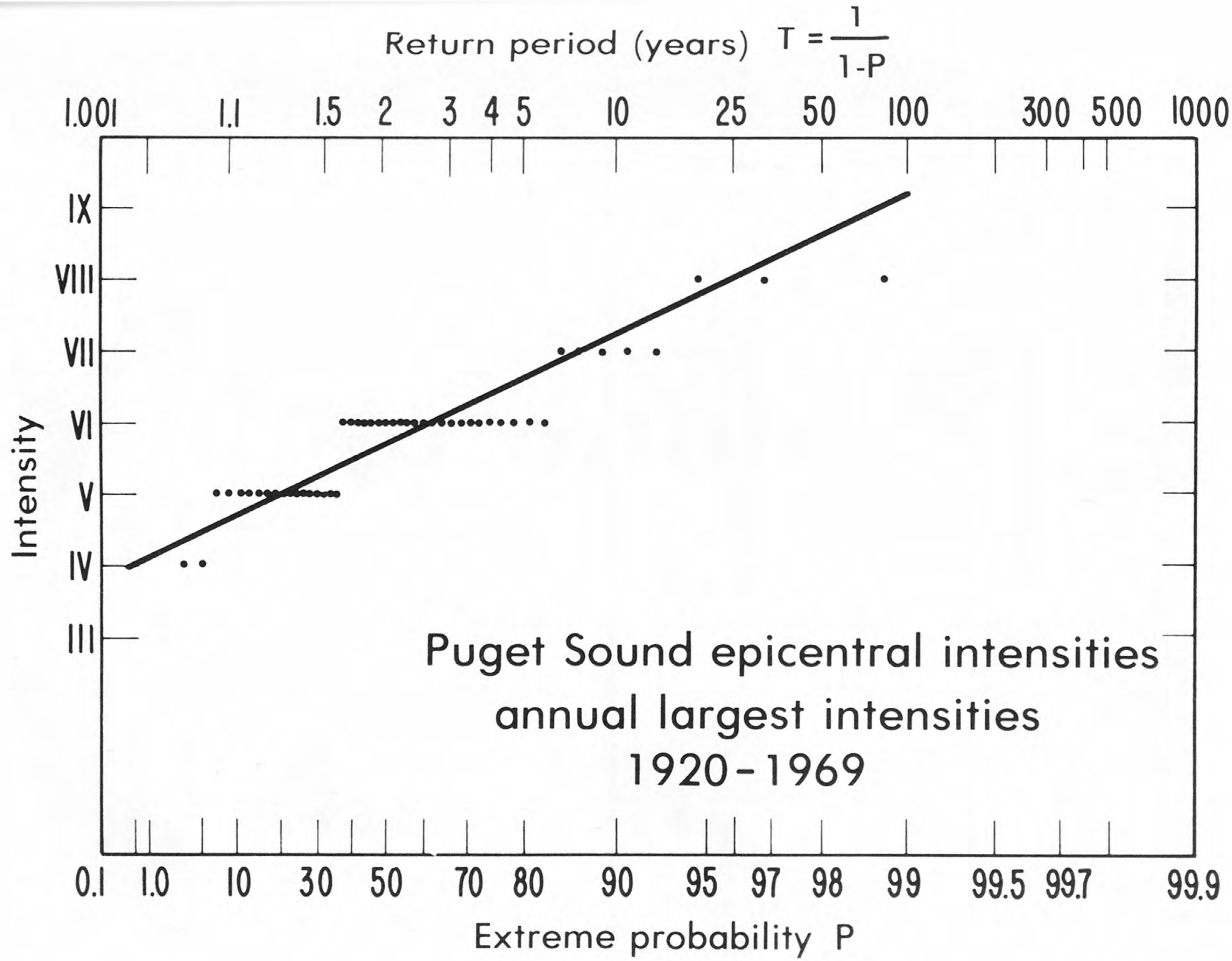


Figure 13.--Extreme probability plot of the largest yearly earthquakes for 50-year sample in the Puget Sound area. Adapted from Stepp (1971)

Table 10.--Predicted yearly numbers and return-periods for Puget Sound, 1920-1969

[Adapted from Stepp, 1971]

Intensity, I	Yearly expected number, N(I)	Mean return period T(I)
4	4.73	.2
5	1.47	.7
6	.46	2.2
7	.14	7.1
8	.04	22.8
9	.01	73.3
10	.00	236.1

Table 11.--Varve-count years between earthquake-induced deformational zones in a 40,000-year-old, 1,800-year-long section in the Puget Sound area

Zone	Varve-years between Zones
Top of Section	32
14th	102
13th	148
12th	208
11th	180
10th	172
9th	246
8th	60
7th	62
6th	63
5th	104
4th	69
3rd	276
2nd	63
1st	19
Bottom of Section	

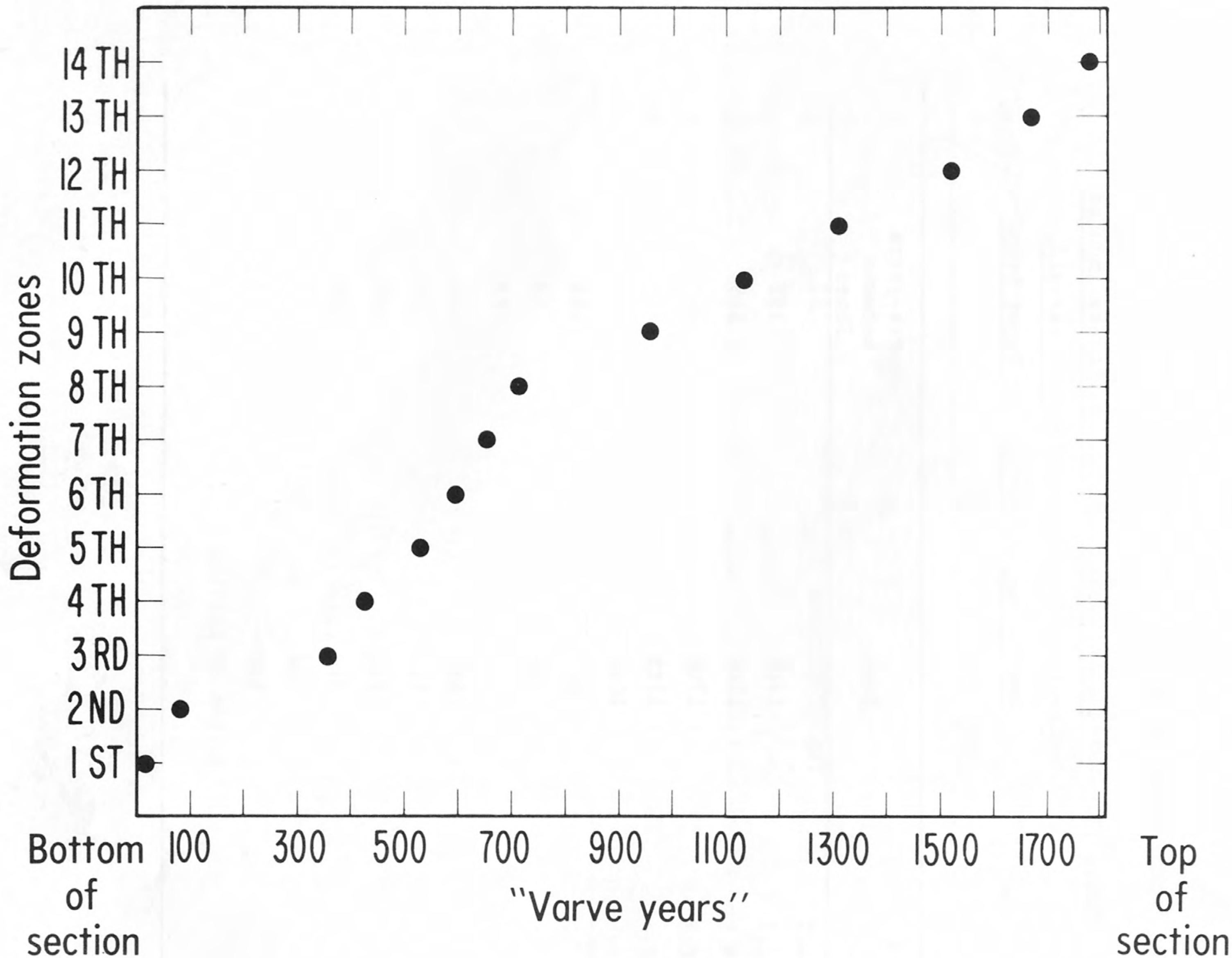


Figure 14.--Varve-count years between earthquake-induced deformational zones in a 40,000-year-old, 1,800-year-long section in the Puget Sound area. Adapted from Sims (written commun., 1975).

in the Seattle area a ground acceleration of 0.22g has a return period of 125 years (David Perkins, oral commun., 1975). Thus, if the rate of occurrence of large earthquakes in the region is the same as it was 40,000 years ago (rate A), then S could be identified as the result of any earthquake producing 0.22g or more at the site. On the other hand, we could identify the current rate with the period of increased rate of S occurrences (rate B), seen in the steep part of the graph (fig. 14). Here the 358 years between the third and eighth events imply a return period of varve deformations of 60 years (358 years/6 structures). In this case, the corresponding event in the current period (for rate B) produces an acceleration of .13g or greater at the site.

Population distribution

The population of the six-county study area is 3,030,300, as shown in table 12; these figures are based on the 1970 census, adjusted to 1973 as reported by the Office of Program Planning and Fiscal Management. At the request of Region 10, Federal Disaster Assistance Administration, metropolitan Seattle (the major population center of the study area) was sectioned into five areas as shown on figures 15 and 29. These areas can be described roughly as:

Area 1. North of the Lake Washington Ship Canal in the City of Seattle, King County, to 164th Street S.W., in Edmonds, Snohomish County;

Area 2. City of Seattle south of the Ship Canal to Dearborn Street;

Area 3. City of Seattle south of Dearborn Street to 160th Street S.W.;

Area 4. King County east of Lake Washington, north to the Sammamish River, south to Petrovitsky Road, and east to Lake Sammamish; and

Remainder. The remainder of King County.

Throughout the report, statistics given for Area 1 in King County, as shown in table 12, do not include statistics for the remainder of Area 1 situated in Snohomish County. Exceptions will be noted in tables and text when statistics represent Area 1 in its entirety.

Counties are named in sequential order around the perimeter of the Puget Sound Basin.

TABLE 12.--POPULATION OF THE SIX-COUNTY STUDY AREA, AS OF APRIL 1, 1973
(Pocket Data Book, State of Washington, 1973, Office of Program Planning and Fiscal Management)

County		Population		County seat
SNOHOMISH		265,600		Everett
		Subtotal	265,600	
KING				Seattle
	Area 1	289,638		
	2	142,021		
	3	283,940		
	4	204,852		
Remainder		223,349		
		Subtotal	1,143,800	
PIERCE				Tacoma
Tacoma		155,500		
Remainder		248,800		
		Subtotal	404,300	
THURSTON		81,300		Olympia
MASON		21,500		Shelton
KITSAP		103,100		Port Orchard
		Subtotal	205,900	
		TOTAL	2,030,300	

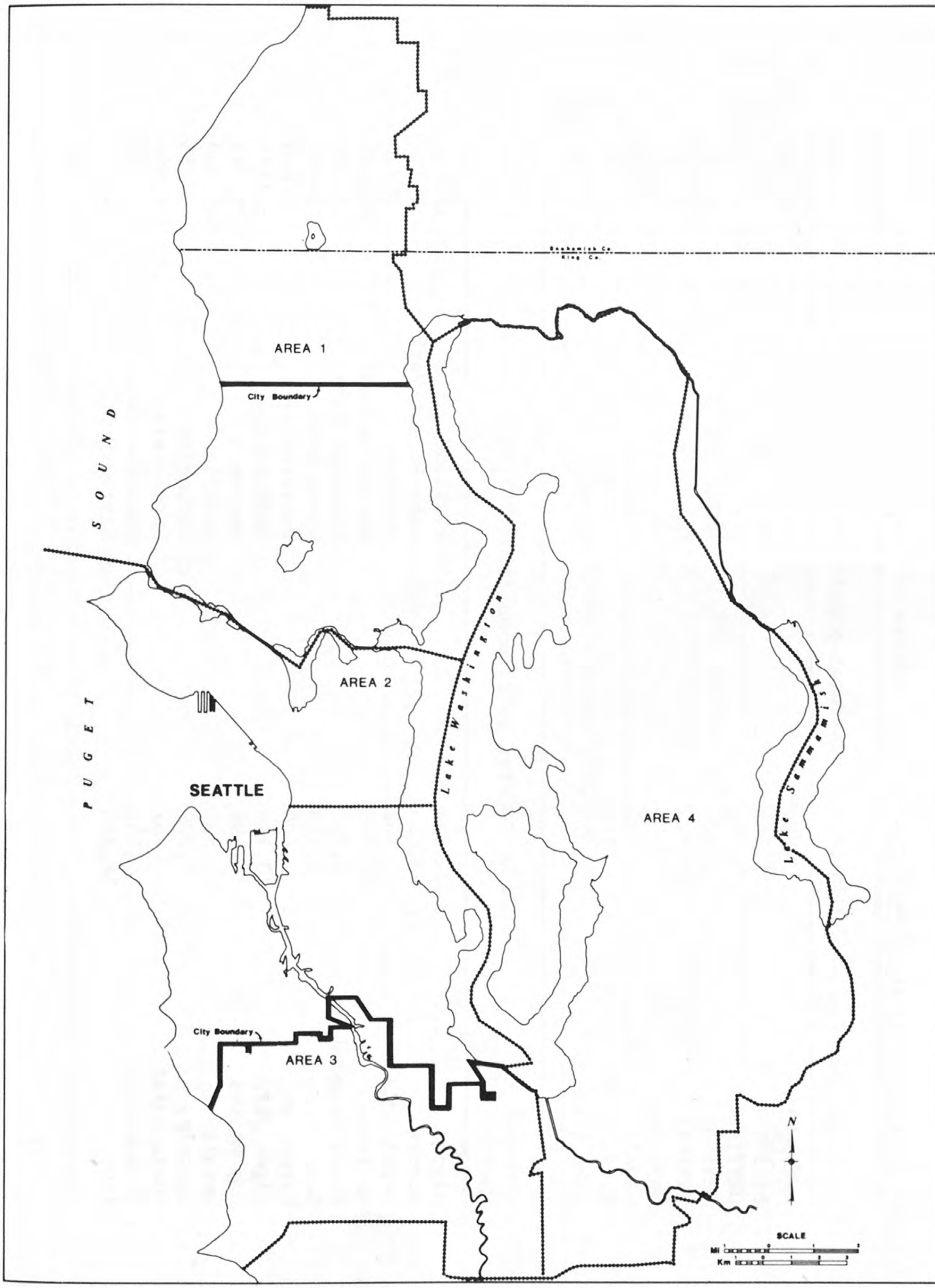


Figure 15.--Outline of areas assigned to metropolitan Seattle.

TABLE 13.--POPULATION OF INCORPORATED CITIES IN THE SIX-COUNTY STUDY AREA

(Pocket Data Book, State of Washington, 1973, Office of Program Planning and Fiscal Management)

SNOHOMISH COUNTY--Total population=139,460

Arlington	2,250	Lynnwood	19,125
Brier	3,050	Marysville	4,220
Darrington	1,160	Monroe	2,700
Edmonds	24,600	Mountlake Terrace	16,725
Everett	53,400	Mukilteo	1,390
Gold Bar	504	Snohomish	4,753
Granite Falls	795	Stanwood	1,359
Index	172	Sultan	1,150
Lake Stevens	1,270	Woodway	837

KING COUNTY--Total population=737,991

Algona	968	Kirkland	15,100
Auburn	21,256	Lake Forest Park	2,545
Beaux Arts	362	Medina	3,460
Bellevue	63,000	Mercer Island	21,000
Black Diamond	1,164	Normandy Park	4,280
Bothell	5,550	North Bend	1,650
Carnation	600	Pacific	1,650
Clyde Hill	3,113	Redmond	13,134
Des Moines	4,699	Renton	26,250
Duvall	590	Seattle	515,000
Enumclaw	4,599	Skykomish	283
Hunts Point	467	Snoqualmie	1,260
Issaquah	4,539	Tukwila	3,420
Kent	16,945	Yarrow Point	1,107

TABLE 13.--POPULATION OF INCORPORATED CITIES IN THE SIX-COUNTY STUDY AREA--Continued

PIERCE COUNTY--Total population=200,639			
Bonney Lake	2,824	Orting	1,643
Buckley	3,165	Puyallup	15,200
Carbonado	390	Roy	364
Du Pont	384	Ruston	680
Eatonville	860	South Prairie	217
Fife	1,339	Steilacoom	3,500
Fircrest	5,750	Sumner	4,325
Gig Harbor	1,577	Tacoma	155,500
Milton	2,624	Wilkeson	297
THURSTON COUNTY--Total population=42,675			
Bucoda	427	Tenino	1,048
Lacey	10,100	Tumwater	5,720
Olympia	24,200	Yelm	632
Rainier	548		
MASON COUNTY--Total population=6,900			
Shelton	6,900		
KITSAP COUNTY--Total population=43,763			
Bremerton	35,975	Poulsbo	2,010
Port Orchard	4,030	Winslow	1,748

Detailed working maps were prepared on which hospitals, freeway overpasses, and other features of significance within the six counties could be located; this information is presented in summary form in the figures of this report.

Table 13 shows the county location as well as population for all incorporated cities within the Puget Sound Basin.

Use of this report

The numerical values associated with each problem area, such as damage to and life loss in hospitals, represent reasonable maximum expected conditions. In other words, these values are credible; they have experience data and (or) experience judgment behind them. The quality of the numbers will vary depending upon the extrapolation (if any) from experience data, the reliability of assumptions supporting the calculations, and the quality of the judgment behind the decisions.

It is improbable that the maximum values established for each type of problem will all occur simultaneously in any given earthquake. One is tempted to assign probability values to the numbers given in each problem area and thereby develop the most likely situation to occur in real life. On the other hand, there is reason to believe that the probability values would have such poor confidence limits in some cases as to be of minimal practical value, particularly when these values are used on a comparative basis to establish priorities.

It must be clearly understood that no two identical magnitude earthquakes in different geographic locations will necessarily have identical effects. The rate of energy release along the fault, focal depths, the relationships of center of energy release to epicenter, and local geology may all be different. Thus, extrapolation of the data to other nearby faults must be done with caution.

In addition to the possible variations in seismological parameters, the response of buildings and structures to earthquake ground motions is not as well understood as some persons might expect. Surprises have occurred in every destructive earthquake, and are one major reason for the many reports emanating from the 1971 San Fernando shock. The expected seismic performance of any particular building can be stated only in a probabilistic sense.

Summing the aggregate losses for various situations must be done with understanding and judgment. For example, maximum landslide hazard conditions occur in the summer season. Also, the population is largely in dwellings and apartment houses during the night hours while a different distribution exists during the working and shopping day; therefore, the failure of a dam causing maximum casulaties in dwellings (night hours) would not be added to the maximum casualties in shopping areas (day hours) resulting from the same dam failure.

Unanticipated events occur in almost every earthquake. A destructive shock may occur on a fault not previously thought to be active, as it did in the 1971 San Fernando shock. Alternately, the earthquake could occur during the height of the Christmas shopping season. In the Seattle-Tacoma area, the earthquake could occur on one of those occasional days when the ground fog halts all air transportation, thereby restricting aid via air. These are possible, credible events and in a sense create "surprise" situations; however, they are sufficiently improbable that they have not been given consideration in this report. On the other hand, no solution stated in this report should be taken so rigidly as to preclude the unexpected, which invariably occurs in some aspects of every great earthquake disaster.

Planning agencies using this report for information purposes should bear in mind that the contents are based on two postulated earthquakes with epicenters approximately coinciding with those of the two most recent damaging earthquakes in the Puget Sound Basin. Intensity patterns throughout the Basin vary in the two earthquakes depending on geographic relationship to the postulated epicenters. Lack of well-defined fault lines severely limits the prediction of future shocks in any specific location; in view of prior earthquake history which indicates recorded shocks scattered through the Puget Sound Basin. Thus, future shocks of damaging magnitude might occur in unexpected locations, severly modifying the intensity pattern. At the same time, the isoseismal maps tend to define areas of higher intensity in relation to geologic and soil conditions such as alluvial plains, areas of precarious land stability, or manmade fills. As a direct result, the areas within a given locality that are subject to greater intensity may be approximated, while shifting of possible epicenters leaves the intensity in any given area open to wide variation.

Some comment on dollar losses is in order. First, consider the "personal" vs. "impersonal" viewpoints on loss and how each affects the loss statistics. Suppose, for example, a wood frame dwelling suffers minor plaster cracking but no structural damage. This could become a $25 "personal" loss if the homeowner pays for the paint and personally makes his own repairs. If, however, the loss is covered by insurance or through government subsidy, the loss becomes "impersonal" from the homeowner's standpoint because others must pay; commercial painters would probably make the repairs for what might reasonably cost $250, or ten times the "personal" loss.

"Impersonal" losses may be one of several kinds; two of these require special attention. Specifically, dollar losses can be determined on the basis of replacement cost or on the basis of actual cash value (or appraised value), and the differences between these two can be significant in some cases. For example, a study by McClure, "Studies in Gathering Earthquake Damage Statistics" (ESSA, 1967) of the 1952 Kern County, Calif., earthquakes showed that the actual cash value of wood frame dwellings in Bakersfield at the time of the 1952 shocks was 36 percent of the replacement value of these buildings. To the extent that the 36 percent is applicable elsewhere, damaged dwellings requiring replacement would have a real loss of about three times their pre-earthquake value as they could not be rebuilt for their depreciated values. Similarly, if all of the damaged hospitals discussed in this study were to be replaced, the cost would be on a replacement value basis insofar as the public loss was concerned. On the other hand, if the Bakersfield experience figure was assumed to apply, then the actual cash value would be only about one-third of the replacement cost. It must be borne in mind that the dollar loss is a function of a financial viewpoint.

EARTHQUAKE INTENSITIES AND ISOSEISMAL MAPS

Materials used

Geologic data used in the construction of the isoseismal maps were obtained from numerous maps at scales ranging from 1:500,000 to 1:31,680. Intensity data for historical Puget Sound earthquakes were obtained from accounts and studies of those shocks.

The core of the regional geologic map derived for this project was provided by Donal R. Mullineaux of the U.S. Geological Survey (unpub. mapping, 1974). Mullineaux's map included the area adjacent to the waters of Puget Sound at a scale of 1:250,000. In addition to serving as geologic consultant for the entire project, he also determined the grouping of mapped geologic units into the four divisions of interest for this study. These are (1) alluvium over 15 m (50 ft) deep, (2) overconsolidated material, (3) bedrock, and (4) normally consolidated material. Fill and peat are also shown, but for attenuation purposes are usually grouped with the deep-alluvium category. Overconsolidated material is defined as any material that has been compacted by more than the weight of what now overlies it. Much of the surface of the six-county study area is overconsolidated glacial till. Because so much of the region is overlain by glacial deposits, most of the bedrock outcrops are in the Cascade Mountains on the eastern edge of the study area. Normally consolidated material primarily includes glacial outwash deposits and alluvium less than 15 m deep.

The remainder of the regional geologic map was derived from a number of geologic quadrangles and county geologic maps. Most extensively used were the geologic maps of central Pierce County (Walters and Kimmel, 1968) and of Thurston County (Noble and Wallace, 1966). These were used both for the regional geologic map and for the enlarged maps of Tacoma and Olympia, respectively. The "Preliminary Geologic Map of Seattle and Vicinity" (Waldron and others, 1962) served as the basis for the enlarged Seattle maps. For the remainder of the regional geologic map, parts of the following maps were used: King County (Livingston, 1971), southwest

King County (Luzier, 1969), northwest King County (Liesch and others, 1963), southeast Mason County (Molenaar and Noble, 1970), Kitsap County (Sceva, 1957), and western Snohomish County (Newcomb, 1952). Where no large-scale geologic map was available, the gaps were filled in by using the 1:500,000 "Geologic Map of Washington" (Huntting and others, 1961). Relevant areas of the above maps were photographed and reduced (or enlarged in the case of the Washington State map) to the 1:250,000 scale of Mullineaux's map. The two county maps, central Pierce (1:48,300) and Thurston (1:70,600), were used at their existing scales for the enlarged maps of Tacoma and Olympia.

In addition to the above maps, the following U.S. Geological Survey geologic quadrangle maps within the six-county study area were consulted: Buckley (Crandell and Gard, 1959), Poverty Bay (Waldron, 1961), Des Moines (Waldron, 1962), Renton (Mullineaux, 1965a), Auburn (Mullineaux, 1965b), Black Diamond (Mullineaux, 1965c), Glacier Peak (Crowder and others, 1966), Holden (Cater and Crowder, 1967), Duwamish Head (Waldron, 1967), and Brothers (Cady and others, 1972). Washington Division of Geology and Earth Resources geologic maps used were Hobart and Maple Valley (Vine, 1962) and Cumberland (Gower and Wanek, 1963).

Intensity data on earthquakes in the Puget Sound area came from a number of sources. The information in table 8, tabulating historical earthquakes, was obtained from the following: the unpublished NOAA Magnetic Tape Earthquake Catalog (updated through 1970), Stepp (1971), the annual serial publication "United States Earthquakes," beginning in 1928 (see individual references), Rasmussen (1967), Milne (1963), Saint-Amand, Lombardi, and Shuler (1963), Milne (1956), Gutenberg and Richter (1954), Coombs (1953), Townley and Allen (1939), Bradford (1935), McAdie (1907), and Holden (1898).

A number of studies of individual earthquakes also proved extremely useful. These included Algermissen and Harding (1965), Mullineaux, Bonilla, and Schlocker (1967), and U.S. Coast and Geodetic Survey (1967), for the earthquake of April 29, 1965; Nuttli (1952), Ulrich (1949), Newmann (1954), the U.S. Army Corps of Engineers (1949), and U.S. Coast and Geodetic Survey (1950), for the earthquake of April 13, 1949; Coombs and Barksdale (1942), for the earthquake of November 13, 1939; and Barksdale and Coombs (1946), for the earthquake of February 15, 1946.

In addition to the above, two primary sources of intensity data were obtained. The intensity surveys done by the University of Washington immediately after the April 13, 1949, and the April 29, 1965, earthquakes were most helpful. It was mainly these data which made possible the detailed maps of Seattle, Tacoma, and Olympia. Moreover, because one of the questions on the University of Washington's 1965 intensity questionnaire asked for a comparison of effects with the April 13, 1949, shock, some additional data on that earthquake were obtained from the 1965 survey. The other primary source consisted of abstracts of newspaper reports pertaining to earthquakes from the Seattle Post-Intelligencer (written commun., 1974). These contained information on both the 1949 and 1965 earthquakes.

Additional intensity information for specific locations was obtained through discussions with Norman Rassmussen and Richard Millard of the University of Washington. Their knowledge of the study area, its geology, and the effects of the larger and more recent earthquakes at numerous sites within the area proved invaluable in the construction of detailed isoseismal maps for those shocks.

Attenuation curves

In order to construct the isoseismal maps for the two hypothetical earthquakes in this study, three things were needed: (1) geologic maps showing the four major classifications described above, (2) a magnitude-intensity relationship for the Puget Sound area, and (3) attenuation curves for each type of geologic division.

A plot of magnitude versus intensity for the largest Puget Sound earthquakes having known magnitudes is shown in figure 16. The line shown is the least squares line through all the points, weighted so that greater importance is given to the two largest earthquakes. This method was employed because it is assumed that different focal mechanisms exist

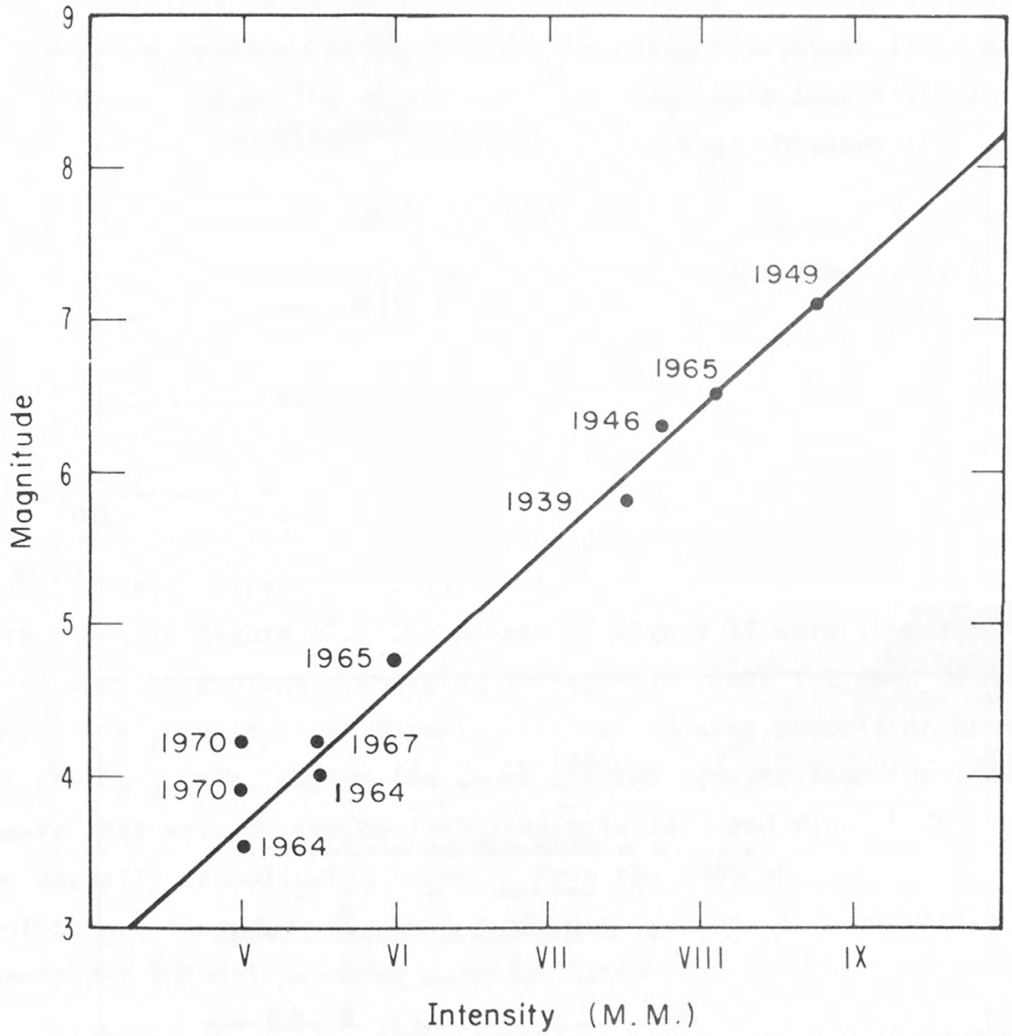


Figure 16.--Plot of magnitude vs. intensity for largest known Puget Sound earthquakes.

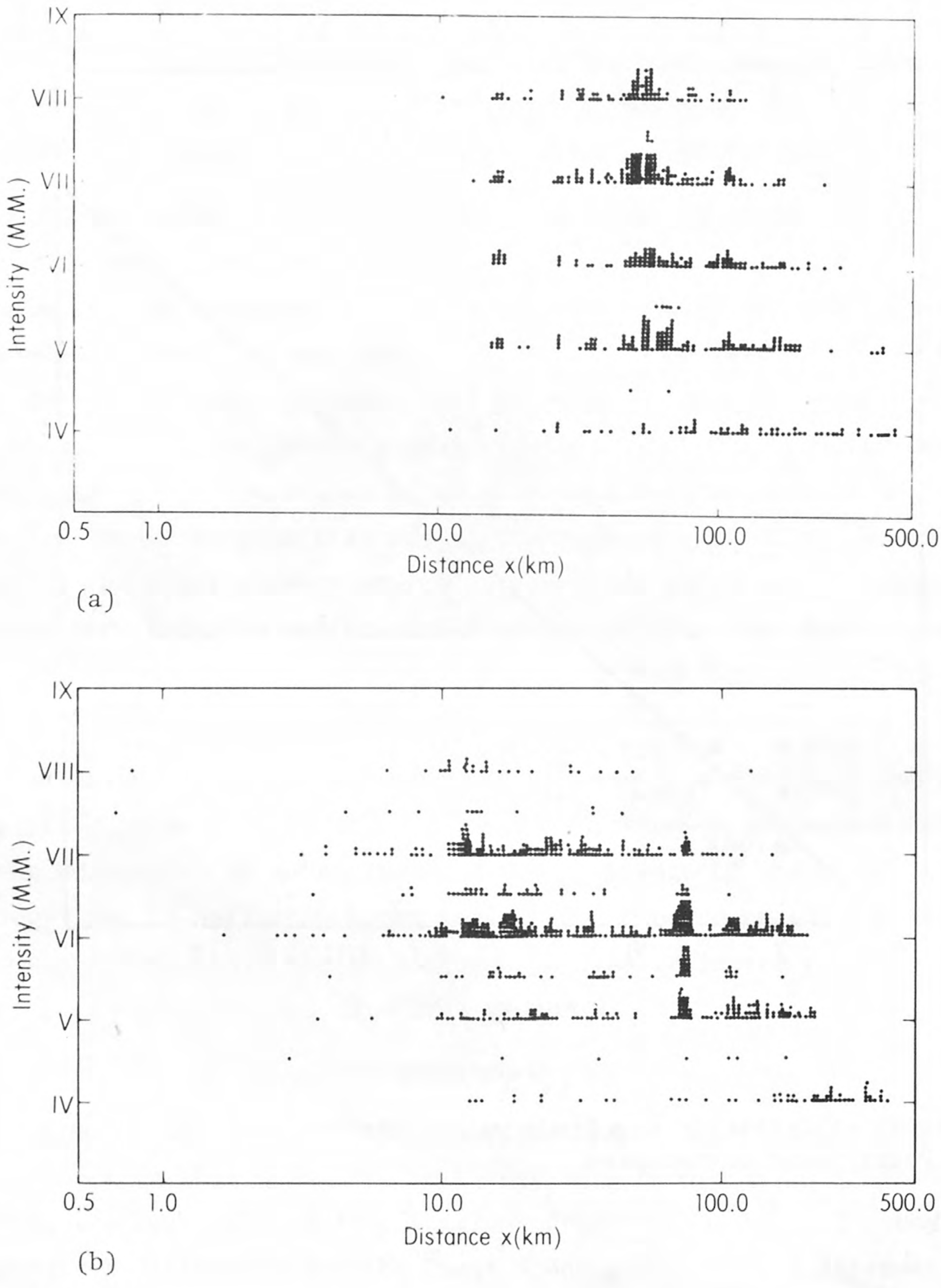


Figure 17.--Intensity as a function of epicentral distance. Each dot represents a reported intensity (a) for the April 13, 1949 earthquake or (b) for the April 29, 1965 earthquake. Clumps of dots appear where there were numerous reports, as from a large city.

for the larger, deeper shocks and the smaller, shallower shocks in the Puget Sound region. In this study the primary interest is in the larger earthquakes and in the extension of the magnitude-intensity line to even higher magnitude values. The relationship thus obtained is

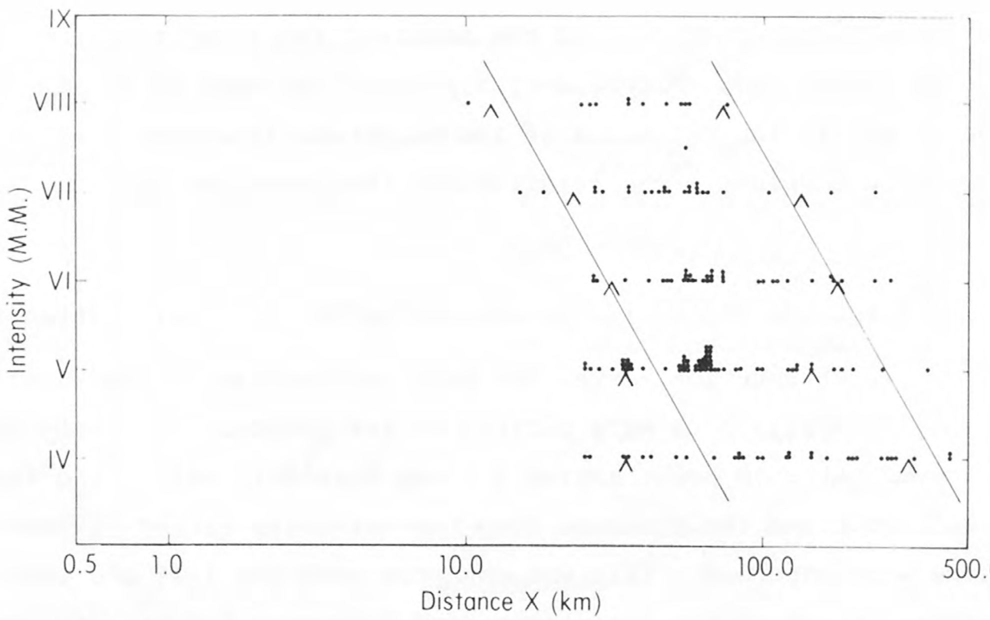
$$M = -.98 + .92\ I_o ,$$

where M is magnitude and I_o is the maximum Modified Mercalli intensity.

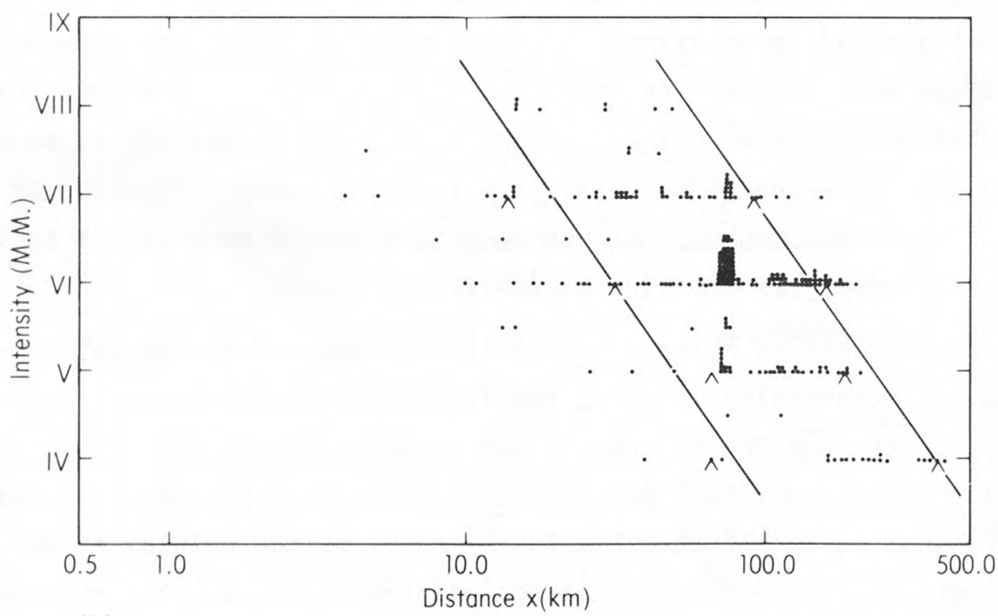
To derive attenuation curves for real earthquakes in the Puget Sound area, intensity data were plotted on the geologic base maps discussed above. At each point having a known intensity value, the type of geologic unit and the distance from the intensity center of that earthquake were recorded. This was done for both the 1949 and 1965 earthquakes. Plots of the intensities and distances for both earthquakes are shown in figure 17. The points of figure 17 were then subdivided according to geology, resulting in separate plots for each of the geologic units. Figure 18 is an example of this, showing reports on only one type of geologic unit; figure 18a shows all the reports from the 1949 earthquake that were on overconsolidated material, and figure 18b gives points on normally consolidated material from the 1965 shock. Clusters of points are caused by numerous responses from one or more cities to the newspaper intensity-survey questionnaires.

Because there is a large spread in the range of distances over which a given intensity is felt, the 10 percent points on each end were chosen, rather than the extremes. For example, figure 18b shows that intensity VI M.M. was felt for distances from 10 to 200 km. Ten percent of the points on the VI line lie to the right of the pointer at 165 km and 10 percent lie to the left of the pointer at 30 km. Attenuation curves were then drawn for the sets of pointers, taking into account the disproportionate number of points on each line.

To obtain attenuation curves for the new, hypothetical earthquakes, the maximum intensity I_o for the assumed magnitude of 7.5 was read from the magnitude-intensity graph (fig. 16). It can be seen that such a shock may be expected to cause damage in the low range of intensity IX.



(a)



(b)

Figure 18.--Attenuation of intensity with epicentral distance. Each dot represents a reported intensity (a) on overconsolidated material for the April 13, 1949 earthquake or (b) on normally consolidated material for the April 29, 1965 earthquake. Clumps of dots appear where there were numerous reports, as from a large city. Eighty percent of the dots on a line lie between the pointers, and 10 percent on either side.

Therefore, the curves derived for the real earthquake were raised by the amount of change in intensity caused by the increase in magnitude. Average distances from the epicenter at which intensity values decrease may be read from the attenuation curves. Using these distances and the geologic maps, the new isoseismal maps were constructed.

Map descriptions

Eight isoseismal maps were derived using the data previously described. The first pair of these, figures 19 and 20 show projected intensities for the whole of the six-county study area for the two assumed earthquakes. Figure 19, for the hypothetical earthquake with epicenter near Tacoma and Olympia, was based primarily on data from the April 13, 1949, shock. Figure 20, centered close to Seattle, was constructed using data from the April 29, 1965, earthquake. These two maps present the maximum likely intensities at any given point within the area. Changes in intensity level from place to place depend on distance from the epicenter, as read from the attenuation curves, and on the geologic category of the site. Further modifications were made, generally to upgrade sites having a known past history of severe shaking or landsliding or having a high water table. Because of the depth of the hypothetical earthquakes and the assumption of no surface-fault rupture, the area of possible maximum intensity is large. As with the smaller historical earthquakes in this region, it is not to be expected that the maximum projected intensity will be experienced by every single point within this wide region. Rather, it is asserted that all points within this area have the potential for such damage, and that many will in fact be subjected to it if one of the postulated earthquakes should occur.

In order to give a more detailed estimation of potential damage to the Seattle area than was possible on the 1:250,000 regional maps, enlarged isoseismal maps were constructed, showing projected intensities in Seattle, Tacoma, and Olympia for each of the two hypothetical earthquakes. Figure 21 depicts the Seattle intensity pattern for the assumed earthquake near Tacoma and Olympia, and figure 22 does the same

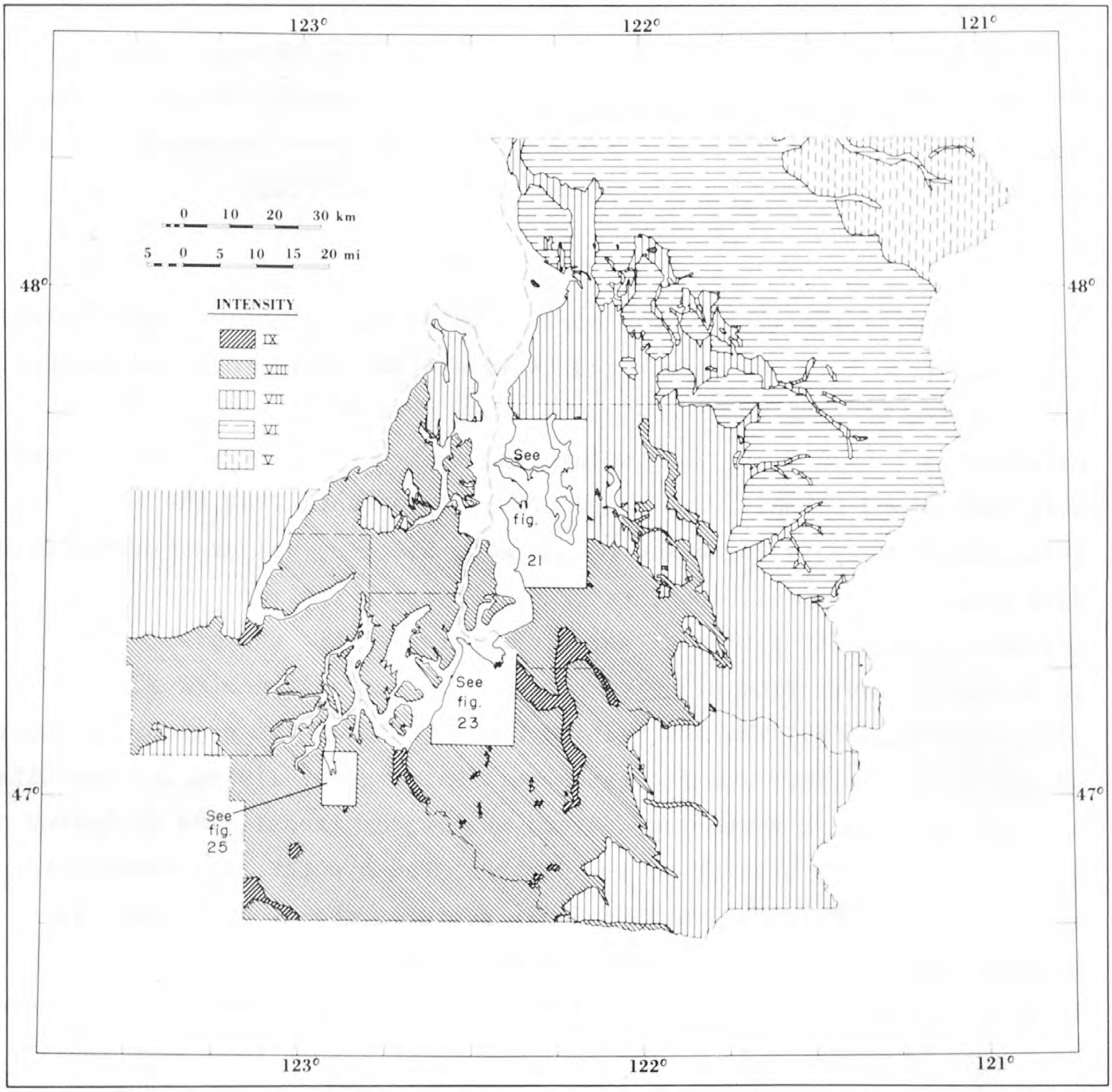


Figure 19.--Map showing estimated Modified Mercalli intensity distribution in Snohomish, King, Pierce, Thurston, Mason, and Kitsap counties for a projected earthquake of magnitude 7.5 located at 47°06' N, 122° 42' W, 50 km deep.

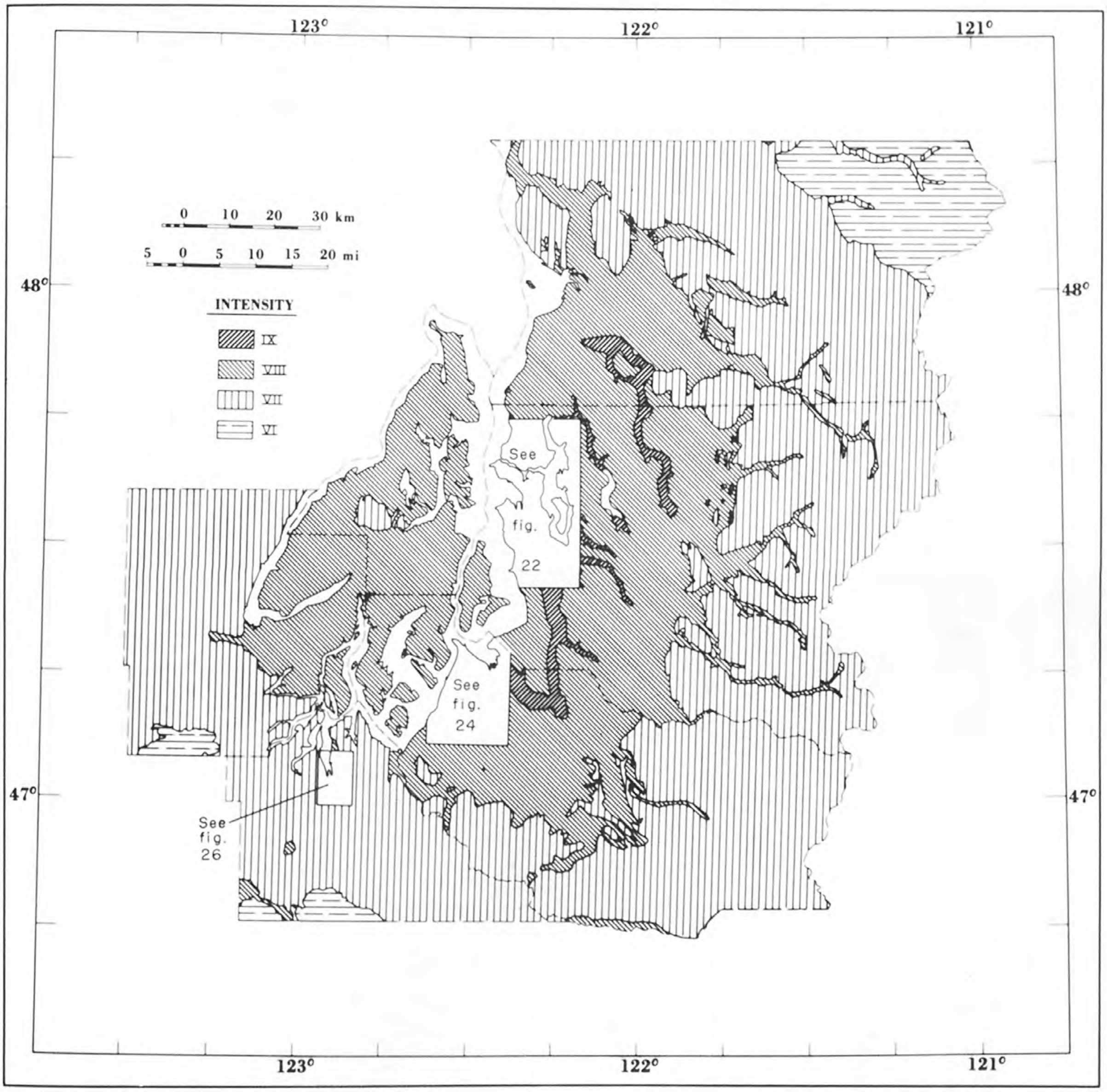


Figure 20.--Map showing estimated Modified Mercalli intensity distribution in Snohomish, King, Pierce, Thurston, Mason, and Kitsap counties for a projected earthquake of magnitude 7.5 located at 47°30'N, 122°12' W, 50 km deep.

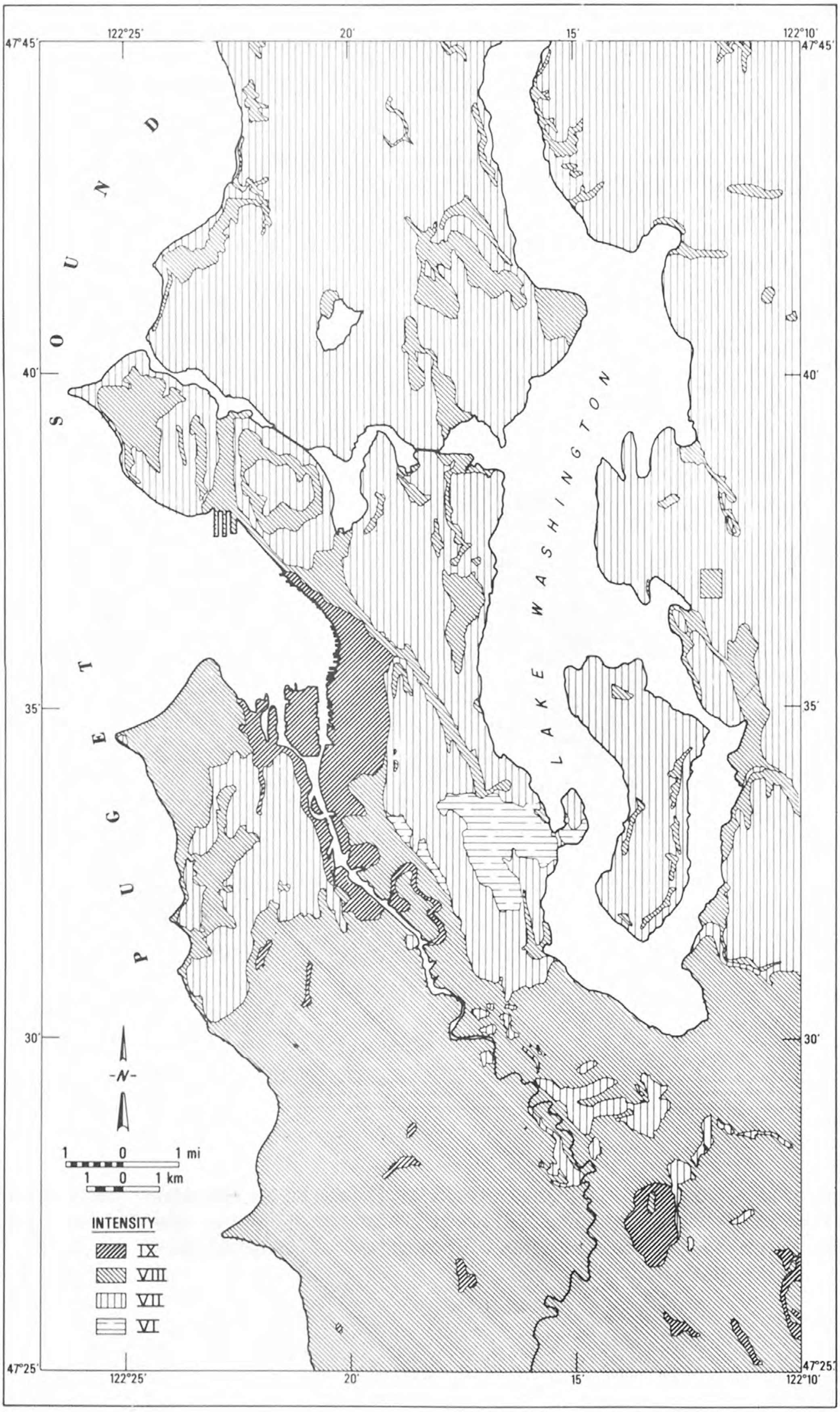


Figure 21.--Map showing estimated Modified Mercalli intensity distribution in Seattle for a projected earthquake of magnitude 7.5 located at 47°06' N, 122°42' W, 50 km deep.

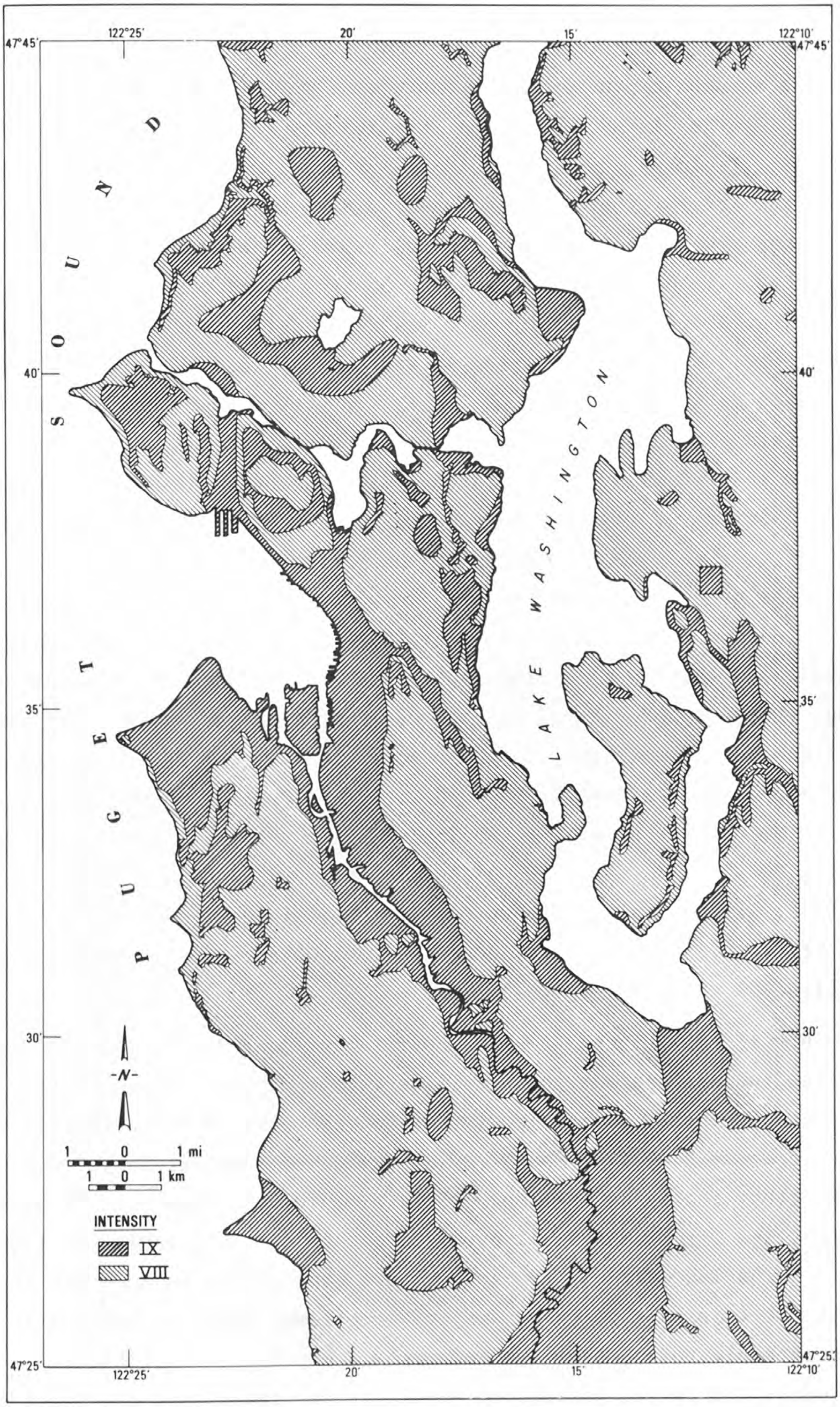


Figure 22.--Map showing estimated Modified Mercalli intensity distribution in Seattle for a projected earthquake of magnitude 7.5 located at 47°30' N, 122°12' W, 50 km deep.

for the assumed earthquake near Seattle. The geologic base map used to derive figures 21 and 22 was the "Preliminary Geologic Map of Seattle and Vicinity" (Waldron and others, 1962), at a scale of 1:31,680. At this scale the attenuation distances used for the regional map did little more than divide the map into several large areas, each of mostly one intensity. To achieve more detail, the 1949 and 1965 intensity surveys of the University of Washington were extensively used. Data obtained from these surveys were plotted on the geologic base maps. From the magnitude-intensity graph (fig. 16), it was determined that the intensity difference between the hypothetical earthquake of magnitude 7.5 and the 1949 earthquake of magnitude 7.1 was about one-half an intensity unit. Similarly, the 1965 earthquake of magnitude 6.5 had a maximum intensity a little over one intensity unit lower than the assumed shock. Thus, the plotted intensities were raised by these amounts as a first approximation to the intensity distributions of the postulated earthquakes. Further modifications took into account the same type of conditions that were considered for the regional map, such as unusual historical damage, landsliding, and high water table. One particular geologic unit mapped on the Seattle map consistently showed enough higher intensities to warrant special attention. This was the Esperance Sand Member, called "Qos" or "Older sand" on Waldron's (1962) map of Seattle. In view of this, all points on this particular geologic unit were raised one intensity unit. This correspondence had been observed earlier by Rasmussen (Mullineaux and others, 1967).

Figures 23 through 26 show the enlarged maps for Tacoma and Olympia for the two assumed earthquakes. The Tacoma map was plotted on the "Areal Geology of Central Pierce County, Washington" (Walters and Kimmel, 1968) at a scale of 1:48,300, and Olympia, on the "Geology of Thurston County, Washington" (Noble and Wallace, 1966) at 1:70,600. The maps of Seattle, Tacoma, and Olympia have all been reduced to the same scale for figures 21-26. The Tacoma and Olympia maps were constructed in much the same way as the Seattle maps, with one major exception. When the 1965 earthquake data were plotted on the Olympia geologic map and the intensities raised to correspond to the postulated shock, it was found that one large area of well-defined intensities cut across both geologic units and the ground water levels as shown on the maps of Noble and Wallace (1966).

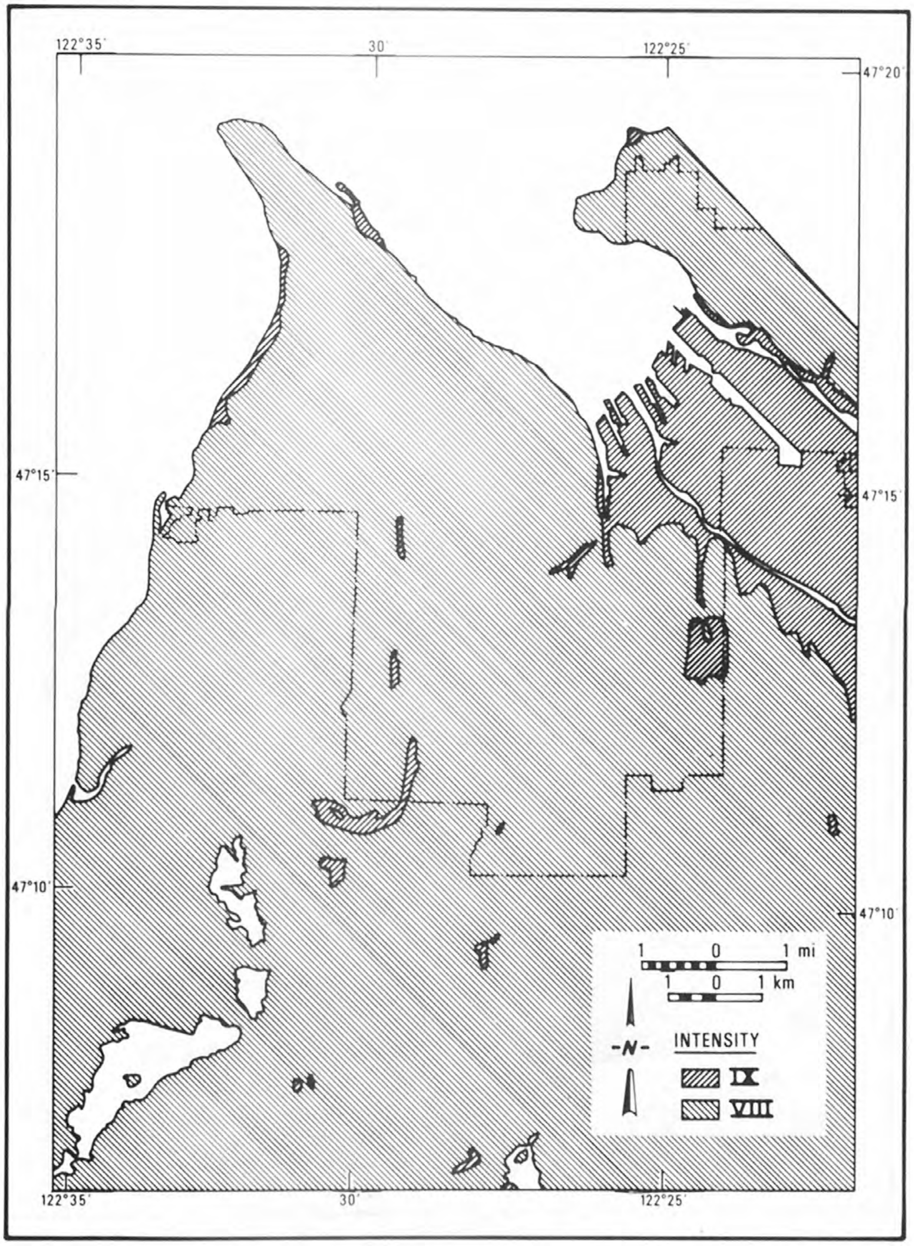


Figure 23.--Map showing estimated Modified Mercalli intensity distribution in Tacoma for a projected earthquake of magnitude 7.5 located at 47°06' N, 122°42' W, 50 km deep.

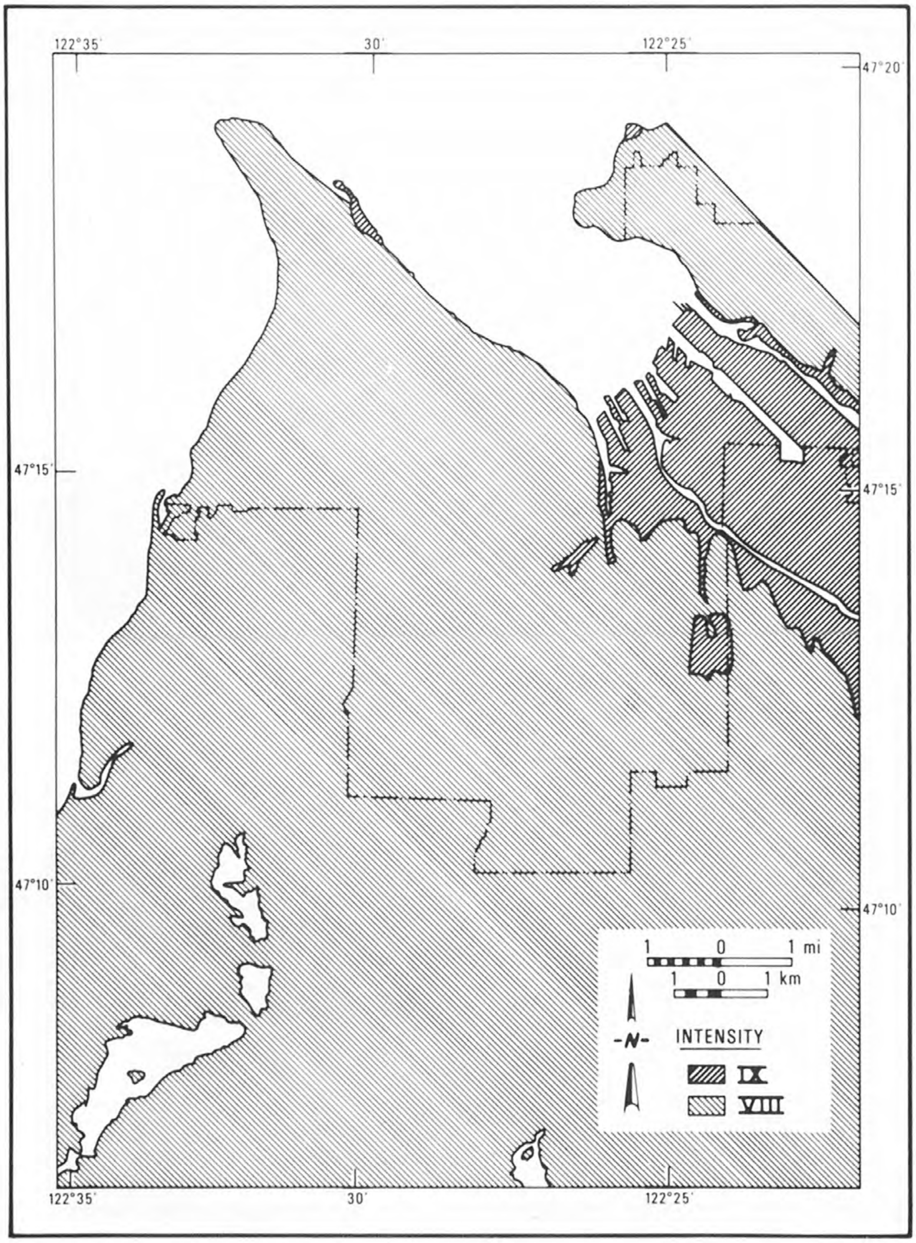


Figure 24.--Map showing estimated Modified Mercalli intensity distribution in Tacoma for a projected earthquake of magnitude 7.5 located at 47°30' N, 122°12' W, 50 km deep.

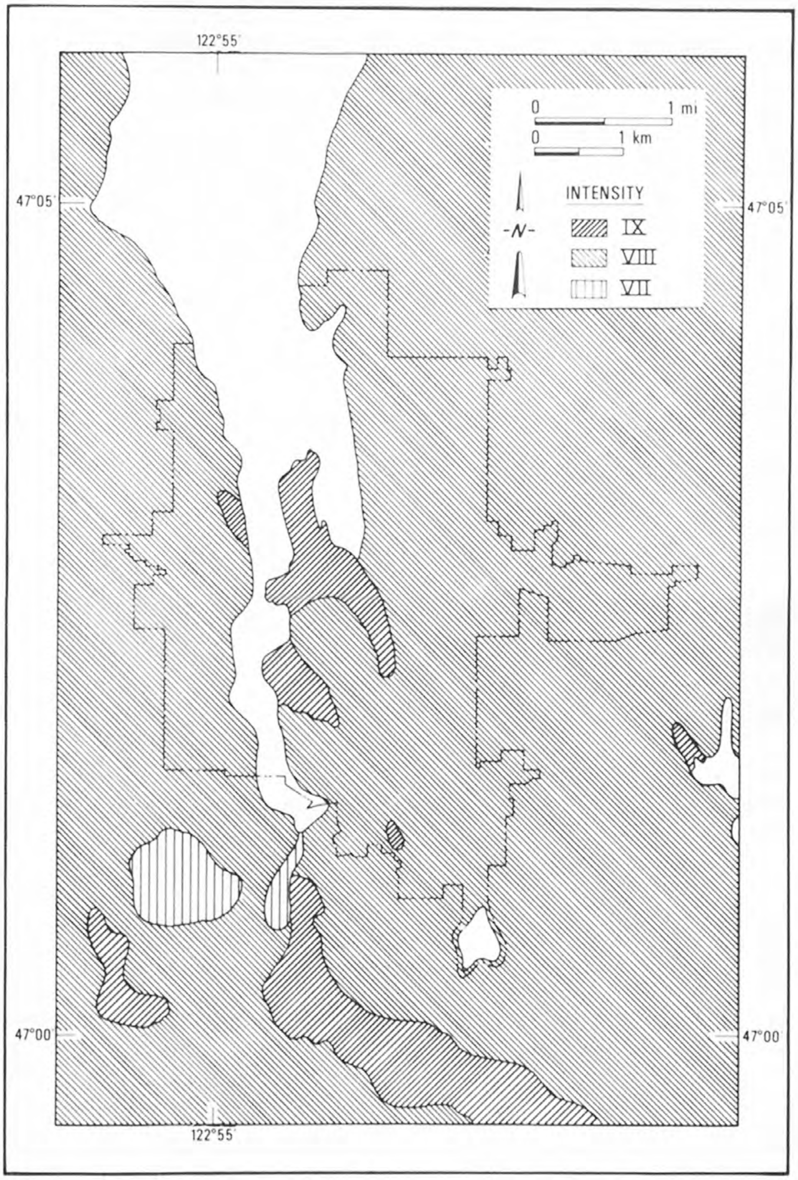


Figure 25.--Map showing estimated Modified Mercalli intensity distribution in Olympia for a projected earthquake of magnitude 7.5 located at 47°06' N, 122°42' W, 50 km deep.

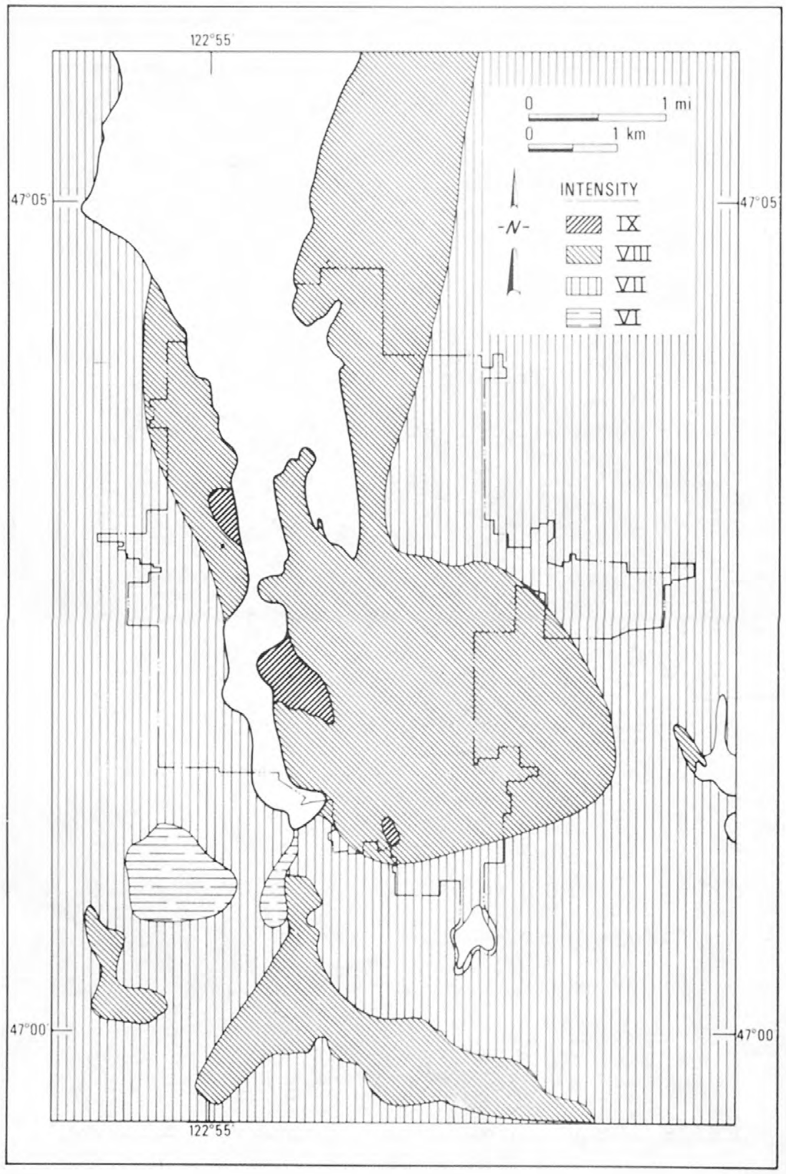


Figure 26.--Map showing estimated Modified Mercalli intensity distribution in Olympia for a projected earthquake of magnitude 7.5 located at 47°30' N, 122°12'W, 50 km deep.

For this reason, the IX and most of the VIII contours for the Olympia isoseismal map were constructed almost completely on the basis of the 1965 intensity data. This method was also employed in the derivation of the other isoseismal maps in that known areas of historically higher damage were given special consideration. The Olympia map, however, is the only one where this means was used to extensively alter an area of an isoseismal map for a projected earthquake.

Long-period effects

At distances of several hundred kilometres, great earthquakes produce seismic waves with 10- to 20-second (and longer) periods and with ground amplitudes of several centimetres. These long-period waves cause the following phenomena:

1. Marginal effects beyond the normal distance of perceptibility, such as dizziness and nausea.
2. Effects on ground and surface water, seiches, oscillations in wells.
3. Earth slides, cracks, fissures.
4. Slow swaying of tall buildings (Richter, 1958, p. 28).

Marginal effects are those described under I and II of the Modified Mercalli intensity scale (p. 284). They include experiences of dizziness or nausea by a few persons and slow swinging of doors and hanging objects. These effects are not damaging, and therefore will require no further discussion.

Effects of long-period waves on ground and surface water include oscillations in wells, earthquake fountains, and seiches. Of these, only the last is of significant interest. A seiche is a standing wave set up in an enclosed, or partially enclosed, body of water, such as a lake, pond, harbor, river, or canal. Seiches are caused by winds, currents, or tides more often than by earthquakes and occur when the dimensions of the body of water correspond to some natural period of oscillation (Richter, 1958, p. 109). Parts of the study area have experienced earthquake-induced seiches on several occasions. For example, an earthquake in 1891 (November 29) near Port Angeles generated a 2½-m disturbance in Lake Washington (Townley and Allen, 1939). Similarly, the Queen Charlotte Islands shock of 1949 (August 22) caused boats to break loose from their moorings in Seattle and produced a noticeable swell on Commencement Bay, Tacoma (Murphy and Ulrich, 1951b). Boats on Lake Union also broke away from their moorings as a result of the magnitude-8.5 Alaska earthquake of March 28, 1964 (Leipold, 1969).

The third type of long-period effect includes landslides, cracks and slumping. These cause such damage as broken water mains and pipes, road and sidewalk cracks, and foundation cracks. Slumping of foundation materials may also cause damage to structures such as bridges, piers, or buildings.

As distance increases from the epicentral area of an earthquake, the longer periods of ground motion begin to predominate. Because, in general, the natural periods of buildings increase with height, it has been observed that tall buildings frequently sustain damage even at distances of 200-300 km from great earthquakes. For example, the 1946 (June 23) earthquake in the Georgia Strait, British Columbia, caused plaster to fall in a 42-story building in Seattle, cracked walls in downtown Tacoma buildings, and cracked windows and plaster in Olympia (Bodle and Murphy, 1948).

Strong-motion instruments in Seattle have recorded an earthquake as far away as southern Alaska (July 10, 1958), showing a maximum horizontal displacement of 0.11 cm with a period of 10 seconds (Brazee and Cloud, 1960). Local earthquakes for which strong-motion records have been obtained include the 1949 (April 13) Olympia-Tacoma shock and the 1965 (April 29) Seattle shock. The 1949 earthquake produced a maximum acceleration of 321 cm/sec^2 (0.3g) and maximum displacements of 0.941 cm at Olympia and 0.246 cm at Seattle (Murphy and Ulrich, 1951b). Records of the 1965 earthquake showed a maximum acceleration of 197 cm/sec^2 (0.2g) and maximum displacements of 1.08 cm at Seattle and 1.76 cm at Tacoma (von Hake and Cloud, 1967).

Tsunamis

Tsunamis are sea waves generated by seismic activity. The waves may be induced by an earthquake of local origin, or they may arrive from a considerable distance, as from Alaska or Japan. Tsunamis of distant origin might travel across the ocean and impinge upon the coastline; however, the narrow and irregular alinement of the entry to Puget Sound would dissipate the wave effect from distant earthquakes, rendering them of limited concern.

Tsunamis generated locally would give little warning time. Tsunamis of local origin would come from (1) large-volume vertical displacements on faults located under Puget Sound, or (2) underwater landslides at unstable locations. Vertical displacement sufficient to initiate tsunami action is not historically established in this area. Both the depth of overburden and the implication of epicentral depth seem to limit the possibility of tsunamis.

Because underwater landslides are related primarily to delta areas, they could affect the seaward construction of the primary ports in the study area. Shifting of underwater masses has been recorded in the past, with some evidence of a relation to prior earthquakes. While a major submarine slide might generate considerable local disturbance, the wave action emanating from any one source would affect a rather limited portion of adjacent shoreline.

In conclusion, insufficient positive information is available to justify any numerical assessment of tsunami-related damage in Puget Sound waters.

Faulting

Because of the thick deposits of glacial materials that blanket the Puget Sound depression, little is known about faulting in the area. The largest earthquakes have occurred at subcrustal depths (50-70 km) and have exhibited no surface faulting. The spatial distribution of small earthquakes in the Puget Sound region indicates deformation over a broad volume of the crust rather than along well-defined faults (Crosson, 1972).

Gravity and geomagnetic data have been used by various authors to deduce structural features of the Puget Sound basin. Results of these studies are summarized by Rogers (1970). Rogers named five major gravity anomalies, from north to south: (1) the Marysville low, (2) the Port Gamble-Cathcart high, (3) the Seattle low, (4) the south Kitsap high, and (5) the Tacoma low (fig. 27). These are broad, flat-topped highs separated from adjacent lows by narrow bands of steep gradients consisting of linear segments with abrupt, angular bends. The geomagnetic field, though much more complex, shows a very close correspondence to the gravity field. An interpretation that fits the observed rectilinear outline of the anomalies would be either fault-bounded blocks or similar blocky units whose flanks consist of steep monoclinal flexures. Rogers inferred five areas of faulting: (1) the South Whidbey-Possession Sound-Everett fault, (2) the Kingston-Bothell fault, (3) the Seattle-Bremerton fault, (4) a possible fault along the Duwamish-Puyallup valley, and (5) the Tacoma-Gig Harbor fault.

The South Whidbey-Possession Sound-Everett fault is broken into three segments separating the Marysville low from the Port Gamble-Cathcart high. It was identified by mapping that showed an abrupt steepening of gradients. The Kingston-Bothell fault and the Seattle-Bremerton fault define the limits of the Seattle low, an east-west-trending, 26-km-wide, trenchlike feature, which is one of the largest isostatic gravity anomalies in the United States or Canada. Rogers postulated a possible fault of large displacement, with the west side upthrown and with a north-south trend along the Duwamish-Puyallup valley, citing geologic evidence as well as magnetic relief and steep gravity gradients along the east side of the south Kitsap gravity high. On the south margin of the south Kitsap block is the Tacoma-Gig Harbor fault, evidence for which includes steep gravity and magnetic gradients, temporal changes in ground level across the area, and seismic profiling of bottom sediments in Commencement Bay (Tacoma harbor), which indicates faulting since the most recent glaciation. Three of the four largest historic earthquakes located in the south part of the Puget Sound Basin have occurred on or very near the postulated structures (Rogers, 1970).

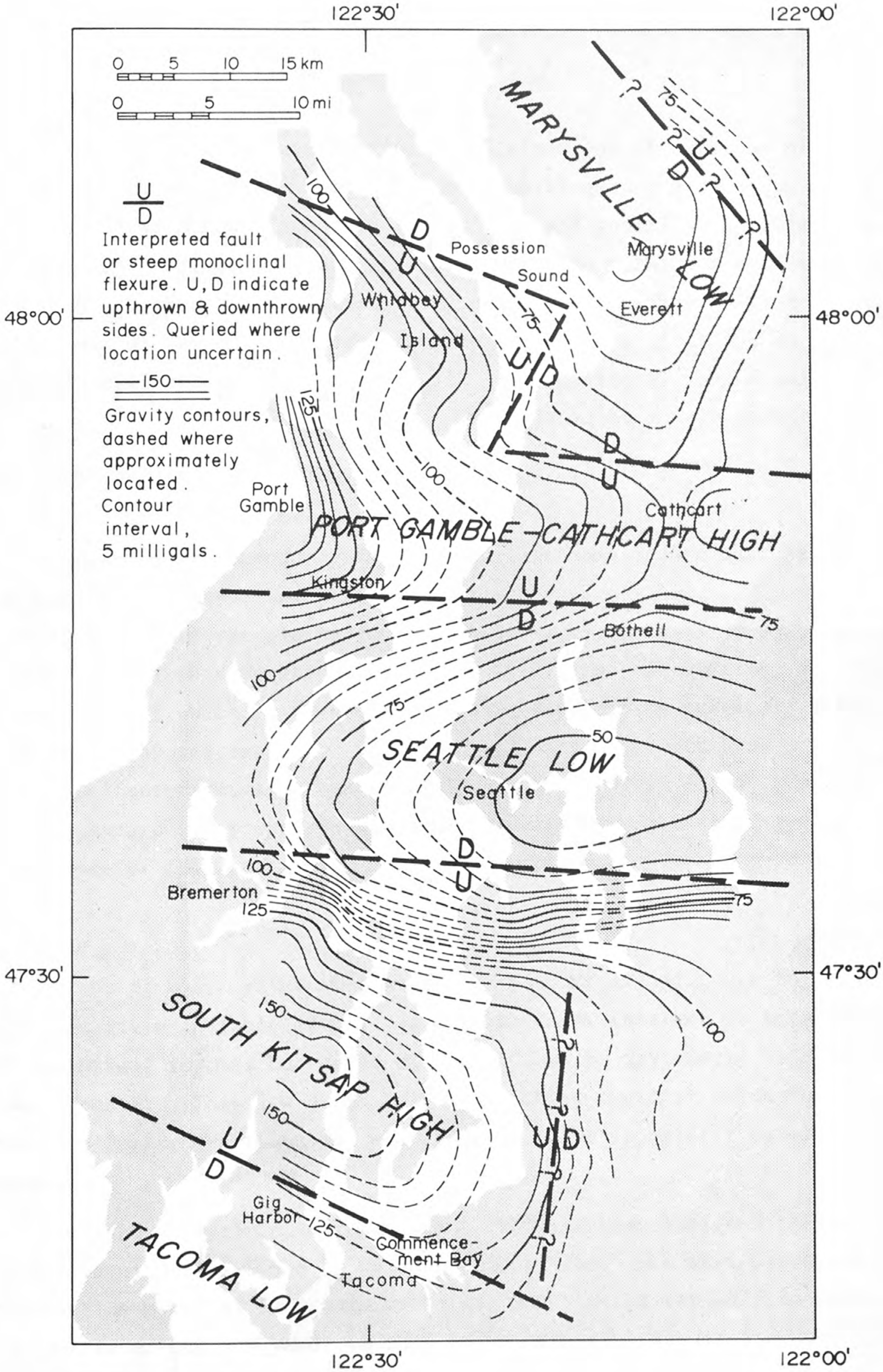


Figure 27.--Map showing structural interpretation on Bouguer gravity base. Adapted from Rogers (1970).

In addition to the postulated faults discussed above, the Puget Sound depression is separated from the Olympic Peninsula on the west by an active fault (along the Hood Canal) of about 4,000 m throw and from the Cascade Mountains on the east by the Mount Si fault. The Mount Si fault strikes north and south in the vicinity of North Bend and Sultan (east of Seattle), and perhaps extends north all the way to the Canadian border (Rogers, 1970). It was the locus of the 1939 and 1945 earthquakes discussed previously.

BASES FOR ANALYSIS

This section is a general discussion of the bases used in this report for determining the potential casualties and property damage for the two specific earthquakes chosen for study in the Puget Sound Basin. The methods vary in keeping with the importance of the particular topic and the types of data that were available for analysis in each problem area. More specific information on certain aspects of the methodology used for type of occupancy and the supporting rationale will be found in the various sections discussing particular facilities.

Studies on projected earthquake casualties and damage must be a combination of several important factors:

1. Data from relevant earthquakes;
2. Theoretical considerations, both scientific and engineering;
3. Experience, which must be tempered with engineering judgment; and
4. Time of day and season of year when the earthquake strikes.

These four factors must be contained in any methodology for determining the life-hazard and property-damage potentials; they are discussed in the balance of this section.

Data from relevant earthquakes

A list of U.S. earthquakes having particular significance to this report is given in table 14. It is of particular interest to note that the death toll to date has never exceeded 1,000 in any single U.S. earthquake disaster. This low death toll is in sharp contrast to death tolls from some foreign earthquakes, and it is of value to briefly examine this contrast.

The Agadir, Morocco, earthquake of 1960 has been assigned the moderate Richter magnitude of 5.5-6 by various authorities. The most prevalent construction material in Agadir was older masonry; it varied from stone, with mortar of mud and sand, to more modern construction of stone or clay tile, with mortar ranging from weak mud-sand to good quality sand cement.

None of the masonry was reinforced. The second most prevalent type of construction was usually a very poor quality reinforced concrete that had not been designed to resist earthquake forces. In other words, Agadir was a "disaster waiting to occur," and the estimated 12,000 deaths and 12,000 injured out of a population of about 33,000 are quite understandable considering that the buildings collapsed due to ground shaking.

The heaviest ground shaking at Agadir most likely did not exceed that experienced in the most heavily shaken areas of the 1971 San Fernando shock. Many other foreign examples could be cited; in almost all cases the masonry would be of extremely poor quality, and construction would be completely different from American practice.

The foregoing example involved ground shaking and not geologic hazards. The May 31, 1970, Peruvian earthquake may be cited as an example of large life loss due to a special geologic hazard. The single, most devastating event was the large debris avalanche that originated from the north peak of Huascaran; it fell 12,000 feet and traveled 7 miles at an average speed of 200 miles an hour, destroying the village of Yungay, among others. This debris slide took a toll of about 25,000-30,000 lives. Clearly, this life loss was related to a special geologic hazard, and it was of a type that could have been identified before the event.

The two foregoing examples make it readily evident that earthquake data used for the purposes of this report must be founded on information from earthquakes affecting comparable construction and comparable geologic hazards. These data are best obtained from a study of U.S. earthquakes plus a few selected foreign earthquakes, such as the 1972 Managua (Nicaragua), 1967 Caracas (Venezuela), and 1960 Chilean earthquakes.

It is far beyond the report's scope and space allotment to review in detail the life-loss and property-damage data contained in studies of past American earthquakes. The bibliography to this report lists the important reports and papers used for this study. It is, however, appropriate to briefly review those data that are of particular significance to this study.

San Fernando earthquake of February 9, 1971

The 1971 San Fernando earthquake has been extensively studied by many authorities. Far better data on life-loss, injuries, and property damage are available for this disaster than for any other American earthquake. The recency of this disaster and the continuing interest in it warrant more than cursory attention. The most important sources of relevant data in press or in print that are known to the authors are the volumes published by NOAA (National Oceanic and Atmospheric Administration,) 1973.

The following is quoted from "Earthquake Damage and Related Statistics" by Steinbrugge and Schader (1973, p.691):

> The Los Angeles County Coroner's Office reported 58 deaths (table 15) directly attributable to the February 9th earthquake out of a current County population of 7,032,000. San Fernando Valley immediately claimed 41 lives; 6 died later as a result of injuries sustained. This was the largest life loss at one location incident to the earthquake. Three deaths occurred at the Olive View Hospital; one due to falling building materials, and the remaining 2 when life supporting power supplies failed. One death occurred in the roof collapse of the old brick masonry Midnight Mission (a charitable facility) located in downtown Los Angeles. If the shock had occurred minutes before, the death toll would have been greatly increased when the upper dormitory area had been fully occupied. The one death occurred when reportedly an occupant had left the building, but was standing in front of it. A collapsing freeway bridge in the heavily shaken area of San Fernando Valley killed two persons when their truck was trapped under a fallen span. One person died from injuries resulting in a fall from the freeway. Four deaths occurred in dwellings. Heart attacks reportedly took 9 lives; however, the County Coroner's report does not list these.
>
> Information on injuries and other earthquake related emergency cases was compiled by the Hospital Council of Southern California. The information in this paragraph and in table 16 is based on their compilation. A total of 127 hospitals responded to their survey with results as shown in table 17. In addition, the Red Cross treated minor injuries for more than 3,000 persons. Thus, one may conclude that the reported injuries and related problems exceeded 5,000, and that thousands of minor self-treated injuries remained unreported.

TABLE 14.--SELECTED U.S. EARTHQUAKES, 1811-1972

Name of Earthquake	Date and (local) Time	[1] Epicenter Location	[2] Maximum Modified Mercalli Intensity	[1] Richter Magnitude	Approximate Length of Surface Faulting (miles)	[3] Lives Lost	[4] Dollar Loss	Remarks
New Madrid, Missouri	Dec. 16, 1811 (about 2:15 AM) Jan. 23, 1812 (about 8:50 AM) Feb. 7, 1812 (about 10:10 AM)	36 N, 90 W	XII (for each shock)	Over 8	See remarks	1 death	---	Richter assigned a magnitude of greater than 8 based on observed effects. Surface faulting possibly occurred: see Fuller, p. 58 (Bibliography).
Charleston, S. Carolina	Aug. 31, 1886 (9:51 PM)	32.9 N, 80.0 W	X	---	None	27 killed outright, plus 83 or more from related causes.	$5,000,000 to $6,000,000	---
San Francisco Calif.	Apr. 18, 1906 (5:12 AM, PST)	38 N, 123 W	XI	8.3	190 minimum 270 possible	700 to 800 deaths.	$400,000,000 incl. fire; $80,000,000 earthquake only.	Portions of the San Andreas fault are under the Pacific Ocean.
Santa Barbara, Calif.	June 29, 1925 (6:42 AM)	34.3 N, 119.8 W	VIII-IX	6.3	None	12 to 14 deaths.	$6,500,000	The dollar loss is for the City of Santa Barbara: losses elsewhere were slight.
Long Beach, Calif.	Mar. 10, 1933 (5:54 PM, PST)	33.6 N, 118.0 W	IX	6.3	---	Coroner's report: 86. 102 killed is more probable.	$40,000,000 to $50,000,000	Epicenter in ocean. Associated with Inglewood fault.
Helena, Montana	Oct. 12, 1935 (0:51 AM, MST)	46.6 N, 112.0 W	VII	---	None	---	$50,000	First of three destructive shocks: Oct. 12, 18, and 31.
Helena, Montana	Oct. 18, 1935 (9:48 PM, MST)	46.6 N, 112.0 W	VIII	6.25	None	2 killed, "score" injured.	$3,000,000 to over $4,000,000	---
Helena, Montana	Oct. 31, 1935 (11:38 AM, MST)	46.6 N, 112.0 W	VIII	6.0	None	2 killed, "score" injured.		---
Imperial Valley, Calif.	May 18, 1940 (8:37 PM, PST)	32.7 N 115.5 W	X	7.1	40 minimum	8 killed outright, 1 died later of injuries.	$5,000,000 to $6,000,000	M. M. IX for building damage and M. M. X for faulting.
Santa Barbara, Calif.	June 30, 1941 (11:51 PM, PST)	34.4 N, 119.6 W	VIII	5.9	---	None killed, 1 hospitalized.	$250,000	Epicenter in ocean.
Olympia, Washington	Apr. 13, 1949 (11:56 AM, PST)	47.1 N, 122.7 W	VIII	7.1	None	8 deaths	$15,000,000 to $25,000,000	---
Kern County, Calif.	July 21, 1952 (4:52 AM, PDT)	35.0 N, 119.0 W	XI	7.7	14	10 of 12 deaths in Tehachapi	$37,650,000 to buildings $48,650,000 total. (incl. Aug. 22 aftershock).	M. M. XI assigned to tunnel damage from faulting: vibration intensity to structures generally VIII, rarely IX. Faulting probably longer, but covered by deep alluvium.
Bakersfield, Calif.	Aug. 22, 1952 (3:41 PM, PDT)	35.3 N, 118.9 W	VIII	5.8	None	2 killed and 35 injured in Bakersfield.	See above.	Aftershock of July 21, 1952.
Fallon-Stillwater, Nev.	July 6, 1954 (4:13 AM, PDT)	39.4 N 118.5 W	IX	6.6	11	No deaths, several injuries.	$500,000 to $700,000, incl. $300,000 to irrigation system.	M. M. IX assigned along fault trace: vibration intensity VIII. First of two shocks on same fault.
Fallon-Stillwater, Nev.	Aug. 23, 1954 (10:52 PM, PDT)	39.6 N 118.5 W	IX	6.8	19	No deaths.		M. M. IX assigned along fault trace: vibration intensity VIII. Second of two shocks on same fault.

Fairview Peak, Nevada	Dec. 16, 1954 (3:07 AM, PST)	39. 3 N, 118. 1 W	X	7. 1	35	No deaths.	---	M. M. X assigned along fault trace; vibration intensity VII. Two shocks considered as a single event from the engineering standpoint.
Dixie Valley, Nevada	Dec. 16, 1954 (3:11 AM, PST)	39. 8 N, 118. 1 W	X	6. 8	30	No deaths.	---	
Eureka, Calif.	Dec. 21, 1954 (11:56 AM, PST)	40. 8 N, 124. 1 W	VII	6. 6	None	1 killed	$1,000,000	---
Port Hueneme, Calif.	Mar. 18, 1957 (10:56 AM, PST)	34. 1 N, 119. 2 W	VI	4. 7	None	No deaths.	---	Epicenter in ocean.
San Francisco, Calif.	Mar. 22, 1957 (11:44 AM, PST)	37. 7 N, 122. 5 W	VII	5. 3	None	No deaths, about 40 minor injuries.	$1,000,000	---
Hebgen Lake, Montana	Aug. 17, 1959 (11:37 PM, MST)	44. 8 N, 111. 1 W	X	7. 1	14	19 presumed buried by landslide, plus probably 9 others killed, mostly by landslide.	$2,334,000 (roads and bridges) $150,000 (Hebgen Dam) $1,715,000 (landslide correction)	M. M. X assigned along fault trace. Vibrational intensity was VIII maximum. Faulting complex, and regional warping occurred. Dollar loss to buildings relatively small.
Prince William Sound, Alaska	Mar. 27, 1964 (5:36 PM, AST)	61. 1 N, 147. 5 W	---	8. 4	400 to 500	110 killed by tsunami; 15 killed from all other causes.	$311,192,000 (incl. tsunami)	Also known as the "Good Friday Earthquake". Fault length derived from seismic data.
Puget Sound, Washington	Apr. 29, 1965 (8:29 AM, PDT)	47. 4 N, 122. 3 W	VIII	6. 5	None	3 killed outright, 3 died from heart attacks.	$12,500,000	M. M. VII general, M. M. VIII rare.
Parkfield, Calif.	June 27, 1966 (9:26 PM, PDT)	35. 54 N, 120. 54 W	VII	5. 5	23½ and 5½	No deaths.	Less than $50,000	Damaging earthquakes in same area in 1901, 1922, and 1934. The 1966 shock had peak accel eration of 50% G.
Santa Rosa, Calif.	Oct. 1, 1969 (9:57 PM, PDT)	38. 47 N, 122. 69 W	VII-VIII	5. 6	None	No deaths. 15 injuries. 1 heart attack.	$6,000,000 to buildings. $1,250,000 to contents.	Two shocks considered as a single event from the engineering standpoint.
Santa Rosa, Calif.	Oct. 1, 1969 (11:20 PM, PDT)	38. 45 N, 122. 69 W		5. 7	None			
San Fernando, Calif.	Feb. 9, 1971 (6:01 AM, PST)	34. 40 N, 118. 40 W	VIII-IX	6. 6	12	58 deaths. 5,000 reported injuries.	$478,519,635	Many reported injuries were minor, but public or charitable services requested.

ABBREVIATIONS:

- M. M. = Modified Mercalli Intensity
- PST = Pacific Standard Time
- PDT = Pacific Daylight Time (Subtract 1 hour for Pacific Standard Time)
- MST = Mountain Standard Time
- AST = Alaska Standard Time

FOOTNOTES:

[1] Slight variations will be found in various publications.

[2] M. M. Intensities are those assigned by the U. S. Coast & Geodetic Survey (now NOAA) when available.

[3] Original sources do not always clearly indicate if deaths include those attributable to exposure, unattended injury, heart attacks, and other non-immediate deaths.

[4] Value of dollar at time of earthquake. Use of these figures requires a critical examination of reference materials since the basis for the estimates vary.

TABLE 15.--LIFE LOSS, SAN FERNANDO EARTHQUAKE

(From Los Angeles County Coroner's Records)

Olive View Hospital		3
Patients	2	
Employees	1	
San Fernando Veterans Administration Hospital		41
Patients	31	
Employees	10	
Victims from Veterans Administration Hospital whose deaths occurred at other hospitals		6
Deaths from residences		4
Deaths from collapse of freeway overpass		2
Death in fall from freeway overpass		1
Death from collapsing wall		1
Total		58

Note: Deaths from reported heart attacks or natural causes attributed to the earthquake are not included.

TABLE 16.--INJURIES AND RELATED PROBLEMS, SAN FERNANDO EARTHQUAKE

(From Hospital Council of Southern California records,)
(April, 1971, 127 hospitals reporting)

Date	Outpatients treated	Inpatients admitted	Total
Feb. 9	1,524	161	1,685
Feb. 10	437	30	467
Feb. 11	367	24	391
Totals	2,328	215	2,543

Outpatient injuries or problems (in percent)		Inpatient or injured, excluding transfers (in percent)	
Lacerations	44	Fractures	26
Fractures or related	18	Cardiac	19
Emotional reaction	9	Head injuries	12
Contusions	8	Psychiatric	12
Cardiac	6	Burns	7
Remainder	15	Remainder	24

TABLE 17.--DAMAGE TO HOSPITALS IN SAN FERNANDO VALLEY, 1971

(Data compiled by Pacific Fire Rating Bureau)

	Facilities and Services										Earthquake Damage and Losses								
				Licensed Bed Use 3/							Est.Repl.Value, Bldg. & Equip	Dollar Loss		Bed	Shut-Down		Start-Up		
Location - City	Owner-ship 1/	Year 2/ Founded	Pre-Eq. Licensed Bed-Capac.	A.C.	Mat.	Ped.	Psy.	R-C	E.C.	Other	($ Millions)	Building	Equipment	Loss	Date	Time	Date	Time	Remarks
1 Burbank	N.P.	1905	115	108	7	---	---	---	---	---	2.0	0	0	0	----	----	----	----	-------
2 Burbank	N.F.	1944	370	324	23	23	---	---	---	---	11.0	--------	---------	0	----	----	----	----	-------
3 Canoga Park	Prop.	1968	72	---	---	---	---	---	---	---	2.2	2,000	1,000	0	----	----	----	----	-------
4 Canoga Park	Prop.	1958	112	108	---	4	---	---	---	---	2.0	0	0	0	----	----	----	----	-------
5 Canoga Park	Prop.	1962	116	116	---	---	---	---	---	---	2.0	0	0	0	----	----	----	----	-------
6 Canoga Park	Prop.	1962	80	64	13	3	---	---	---	---	2.75	50,000	(combined---)	0	----	----	----	----	-------
7 Encino	Prop.	1954	189	144	---	18	---	---	---	17	6.6	0	0	0	----	----	----	----	-------
8 Encino	N.P.	1955	152	104	34	14	---	---	---	---	2.1	0	0	0	----	----	----	----	-------
9 Glendale	N.P.	1947	98	84	14	---	---	---	---	---	3.0	0	0	0	----	----	----	----	-------
10 Glendale	N.P.	1905	380	252	27	17	60	24	---	---	11.4	--------	---------	0	----	----	----	----	-------
11 Glendale	N.P.	1954	152	---	---	---	---	---	---	---	5.3	--------	---------	0	----	----	----	----	-------
12 Glendale	N.P.	1926	310	270	28	12	---	---	---	---	10.9	20,000	0	0	----	----	----	----	-------
13 Glendale	Prop.	1955	31	27	4	---	---	---	---	---	0.9	0	0	0	----	----	----	----	-------
14 Glendale	----	----	22	---	---	---	---	---	---	---	0.66	0	0	0	----	----	----	----	-------
15 Granada Hills	N.P.	1966	201	169	16	16	---	---	---	---	6.0	5,000	0	0	----	----	----	----	-------
16 North Hollywood	Prop.	1969	73	59	8	6	---	---	---	---	2.2	0	0	0	----	----	----	----	-------
17 North Hollywood	Prop.	1952	84	84	---	---	---	---	---	---	2.5	5,000	5,000	0	----	----	----	----	-------
18 Northridge	N.P.	1955	206	134	13	28	11	20	---	---	6.0	300,000	55,000	0	----	----	----	----	-------
19 Olive View	L.A.Co.	1920	888	120	(post EQ)		100	---	---	25		--------	---------	643	2/9/71	10 A.M.	9/71	----	1,5 (OV)
a. Medical Treatment and Care Bldg.,			---	---	---	---	---	---	---	---	25.0	25,000,000	---------	---	----	----	----	----	-------
b. Psychiatric Bldg.,		----	---	---	---	---	---	---	---	---	6.0	6,000,000	---------	---	----	----	----	----	-------
c. Central Heating Plant		----	---	---	---	---	---	---	---	---	1.5	375,000	---------	---	----	----	----	----	-------
20 Pacoima	N.P.	1957	110	82	---	---	28	---	---	---	4.75	6,000,000	(combined--)	110	2/9/71	6 A.M.	3/2/71	----	5 (PL)
21 Panorama City	N.P.	1962	321	202	41	32	---	---	46	---	9.1	250,000	(combined--)	0	----	----	----	----	-------
22 Panorama City	----	----	96	---	---	---	---	---	---	---	3.0	--------	---------	---	----	----	----	----	-------
23 San Fernando	N.P.	1961	259	---	---	---	---	---	---	---	9.0	4,000,000	1,000,000	209	2/9/71	3 P.M.	3/72	(tent)	2,5 (HC)
24 San Fernando	Prop.	1922	69	69	---	---	---	---	---	---	1.4	1,000	1,000	0	----	----	----	----	-------
25 Sepulveda	F.G.	1955	906	385	---	---	341	80	---	100	30.0	900,000	(combined--)	0	----	----	----	----	-------
26 Sherman Oaks	Prop.	1959	160	148	---	12	---	---	---	---	4.8	0	0	0	----	----	----	----	-------
27 Sun Valley	Prop.	1967	111	99	12	---	---	---	---	---	4.0	1,000	0	0	----	----	----	----	-------
28 Sylmar	F.G.	1926	365	---	---	---	---	---	---	---	15.0	10,000,000	(combined--)	365	2/9/71	6 A.M.	----	----	5 (VET)
29 Van Nuys	----	----	113	---	---	---	---	---	---	---	3.0	500	0	0	----	----	----	----	-------
30 Van Nuys	Prop.	1929	66	66	---	---	---	---	---	---	2.0	0	0	0	----	----	----	----	-------
31 Van Nuys	N.P.	1958	281	235	28	18	---	---	---	---	18.0	70,000	5,000	0	----	----	----	----	-------
32 Van Nuys	N.P.	1964	63	---	---	---	---	---	---	---	2.0	0	0	0	----	----	----	----	-------
33 Woodland Hills	N.P.	1921	--180	73	---	---	10	---	97	---	5.0	0	0	0	----	----	----	----	-------
			6,652								223.06	52,078,500	1,067,000	1,327					

1/ N.P. - Non-Profit; Prop. - Proprietary; L.A.Co. - L.A. County; F.G.-Federal Govt.
2/ All structures on site not necessarily erected this date.
3/ A.C. - AcuteGeneral; Ped. - Pediatrics; R-C - Rehab.-Convalescent
Mat. - Maternity; Psy. - Psychiatric; E.C. - Extended Care

REMARKS:
1. Hospital not operating at licensed capacity.
2. In-patient facilities temporarily closed.
3. Only hospital functioning within 5 mile radius after earthquake
4. Cottage style (58 occupancy) on grounds.
5. OV-Olive View; PL-Pacoima Lutheran; HC-Holy Cross; VET-Veterans

NOTE:
Where replacement values were unknown a value of $20,000 to $35,000 per bed was used.

In table 16, it is important to note that emotional reactions and cardiac problems existed. The psychological aspects of earthquakes have not been adequately studied. Additionally, 3 of the 4 greatest problem areas were related to pre-earthquake engineering and/or planning, and not directly to any medical deficiencies.

The resources of metropolitan Los Angeles were more than adequate for housing and feeding the displaced persons, and the large majority of persons having these problems were able to take care of their own needs. Despite the foregoing, one relief agency (The American National Red Cross) reported for the period of February 9 through March 5, 1971, that they fed and housed 17,000 persons at 10 public schools used as shelters. About 175,000 meals were served by the Red Cross (66,500 in shelters which also housed refugees plus 108,600 at mass feeding locations). The availability of undamaged earthquake resistive Field Act schools (schools designed to be earthquake resistive) greatly facilitated the emergency housing and feeding, and this type of facility is an important consideration in earthquake disaster planning.

(end of quotation)

Much additional text and tabular information exist in the aforementioned paper, particularly for dwellings, light industrial buildings, and hospitals; the information on hospitals is presented in this report as table 17. The paper clearly noted that earthquake resistive buildings performed much better than those which were not designed to be earthquake resistive. Comparable construction, both old and recent, in the Puget Sound Basin makes this data significant.

Olympia, Washington, earthquake of April 13, 1949

The Olympia, Washington, earthquake of April 13, 1949, had a felt area of 150,000 square miles (388,500 km^2), and a Richter magnitude of 7.1, which was the same magnitude as that of the El Centro shock of May, 1940, and greater at that time than any other shock felt in the United States since the San Francisco earthquake of 1906. Table 18 shows the history of other earthquakes in the Puget Sound area in recent years.

TABLE 18.--RECENT SIGNIFICANT EARTHQUAKES IN THE PUGET SOUND AREA.

Date	Location	Felt Area (Mi^2)	Modified Mercalli Intensity	Remarks
November 12, 1939	Few miles north-west of Olympia	60,000	VII	Felt over most of Washington and north-west Oregon.
April 29, 1945	Southwest of Seattle	50,000	VII	Felt over most of Washington, north Oregon, west Idaho.
February 14, 1946	About 20 miles west of Tacoma	70,000	VII	Felt over most of Washington, north-west Oregon, and southwest British Columbia.
June 23, 1946	Campbell River, B. C.	100,000	VIII	Considerable damage to sections of Victoria resting on poor foundations.
April 13, 1949	Near Olympia	150,000	VIII	Strongest shock in the study area. Felt over broad area, western Washington, northwest Oregon.
April 29, 1965	Southeast of Seattle	130,000	VIII	Epicenter adjacent to urban area.

Only two accelerograph records, one from Olympia and one from Seattle, were available to indicate the violence and duration of the 1949 Olympia earthquake, and the seismograph at the University of Washington was thrown off the scale during the most violent phase of the earthquake, giving information of doubtful value. The earthquake originated at a point forty-three miles (70 km) in depth, and southeast of Olympia, Washington. The destructive phase continued for less than one minute, although there are reports of continued shaking lasting for several minutes. The high-amplitude portions of the accelerographs, both in the Seattle and

Olympia records, extend for a period of approximately twenty-five seconds. The earthquake was classified as intensity VIII on the Modified Mercalli scale through a zone extending along Puget Sound from Everett in the north to Olympia, and continuing along the Puget Sound trough to Longview in the south. It is interesting that the subjective classification of Modified Mercalli Intensity did not exceed VIII in this earthquake, although it exhibited a Richter magnitude of 7.1, whereas in the Long Beach earthquake of 1933 the Modified Mercalli Intensity was reported to reach IX, although the Richter magnitude of the earthquake was only 6.3. This might appear inconsistent, but it must also be viewed in light of a variation in depth of hypocenter and in the geologic makeup of the different locations subjected to earth shaking. Similarly, construction types, population and construction class and density, and the immediate nature of foundation material all create variables making assessment of actual significance difficult.

In spite of the fact that Seattle, the major urban area in the earthquake felt zone, was approximately 80 miles (128 km) from the epicenter, there was substantial building damage. Damage by class of construction followed the patterns which have developed in the evaluation of prior disasters. Structures having walls of brick masonry with sand-lime mortar, and wood floors and roofs lacking adequate wall anchorage suffered severely. Extensive damage was experienced in structures in downtown Seattle in the vicinity of Pioneer Square. Most of these had been built about 1890 or soon thereafter, using inferior quality brick cemented together with weak mortar, and having framing frequently lacking in anchorage to floor and roof joists. Much damage also occurred in the industrial area along the Duwamish River and adjacent to the East Waterway where the ground is principally hydraulic fill.

Multistory building damage was relatively limited, although in the cases of structures having tile interior partitions, as well as of some having brick or tile exterior wall panels, nonstructural damage was incurred. The pounding damage between multistory buildings was common throughout the business district, even though fundamental structural damage to the individual buildings did not occur or was limited.

Several emergency water supply tanks, mounted on towers on building roofs, were toppled. The use of such water reservoirs for emergency purposes has subsequently been abandoned.

Wood-frame residences were relatively free of damage. Many of the residences, however, included unreinforced brick fireplaces, and the amount of damage to stacks projecting above roofs was quite high, particularly in portions of the West Seattle residential area.

Fire did not follow the earthquake disaster, although some service mains in the industrial area of Seattle were broken, and in Tacoma a 60-inch diameter line at the city's reservoir was broken and cut off. Water was available at all times for firefighting purposes in Seattle and in Tacoma.

Numerous problems with bridge structures were encountered. Bascule bridges and lift bridges were made inoperable and, as a result, for several days water traffic was limited to smaller craft able to pass under the bridges in their closed positions. Railroad lift bridges, which are normally left in their open positions, could not be properly closed, and delay ensued while corrective steps were taken.

One major landslide occurred three days subsequent to the earthquake in the Tacoma area. It fortunately caused no property damage or loss of life, although the extensive existence of bluff conditions along the Puget Sound shoreline, together with renewed slide problems, served as a warning of future potentials for major landslides in the area.

In the capital city of Olympia, damage in the industrial and commercial area was severe in old masonry and brick-veneer structures. A large portion of the industrial area is on made land extending out into Puget Sound and this area settled approximately five inches. The State Capitol campus is located on higher ground south of the business district and was not subjected to settlement problems. At the same time, many of the Capitol campus buildings were damaged. The old structures are generally brick buildings with stone facing, having little lateral-load-resisting capability and lacking any well-planned or executed system of bracing and ties. Serious utility problems were experienced, resulting from many breaks in Olympia water mains. The hazard was aggravated by serious gasoline and fuel oil pipeline breaks, to such an extent that the business district was temporarily closed.

Prince William Sound, Alaska, earthquake of March 27, 1964

The Prince William Sound, Alaska, earthquake ("Good Friday" earthquake) is important for the usable data on modern earthquake-resistive construction and its effect on reducing casualties. Tsunami (seismic sea wave) resulted in 110 deaths; only 15 died from other causes including building collapses.

Modern precast concrete performed poorly when compared with other construction materials; undoubtedly similar problems will occur in Puget Sound on a much greater scale in the event of the maximum credible earthquake. Multistory building damage in Anchorage is given in summary form in table 19.

This 8.4 Richter magnitude earthquake was a slightly greater shock than the 1906 San Francisco shock with its magnitude of 8.3; both shocks are greater than the magnitudes to be considered in this report. It follows, then, that the data from the 1964 Alaska shock are representative of the upper limit damage under similar epicentral distances and similar geologic environments for similar construction.

Puget Sound, Washington, earthquake of April 29, 1965

The Puget Sound earthquake of April 29, 1965, had a felt area of 130,000 square miles (336,700 km^2) and a Richter magnitude of 6.5. There were some limited areas in which the maximum intensity was VIII; however, the general intensity over most of the area of substantial damage was VII. The focal depth of the earthquake was about thirty-seven miles (59 km), comparable to that experienced in 1949, and in this event was well-documented from many stations.

Damage surveys indicate that the 1949 earthquake was more destructive. The damage pattern was quite similar for the two occurrences, and because the 1965 epicenter was substantially closer to Seattle, the major urban center, there was less opportunity for attenuation of high frequency impulses generally affecting short-period structures.

TABLE 19.--DAMAGE TO MULTISTORY BUILDINGS IN ANCHORAGE, ALASKA, 1964 (Source: The Prince William Sound, Alaska Earthquake of 1964 and Aftershocks (Leipold, 1969)

Building name and occupancy	Year built	Stories	UBC seismic zone	Structural system: Frame	Floors	Exterior walls	Core	Principal lateral force bracing system	Percent damage (of replacement value)	Remarks
Airport Control Tower	1952	6 and basement	?	R/C	5 and 6 inches R/C	Insulated metal	None	R/C frame	100	Also damaged in 1954 shock.
Anchorage-Westward (hotel)	1960, 1964	14 and basement	3	Steel, with some R/C columns	5½ to 6½ inches R/C on MD on steel beams	Insulated metal and R/C	See remarks	R/C shear walls	12	Landslide shifted building about 1 foot. R/C around elevators not a major core.
Cordova (office)	1960	6 and basement	2 (?)	Steel	2½ inches R/C on MD on steel joists and beams	Insulated metal and 4 inches R/C	R/C	Steel moment connections; shear walls in R/C core	20	
Elmendorf Hospital	1955	7 and basement	3	R/C	6 inches R/C	Nonstructural hollow concrete block	R/C	R/C shear walls	1 (see remarks)	Lower height buildings not listed. Structural damage 1 percent; nonstructural greater.
Four Seasons (apartments)	1964	6	3	None	8 inches prestressed post-tensioned R/C; tendons not grouted	Plastered studs	R/C	Shear walls in R/C central	100	Lift slab using steel columns.
Hill (office)	1962	8	3	Steel (see remarks)	5 inches R/C on steel beams	Insulated metal	R/C	Shear walls in R/C central core	20-25	Central core was R/C bearing.
Knik Arms (apartments)	1950	6 and basement	2	Incomplete R/C	5½ inches R/C	R/C	R/C	R/C shear walls	Negligible	Building moved 10 to 11 feet, due to landslide.
Mt. McKinley (apartments)	1951	14 and basement	2	R/C (see remarks)	5½ inches R/C on R/C beams	R/C bearing	R/C	R/C shear walls	40	R/C interior beams and columns. Walls bearing. Almost identical to 1200 L Building.
1200 L (apartments)	1951	14 and basement	2	R/C (see remarks)	5½ inches R/C on R/C beams	R/C bearing	R/C	R/C shear walls	30	R/C interior beams and columns. Walls bearing. Almost identical to Mt. McKinley Building.
Penney (department store)	1962	5	3	None	10-inch R/C slabs on R/C columns	Precast R/C on 2 sides; R/C on 4 sides	Essentially none	R/C exterior walls	100	Some hollow concrete block exterior walls.
Providence Hospital	1961	5 and basement	3	Steel	5¼ inches R/C on MD on steel beams	Insulated metal	R/C	Shear walls in R/C central core	2½	Stair and elevator tower and lower height buildings not listed.

ABBREVIATIONS: UBC—Uniform Building Code.
R/C—Reinforced concrete. Poured-in-place unless otherwise specified.
MD—Metal deck. Usually having trade name "Corruform" or "Cofar".

The building damage by class of construction was essentially unchanged. Some buildings that had been damaged in 1949 and left unrepaired, as well as some in which repairs appeared inadequate, suffered additional or repeated damage. Furthermore, there was probably some amount of undetected structural distress from the earlier earthquake that resulted in additional damage or apparently new areas of damage in 1965.

Older, turn-of-the-century brick masonry structures were the most seriously damaged and also provided the maximum hazard from falling materials. Frame dwellings survived quite well, with the exception of damage to split-level type construction where differences in stiffness occur and where large openings reduce lateral building restraint. This is quite comparable to single-family-dwelling experience in San Fernando in 1971. While wood structural frames functioned satisfactorily, many homes having masonry fireplaces, particularly when attached to the side of the house, suffered substantial chimney damage.

It is interesting that while much masonry damage occurred as anticipated in older buildings where poor construction had been observed, at the same time, one practically new concrete block structure suffered severe damage to exterior walls due to wracking of the building framing. Broken masonry in the cited building disclosed that some reinforced cells in the hollow masonry unit walls had not been filled with grout, through poor construction procedures and inadequate inspection. Most major commercial structures and high-rise buildings in the urban areas were subject only to minor damage. In the industrial area, where buildings were situated on sites of hydraulic fill or deep alluvium, damage was caused by the development of incipient liquefaction and settlement, as well as through ground shaking. In some cases, waterfront structures experienced substantial lateral shifting. This can be related to shifting of fill at the water margin bulkheads as well as to inadequate bracing of the pile-supported dock structures.

Although the epicenter was reasonably close to Seattle, the accelerations experienced on the Olympia seismograph were greater than those experienced in Seattle or Tacoma. Damage to capitol buildings, particularly to the dome of the State Capitol and to older structures in the capitol complex, was severe. More recent buildings showed little damage or only superficial structural damage. Corrective measures taken in repair of the dome following the 1949 damage were inadequate to prevent further serious damage to this structure. Older state buildings remain subject to damage from future seismic actions. An extensive survey covering some 1,500 buildings by the Seattle Fire Department, together with the Seattle Building Department and the Corps of Engineers following the 1965 earthquake, provided a mass of detail concerning damages at all levels. Areas of major damage automatically required repair; however, buildings having secondary damage, and many structures showing only some evidences of minor distress may remain with breaks in mortar bond and distress in connection details, leaving them susceptible to further damage in future earthquakes.

Transportation arterials were not seriously affected. There were some cases of bascule-bridge jamming, causing temporary bridge closure to water traffic. In addition, a triggered landslide cut one railroad branch line in the Olympia area. A number of water main breaks occurred; the most serious was that of two forty-eight-inch mains carrying water across Ebey Slough to serve the city of Everett. No fire problems occurred in conjunction with this earthquake; however, the serious water main loss in Everett substantially reduced the margin of safety until corrective steps were taken.

General comments

By no means have all of the data for each of the selected earthquakes been discussed. Interested readers can obtain more detail from the reading material listed in the selected bibliography and references found at the end of this report. The importance of adequate building-damage data in connection with casualty estimates cannot be overestimated. Ground shaking does not kill people; it is the collapse of manmade structures such as buildings and dams that creates casualties during severe ground shaking.

The earthquake geologic hazards of structurally poor ground and landsliding can be and have been identified; they are discussed elsewhere in this report.

Isoseismal maps presented in this report (figs. 19-26) are a summary of the expected effects at any particular location. Any application of generalized maps, such as isoseismal maps, requires an understanding of the many exceptions to the generalized rules implicit in the maps. Most important of these exceptions for the purposes of this study are the so-called long-period effects. By this is meant that certain kinds of structures such as high-rise buildings may be subject to damage at large distances from the earthquake while nearby low-rise buildings would generally not be affected.

The long-period effects are due to the changes in the seismic waves as they travel from their source. At the epicenter and in the energy release regions, because all seismic frequencies are present, both low and tall buildings are affected. However, as these waves travel from their origins, the high-frequency components (the rapid back-and-forth motions) die out more rapidly with distance than do the long-period components (the gentle back-and-forth swaying). As a result, at distances of 50-100 miles (81-161 km), and much further, the predominant surface motion becomes the long-period motion. These latter motions have periods of vibration that more nearly coincide with the natural periods of vibration of tall buildings than with those of low buildings. As a result, conditions bordering on quasi-resonance may occur for high-rise structures, resulting in heavy damage to them. These effects have been considered throughout this report, and may or may not be specifically mentioned.

Theoretical considerations in building damage analysis

Theoretical considerations include, among others, the mathematical determination of a structure's expected performance in an earthquake having a given Richter magnitude. The mathematical analyses must include the response of structures to horizontal and vertical dynamic forces, and consider all site characteristics such as soils and geologic hazards.

The foregoing mathematical studies would cost millions of dollars if done for all structures; time requirements would also be prohibitive. On the other hand, sufficient data can be (and have been) compiled for a sufficient sampling of structures to allow the authors to adequately estimate the degree of thoroughness with which the mathematical analyses were made by the original designers of the structures. Additionally, compiled data give the standards used in the original design and their degree of adequacy for a satisfactory performance in a given earthquake. The approach used in this study, then, is to review the building's original design criteria on a class rating basis, in which a group of structures similar in construction-material type, occupancy type, and earthquake-resistance characteristics are evaluated together. The results are average values for the probable damage.

Based on the theoretically determined building damage, it is possible to develop relationships between casualties and damage. Again, care must be used; a building might be an effective 100 percent loss from a dollar standpoint but casualties might be few. For examples, one might cite the Penney Building in the 1964 Alaskan shock and the new multistory Olive View Hospital in the 1971 San Fernando shock; life losses were less than one percent of actual occupancy in each of these total property losses.

The use of existing theoretical methods by themselves has numerous weaknesses. First, earthquake forces generated in moderate to great magnitude shocks are still imperfectly known. For example, the 1971 San Fernando earthquake is the most significant to date from a strong-motion standpoint, both in the number of records obtained and in the strength of the earthquake. While a strong-motion acceleration of 1.25g was the recorded maximum, many authorities believe that, due to special site conditions surrounding the instrument's location, a factor of about 0.75g might be more reasonable; others disagree. "G-value" is the acceleration due to gravity force, and is one measure of the strength of an earthquake at a particular site. Obviously, a 25-50 percent difference of opinion on the earthquake design force (which is based on the g-value) will lead to quite different casualty and damage figures if no other factors are considered. On the other hand, on a class-rating approach, the overall life-loss and damage patterns from the 1971 San Fernando earthquake were within expected values.

Building codes normally determine the criteria used for the design of a building. The seismic provisions in these codes change over the years, constantly improving or being revised to meet new construction types. These codes, from their origins to the present date, and their degrees of enforcements are well known to the authors. Space requirements make it inappropriate to discuss the history and changes in the seismic provisions of building codes here.

Building codes have been often criticized, and rightly so, but, beyond question, the seismic provisions represent a consensus of the current thinking of the structural engineering profession and the earthquake sciences. Lastly, the intent of the codes, as expressed in "Recommended Lateral Force Requirements and Commentary" (Seismology Committee, Structural Engineers Association of California, 1973, p. 34) is as follows:

1. Resist minor earthquakes without damage,
2. Resist moderate earthquakes without structural damage, but with some nonstructural damage.
3. Resist major earthquakes, of the severe intensity of the strongest experienced in California, without collapse, but with some structural as well as nonstructural damage.

This document is widely used as a guide by engineers designing structures in the Puget Sound Basin, and has even been a formally recognized reference by the independent Seattle Building Code for many years.

Obviously, the performance of the new Olive View Hospital buildings in the 1971 San Fernando earthquake was less than the intent expressed in this document. Although there may be some valid criticisms regarding building design and construction, the new Olive View Hospital structures were designed by competent engineers, the plans were reviewed by a public authority deemed superior to most, and construction (and inspection) were also considered to be competent. Clearly, the sum total of the foregoing was not sufficient. Similarly, some of the modern buildings in Managua, Nicaragua, damaged in the earthquake of December 23, 1972, were designed by competent engineers using the same or comparable approaches to those stated in this document.

It is not the point here to judge these particular buildings, but to indicate that the <u>sole</u> reliance on building codes, without judgment, can lead to erroneous results; when used by the inexperienced, casualties and dollar losses are normally underestimated.

Experience in building damage analysis

Appropriate experience, which forms the basis for informed critical judgment, is vital for the synthesis of theoretical considerations and inadequate and (or) incomplete data from relevant earthquakes into usable information. As has been mentioned, the earthquake data and experience must be relevant; the 35 percent death and 35 percent injury factor experienced in Agadir, Morocco, has no significance in the present study. On the other hand, experience in the 1949 Olympia earthquake and the 1965 Puget Sound earthquake is relevant, as much of the older type of construction still remains. In addition, physical problems experienced in San Fernando, in 1971, can provide useful guidance.

The consultants for this study were chosen for their experience in earthquake design and earthquake effects. They have field inspected some significant earthquakes that have occurred in the United States in the past quarter-century, as well as in Venezuela in 1967, and in Nicaragua in 1972. Also, they have designed major structures and facilities for construction in areas of high seismicity, including Alaska, Washington, Hawaii, and California.

In addition to their first-hand studies of earthquakes, they are well informed concerning numerous other shocks, including, among others, 1940, El Centro, (California); 1933, Long Beach, (California); 1906, San Francisco, (California); and 1963, Skopje, (Yugoslavia).

Earthquake geologic hazards of faulting, landsliding, and structurally poor ground have been equally well studied. Extensive work has been performed and reported particularly with regard to the Prince William Sound, Alaska, 1964 earthquake; studies of geological and soil problems in the area of this study and in other areas of high seismicity have also been performed.

The need for judgment based on experience is vital in the evaluation of the Modified Mercalli Intensity maps. When Wood and Neumann introduced the Modified Mercalli Scale, they stated (1931, p. 278):

> To evaluate intensity critically, account must be taken of duration of shaking; nature of ground underneath locality and whether surface is level, gently sloping or steep; whether observers were outdoors, or indoors, in what kind of structure, on what floor, whether quiet or active, and if active how occupied; also whether the motion is rapid or slow, simple or complex, and whether it begins gradually or abruptly. This requires experience. Because of the entry of these factors in different degrees no intensity scale of this kind is suitable for general use, even though correct estimates might often be made.

The lowest intensity values rely heavily on human reactions, the middle range intensity values principally relate to building damage, and the highest intensity values are strongly influenced by geologic effects. Human reactions, building damage, and geologic effects are not truly compatible. For example, items have not fallen from shelves in buildings adjacent to major fault scarps. New building materials, new construction techniques, and new design methods have complicated the application of the Modified Mercalli scale. For one example, the phrase "good construction," used in the scale, has different meanings depending on the earthquake provisions in the building codes in different areas. In some areas, brick walls must be heavily reinforced with steel to be classified as "good construction," while in other areas the walls require no reinforcement to be classified as "good construction."

Time of day and season of year

The number of injuries sustained as the result of an earthquake is highly dependent on the time of day that the shock occurs. In this report, therefore, the timing of the earthquake has been accepted as one of the variables. Accordingly, for the purposes of the study, three respective times of day have been assumed, as follows:

1. 2:30 a.m., when the greatest proportion of the population would be at home in bed;
2. 2:00 p.m., when the greatest proportion of the population would be away from home;
3. 4:30 p.m., the beginning of the rush hour.

The season of year, namely wet or dry season, has a definite effect on the conflagration potential as well as the landslide potential. Additionally, the occurrence of an earthquake in the rainy season could create a greater need for shelter of the homeless in the Puget Sound Basin and could expose goods to water damage. In winter an earthquake might trigger avalanche activity in mountain passes, thus interrupting rail and highway transportation routes.

Major hospitals

A major hospital facility was defined, for this report, as one having a patient occupancy of 50 beds or more. While there are more than 50 hospitals located in the six counties of the Puget Sound Basin, this study limits itself to the analysis of 40 major hospitals. These include public health and veterans facilities, but exclude military hospitals and mental health facilities. The total number of hospitals and bed capacities, summarized in table 20, is in a constant state of flux, changing whenever the construction of a new hospital building is completed or whenever obsolete facilities undergo remodeling or demolition in order to meet State licensing requirements.

A total regional inventory is presented in table 21 for all types of health facilities licensed by the Department of Social and Health Services of the State of Washington. Although smaller hospitals were not reviewed as part of this report, the hazards and problems they face in responding to a natural disaster will be similar in scope and character to those encountered by major hospitals.

Data collection

Identification and location of the major general hospitals were obtained from the 1975 Directory of Licensed Hospitals issued by the Department of Social and Health Services, whose Planning and Construction Division also furnished building-construction data on the hospitals. Additional data for specific hospitals were obtained from records on file in permits and plans archives of respective city building departments and from the files of the Civil Defense Support unit of the Naval Facilities Engineering Command, 13th Naval District.

General information on military and veterans hospitals located in the six-county area was obtained from the Puget Sound Health Planning Council. The military and State mental health facilities are complexes of many

TABLE 20.--INVENTORY OF MAJOR MEDICAL HOSPITALS HAVING CAPACITIES OF 50 OR MORE BEDS, EXCLUDING MILITARY, PUBLIC-HEALTH-SERVICE, AND VETERANS ADMINISTRATION HOSPITALS

(Data from Department of Social and Health Services, written commun., 1974, and Puget Sound Health Planning Council, written commun., 1974; no., number; cap., capacity)

	Type of hospital facility											
	General		Mental health				Regional		Veterans		Military	
			Public		Private							
County	Total no.	Bed cap.	Total no.	Bed cap.	Total no.	Bed cap.	Total no.	Bed cap.	Total no.	Bed cap.	Total no.	Bed cap.
SNOHOMISH---	4	621	0	0	0	0	0	0	0	0	0	0
KING--------	22	4,400	0	0	2	160	1	247	1	351	0	0
PIERCE------	8	1,391	2	3,350	0	0	0	0	1	603	1	861
THURSTON----	1	180	0	0	0	0	0	0	0	0	0	0
MASON-------	1	66	0	0	0	0	0	0	0	0	0	0
KITSAP------	1	177	0	0	0	0	0	0	0	0	1	175
Totals-----	37	6,835	2	3,350	2	160	1	247	2	954	2	1,036

TABLE 21.--REGIONAL INVENTORY OF ALL HEALTH FACILITIES LICENSED BY THE STATE OF WASHINGTON IN THE SIX COUNTIES OF THE PUGET SOUND BASIN AS OF DECEMBER 31, 1974

(Data from Department of Social and Health Services, Olympia, Wash., written commun., 1974; no., number; cap., capacity)

County	General hospitals		Nursing homes		Mental health		Other [1/]	
	Total no.	Bed cap.	Total no.	Bed cap.	Total no.	Bed cap.	Total no.	Bed cap.
SNOHOMISH--	5	649	20	1,850	0	0	22	328
KING-------	25	4,487	81	8,348	2	160	66	5,215
PIERCE-----	8	1,391	36	2,800	0	0	28	674
THURSTON---	1	180	7	530	0	0	3	55
MASON------	1	66	1	100	0	0	3	153
KITSAP-----	1	177	11	1,018	0	0	10	142
Totals----	41	6,950	156	14,646	2	160	132	6,567

1/ Other includes boarding homes, group homes, maternity homes, and alcoholism treatment facilities.

buildings covering extensive areas. It was not possible to obtain sufficient data for these facilities, but site plans of State complexes were obtained to study the relationship of individual units to known hazards, accessibility routes, and circulation patterns.

On-site inspections of medical facilities were conducted by an engineer or professionally trained field consultant in order to confirm the following data: year built, location and orientation, site description, building shape, size in square feet, number of stories, type of construction, earthquake-resistive system, materials of construction, emergency systems, street access, building condition, and type of facility.

Figures 28 and 29 show the location and geographic distribution of all types of major hospitals considered in this section of the study. Table 22 tabulates the 37 major hospitals considered in the analysis by geographical area and bed capacity.

Analysis

The tactical and logistical problems to be faced by major hospitals and other health facilities during and after a severe earthquake will be considerable and unexpected. The care of the injured immediately following the main shock would become one of the greatest area-wide problems. Although it could be predicted that most of the hospitals would be in operation, the San Fernando, Calif., earthquake of 1971 indicates that it is highly possible that hospital facilities and medical centers could be more severely damaged than was originally anticipated, and thus could be critically handicapped during the postearthquake recovery period. Using the 1971 San Fernando earthquake as a model, it is possible to envision a major hospital facility that might become a burden rather than an aid after a major earthquake.

Analysis of health facilities is complicated by the fact that many hospitals are composed of several buildings that were built at different times using varying construction materials and physical configurations. In meeting the needs of an expanding population and in recognizing the advantages of new technological equipment, hospital buildings may be renovated or enlarged by the addition of annexes attached to the original building

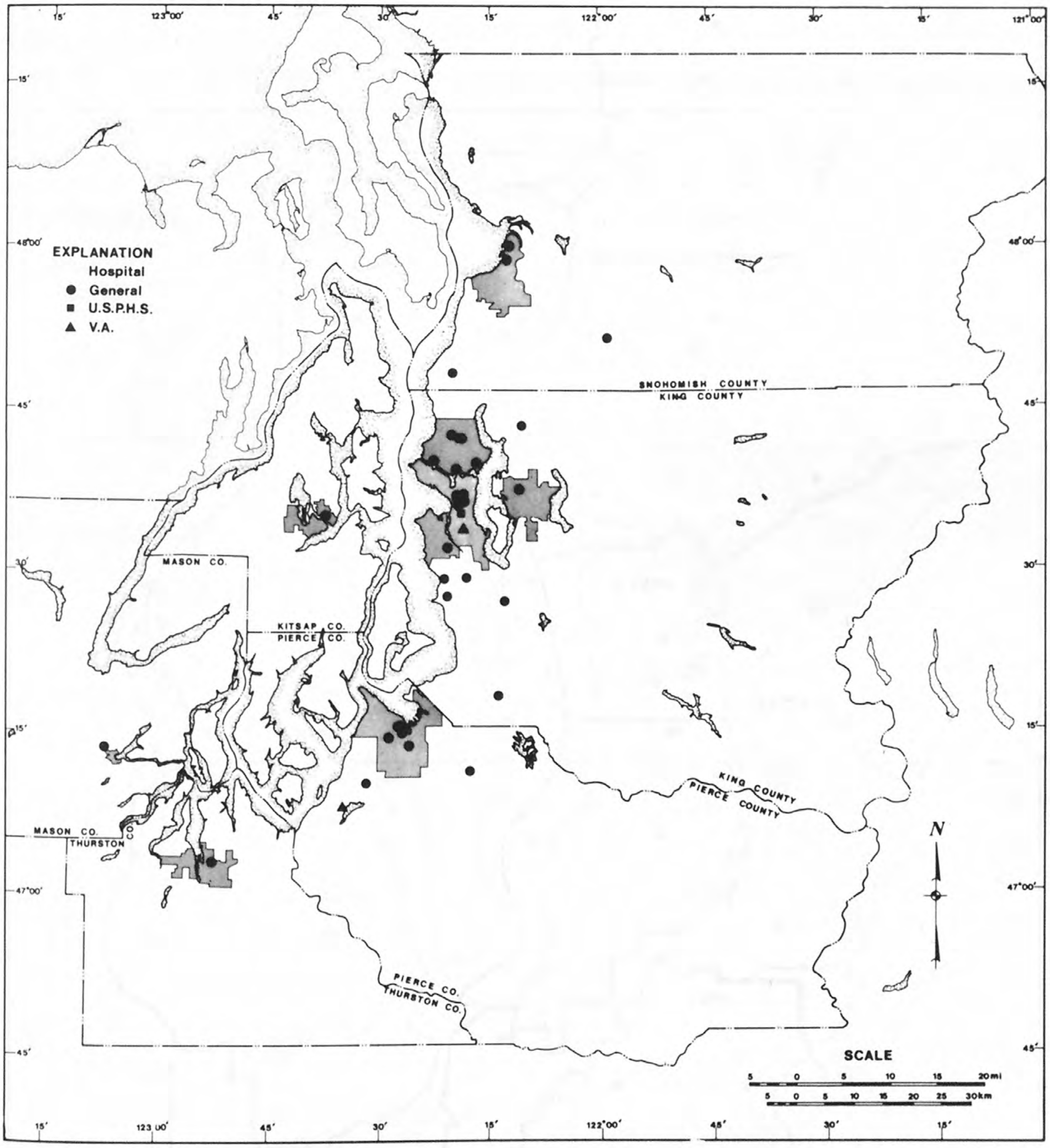


Figure 28.--Location of major hospitals in the six-county study area. One dot may represent more than one facility.

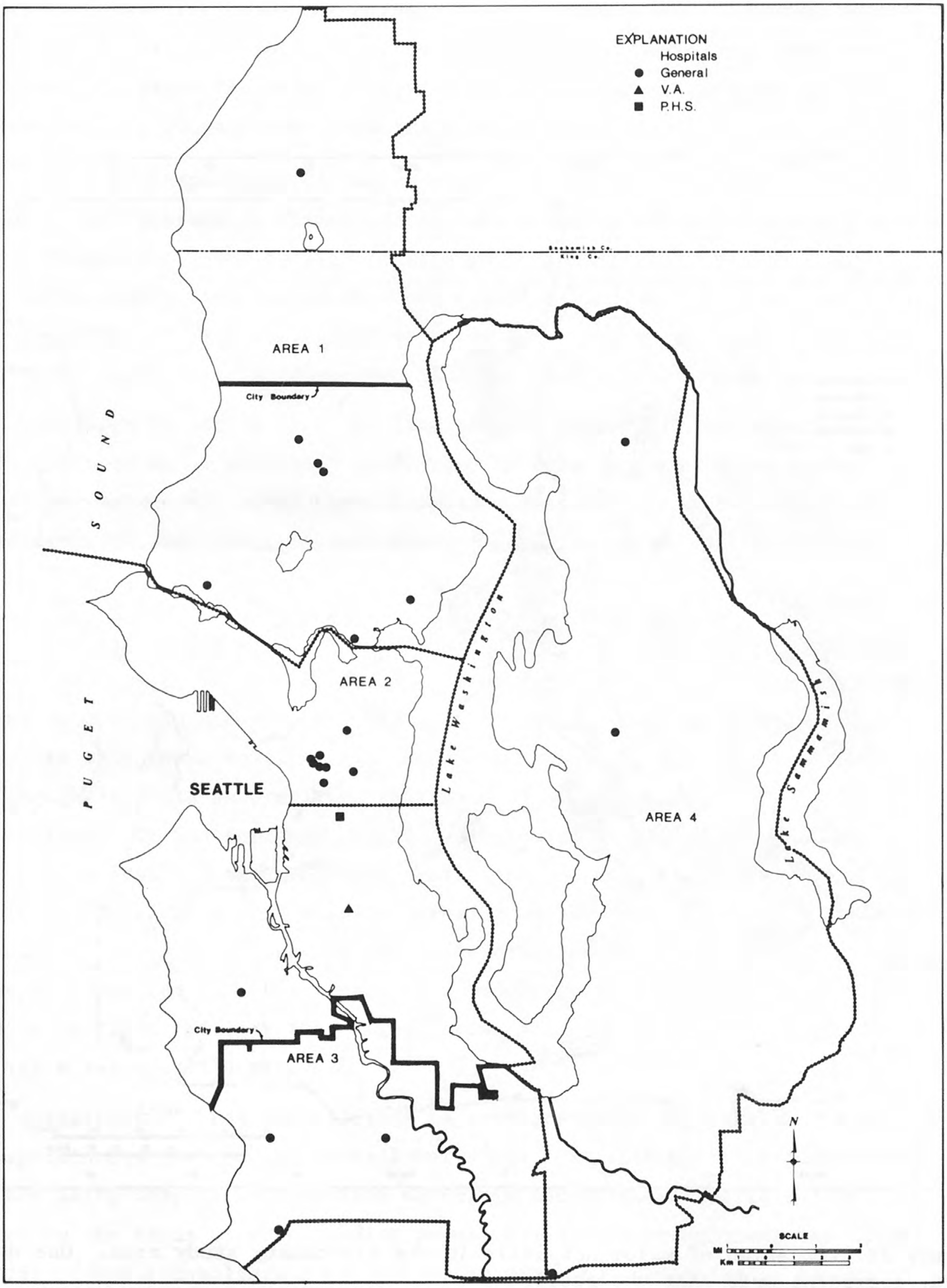


Figure 29.--Location of major hospitals in the metropolitan Seattle area.

TABLE 22.--DISTRIBUTION OF GENERAL HOSPITALS BY BED CAPACITIES, EXCLUDING MILITARY, PUBLIC-HEALTH-SERVICE, AND VETERANS ADMINISTRATION HOSPITALS IN THE SIX-COUNTY AREA.

County	Number of hospitals by number of beds			
	50 to 99	100 to 199	200 to 400	over 400
SNOHOMISH------	1	2	1	0
KING				
Area:				
1--------	1	3	2	0
2--------	0	2	4	2
3--------	1	3	0	0
4--------	1	1	1	0
Remainder-----	1	0	0	0
PIERCE---------	3	1	4	0
THURSTON-------	0	1	0	0
MASON----------	1	0	0	0
KITSAP---------	0	1	0	0
Totals------	9	14	12	2

as many as three or four times within a period of 20 years.

Five of the 40 major medical hospitals shown on figure 28 are located in areas of MMI IX in the event of either postulated earthquake, and the remainder may be subjected to MMI VIII. Local major-hospital resources will be diminished as a result of building damage, loss of utility services, loss of medical supplies, and deaths and injuries to occupants.

Although a major medical facility may have the most modern equipment available, portions of it may be located in a structure built before 1949. Table 23 indicates the dates of construction (or age) of some of the original parts of building complexes that are still being used in certain operations of the major hospitals, including one public health service hospital and two veterans hospitals. It is significant to note that 18 of the 40 hospitals (45 percent) are still housed, in part, in structures built prior to 1949. Therefore, it may be presumed that those structures were not specifically designed for earthquake resistance.

Table 23 also supplies important information regarding construction types and the heights of the major hospitals surveyed as a part of this study. Twenty-two percent of all the major hospitals located in the six-county area are of masonry or mixed construction of a type that often performs poorly even during a moderate earthquake.

It will be noted that 55 percent of the facilities are one to four stories in height, 28 percent are five to eight stories, while the remaining 17 percent are over nine stories high. Several of the multistory hospitals may have to be evacuated if heavily damaged, even though they may not be subject to total collapse. Others will have to be evacuated pending inspection by qualified engineers to determine whether their structural integrity has been compromised beyond acceptable levels.

Inside and outside utilities critical to the functioning of a hospital include electrical power, communications, elevators, auxiliary power, heating, water, sewerage, and gas systems. Various combinations of damage patterns affecting hospital resources would occur in each of the postulated earthquakes assumed for this study.

TABLE 23.--INVENTORY OF BUILDING DATA FOR MAJOR HOSPITALS IN SIX-COUNTY AREA

County	Total number of hospitals	Total number of beds	Construction date: pre-1949	Construction date: 1949-1960	Construction date: 1961-1974	Construction type--oldest part of bldg.: Concrete	Steel	Masonry and concrete	Masonry and wood	Wood	Mixed	Number of stories: 1-4	5-8	9-13	13+
SNOHOMISH--	4	621	3	0	1	3	0	0	1	0	0	2	2	0	0
KING															
Area:															
1----	6	1,091	0	5	1	3	2	0	0	1	0	3	2	0	1
2----	8	2,279	7	1	0	5	0	1	1	0	1	1	5	1	1
3----	6	1/ 1,033	3	2	1	2	2	1	0	1	0	4	0	1	1
4----	3	505	0	1	1	0	0	1	0	0	1	3	0	0	0
Remainder-	1	90	0	1	1	1	0	0	0	1	0	1	0	0	0
PIERCE-----	9	2/ 1,994	5	2	2	4	2	2	0	1	0	6	2	1	0
THURSTON---	1	180	0	0	1	0	1	0	0	0	0	0	0	1	0
MASON------	1	66	0	0	1	1	0	0	0	0	0	1	0	0	0
KITSAP-----	1	177	0	0	1	1	0	0	0	0	0	1	0	0	0
Totals---	40	8,036	18	12	10	20	7	5	2	4	2	22	11	4	3
Percentages of building types-						50	18	12	5	10	5	55	28	10	7

1/ Includes Public Health Service and Veterans Hospitals.

2/ Includes a Veterans Hospital.

Table 24 tabulates the expected bed loss, the percent impairment of critical utilities, and the percent loss to medical supplies owing to earthquakes "A" and "B". Table 25 lists the approximate replacement value of the 37 general hospitals with over-50 bed capacity existing in the study area, using an estimated value (1975) of $60,000 per bed.

The loss of medical supplies stored in a hospital building is a function of two variables: loss of supplies stored in fragile containers caused by falling from shelves, and equipment falling from tops of counters. Reliable reports of losses to medical supplies caused by the 1969 earthquake at Santa Rosa, Calif., and of the losses to 30 hospitals subjected to the 1971 San Fernando, Calif., earthquake proved valuable to this study. While, admittedly, the two earthquakes were limited to the extent of the area affected and little loss was reported, large earthquakes will have a larger proportional loss of specific supplies, particularly to liquid-type drugs and chemicals stored on shelves in fragile containers. Table 24 indicates the conceivable upper-limit percentile losses of medical supplies, by area, for earthquakes "A" and "B".

Thirty-seven general hospitals in the study area accommodate approximately 7,000 beds and have the current type and rate of occupancy listed in table 26. The percentages for this table were developed from the composition of specific hospital personnel and other occupants obtained from the administrative staff of representative hospitals throughout the region. On the basis of the bed occupancy rate, the location and physical characteristics of the hospital building, and the hypothesized earthquake intensity at each site, the total number of deaths and injuries to occupants and personnel in the building were computed for the two postulated earthquakes for three assumed times of day.

Casualty distributions (death and significant injury) among patients, doctors, staff, visitors, and outpatients were calculated for the two postulated earthquakes on a hospital-by-hospital basis. During the afternoon hours, the greatest percentage of casualties would be among the hospital staff. However, with a reduced staff and fewer doctors and visitors present in the early morning hours, overall casualties would be reduced and

TABLE 24.--DAMAGE TO GENERAL HOSPITALS HAVING CAPACITY OF 50 OR MORE BEDS

County	Earthquake "A", magnitude=7.5						Earthquake "B", magnitude=7.5					
	Bed loss		Impairment or nonfunctioning (in percent)			Loss to medical supplies (in percent)	Bed loss		Impairment or nonfunctioning (in percent)			Loss to medical supplies (in percent)
	Per-cent	No.	Elev-ators	Communi-cations	Aux. power		Per-cent	No.	Elev-ators	Communi-cations	Aux. power	
SNOHOMISH--	4	25	8	0	0	4	16	98	26	4	7	45
KING												
Area: 1----	4	43	8	0	0	4	8	85	15	0	2	39
2----	7	157	14	0	0	7	14	315	28	0	3	69
3----	15	66	26	3	6	48	15	66	25	3	6	48
4----	6	29	11	0	1	4	8	41	16	0	2	40
Remainder-	6	5	0	0	0	4	0	7	0	0	0	40
Subtotals-		300						514				
PIERCE-----	13	175	23	2	4	50	13	175	23	8	4	50
THURSTON--) MASON-----) KITSAP----)	13	57	20	4	7	30	4	19	9	0	1	21
Totals---		557						806				

TABLE 25.--REPLACEMENT VALUE (1975) OF GENERAL HOSPITALS, BASED UPON ASSUMED COST OF $60,000 PER BED

County	Number of hospitals	Total number of beds	Approximate total present value (at $60,000/bed)
SNOHOMISH--	4	621	$ 37,260,000
KING			
Area: 1----	6	1,091	65,460,000
2----	8	2,279	136,740,000
3----	4	1/435	26,100,000
4----	3	505	30,300,000
Remainder-	1	90	5,400,000
PIERCE-----	8	2/1,391	83,460,000
THURSTON---	1	180	10,800,000
MASON------	1	66	3,960,000
KITSAP-----	1	177	10,620,000
Totals----	37	6,835	$ 410,100,000

1/Does not include Public Health or Veterans Hospitals.

2/Includes a Veterans Hospital.

TABLE 26.--HOSPITAL POPULATIONS AS A FUNCTION OF BED CAPACITY

(in percent)

	Hospital population per bed capacity		
	2:00 p.m.	4:30 p.m.	2:30 a.m.
Patients per bed -------	0.80	0.81	0.82
Physicians on duty------	.08	.06	.02
Nurses on duty----------	.44	.28	.14
Other staff on duty-----	.82	.51	.08
Outpatients-------------	.08	.07	.004
Visitors----------------	.40	.33	.02
Percentage of total-bed occupancy	80	81	82

the majority of casualties would occur among patients. Tables 27 and 28 list the projected casualty and injury distribution for the three times of day assumed for the occurrence of the postulated earthquakes "A" and "B". Seattle epicenter, earthquake "B", would be potentially more hazardous to hospital occupants than the Olympia-Tacoma epicenter, earthquake "A", owing to the greater concentration of hospitals in the Seattle area.

TABLE 27.--DEATHS AT GENERAL HOSPITALS THROUGHOUT THE SIX-COUNTY STUDY AREA (EXCLUDING PUBLIC HEALTH AND VETERANS HOSPITALS)

County	Number of hospitals	Earthquake "A", magnitude=7.5			Earthquake "B", magnitude=7.5		
		2:30 a.m.	2:00 p.m.	4:30 p.m.	2:30 a.m.	2:00 p.m.	4:30 p.m.
SNOHOMISH--	4	0	0	0	6	14	12
KING							
Area: 1----	6	0	0	0	8	16	13
2----	8	0	0	0	31	61	50
3----	4	3	10	8	3	10	8
4----	3	2	3	3	4	8	6
Remainder-	1	1	2	2	2	2	2
Subtotals-	22	6	15	13	48	97	79
PIERCE-----	8	15	30	25	15	30	25
THURSTON--) MASON-----) KITSAP----)	3	4	8	6	2	4	3
Totals----	37	25	53	44	71	145	119

TABLE 28.--HOSPITAL INJURIES AT GENERAL HOSPITALS THROUGHOUT THE SIX-COUNTY STUDY AREA (EXCLUDING PUBLIC HEALTH AND VETERANS HOSPITALS)

County	Number of hospitals	Earthquake "A", magnitude=7.5			Earthquake "B", magnitude=7.5		
		2:30 a.m.	2:00 p.m.	4:30 p.m.	2:30 a.m.	2:00 p.m.	4:30 p.m.
SNOHOMISH--	4	15	30	25	47	94	76
KING							
Area:							
1----	6	25	49	41	50	98	80
2----	8	95	190	155	188	358	300
3----	4	31	60	51	31	60	51
4----	3	17	35	28	24	48	39
Remainder-	1	8	16	13	8	16	13
Subtotals-	22	176	350	288	301	580	483
PIERCE-----	8	94	186	151	94	186	151
THURSTON--) MASON-----) KITSAP----)	3	25	51	40	12	22	17
Totals----	37	310	617	504	454	882	727

Health manpower

Health-manpower problems at respective hospitals in the six-county study area have been discussed in this section under Hospitals. However, when away from the hospital health manpower faces the same hazards as the bulk of the population. The following discussion will emphasize problems for physicians and registered nurses, but the general findings are applicable to all types of health manpower.

Data collection

The main source of information for this section was the Division of Professional Licensing in the Department of Business and Professions for the State of Washington. The Department's listing of data on health-manpower resources, as of July 1974, is the basis for the inventory by county, shown in table 29, for the various health service professions licensed by the State of Washington through respective Boards of Examiners.

Analysis

As standard procedure after a disaster, medical specialists and personnel are expected to report immediately to the hospitals to which they are attached. If for any reason they are unable to reach their hospitals, they are expected to report to the nearest hospital available to them. Thus, it is important to correlate the locations of the major general hospitals with respect to major transportation arterials and medical-manpower resources. Table 29 gives the number and distribution of physicians, surgeons, and registered nurses in the six-county area, and table 21 gives the number of general hospitals and their various bed capacities for the same general areas. On the basis of the data given in these tables, the comparative percentages given in table 30 were computed.

A listing of medical personnel by areas in any given county is not available from any sources known to the consultant staff. The King County Medical Society furnished data obtained from the 1970 U.S. Census "Specialty Location Chart," which shows the distribution of physicians by specialty throughout King County. Percentages for the five geographical areas where

TABLE 29.--INVENTORY OF MEDICAL MANPOWER BY COUNTY IN SIX-COUNTY AREA

(Licensing Division of the Business and Professions Admin., Olympia, Wash., written commun., 1974)

MEDICAL MANPOWER	COUNTY					
	SNOHOMISH	KING	PIERCE	THURSTON	MASON	KITSAP
Chiropractors------------	47	94	60	11	2	17
Dentists-----------------	146	1136	236	60	12	53
Naturopaths--------------	4	24	3	2	0	1
Dispensing opticians-----	21	104	39	9	1	6
Optometrists-------------	28	136	42	11	3	13
Osteopathic physicians and surgeons-----------	9	112	10	4	0	5
Physical therapists------	22	295	76	15	0	12
Physicians and surgeons--	220	2730	523	130	17	133
Registered nurses--------	1653	9124	2297	471	103	594
Licensed practical nurses----------------	607	2416	1675	228	80	323
Psychologists------------	10	167	51	6	0	4
Podiatrists--------------	5	34	12	2	0	1
Veterinarians------------	50	206	65	27	3	13

TABLE 30.--DISTRIBUTION OF PHYSICIANS AND SURGEONS, REGISTERED NURSES, AND HOSPITAL BEDS IN THE SIX-COUNTY STUDY AREA, EXCLUDING MILITARY, VETERANS AND PUBLIC-HEALTH-SERVICE FACILITIES

(Developed from statistics supplied by Washington State Department of Social and Health Services, written commun., 1974, and the Division of Professional Licensing, Olympia, Wash., written commun., 1974)

County	Physicians and surgeons: Total number	Physicians and surgeons: Percentage	Registered nurses: Total number	Registered nurses: Percentage	Hospital beds: Total number	Hospital beds: Percentage
SNOHOMISH--	220	5.9	1,653	11.6	649	9.3
KING-------	2,730	72.7	9,124	64.1	4,487	64.6
PIERCE-----	523	13.9	2,297	16.2	1,391	20.0
THURSTON---	130	3.5	471	3.2	180	2.6
MASON------	17	0.5	103	0.7	66	1.0
KITSAP-----	133	3.5	594	4.2	177	2.5
Totals---	3,753	100.0	14,242	100.0	6,950	100.0

they practice are as follows:

King County	Physicians	Total (in percent)
Area:		
1-----	510	27
2-----	891	46
3-----	173	9
4-----	184	10
Remainder--	160	8
Total----	1,918	

Some medical personnel will not be available when the postulated earthquake strikes because of disruption to transportation routes. Although the King County Nurses Association was unable to furnish a distribution of registered nurses by geographical location, their membership roster indicates that many registered nurses work in King County and commute to their work from Snohomish and Pierce Counties. The difficulty or ease with which medical personnel will be able to reach their hospital stations will depend on the conditions of ground transportation.

Because it is reasonable that the residence and commuting habits of medical manpower do not differ significantly from that of the general public, it is likely that most of the personnel will use automobiles, or buses in a few cases, and the movements of these vehicles will be limited by the conditions of the freeways and surface streets. Blocked streets caused by fallen overpasses, building debris, and landslides in the MMI VIII and MMI IX areas will present difficulties, but these will not be so severe that alternate routes cannot be used in the vast majority of cases. It is reasonable to assume that the problems of transporting the injured to hospitals and to other centers will take even longer than that required for the uninjured medical personnel to arrive. It should be expected that the freeway system will be partly closed in some areas, due to the effects from overpass collapse, local subsidence, lurch cracking, or landslides.

Lack of telephone communication will create problems in handling assignments of hospital personnel. However, if the majority of the able personnel report to some hospital, then reassignments could be handled by use of the hospital emergency-radio-communications network. Experiences in past earthquakes indicate that radio communications will be seriously impaired, due to the loss of commercial electrical power and failures of emergency generators' equipment because of inadequate anchorage of generating units, batteries, and fuel systems.

It is likely that most of the hospital personnel, who have not been incapacitated, will be able to report either to their regular hospitals or to alternate locations closer to their residences. Transportation and communication problems singular to health manpower are discussed and analyzed in the section devoted to the effects of earthquake on vital public needs.

For health manpower, transportation problems, deaths, and injuries, caused by earthquake "A", will be most severe in the congested localities of high-density population. Table 31 indicates the expected deaths to selected health manpower. Greater earthquake intensities will be experienced in the southern portions of the six-county area, in close proximity to the epicenter; however, the general population is less dense in this part of the study area and medical facilities even disproportionately less. Damaged transportation arterials will not affect the ability of personnel to reach duty stations as much as in other locations. In the more distant sections of the six-county area, attenuation will lessen the damaging effects. On the other hand, a possible major building collapse in the proximity of the epicenter could cause many casualties. If these overtax the limited medical-personnel resources in the southwest area, it might be necessary to evacuate casualties to other facilities some distance away.

Under conditions of earthquake "B", more severe transportation problems for health manpower will exist in the urban areas marked by railway and highway bridge closures and freeway interdiction. Movement of off-duty medical personnel to their assigned hospitals will be hindered, but not generally prevented. A great number of medical facilities and personnel are concentrated in the urban areas nearest the epicenter. Deaths and casualties will be somewhat higher there for health manpower than for the general populace. Disruption of communications, wire or radio, will increase the difficulty in notifying personnel of duty assignments to areas of greatest need in the event of a disaster.

TABLE 31.--DEATHS TO PHYSICIANS AND NURSES AT NON-HOSPITAL LOCATIONS IN SIX-COUNTY AREA AT 2:00 P.M. FOR TWO POSTULATED EARTHQUAKES.
(Developed from tables 12, 29, and 47)

Earthquake "A", Olympia-Tacoma epicenter

County	Deaths to physicians	Deaths to registered nurses
SNOHOMISH--	0	1
KING-------	3	11
PIERCE-----	1	2
THURSTON---	0	1
MASON------	0	0
KITSAP-----	0	0
Totals---	4	15

Earthquake "B", Seattle epicenter

County	Deaths to physicians	Deaths to registered nurses
SNOHOMISH--	0	1
KING-------	4	12
PIERCE-----	1	2
THURSTON---	0	0
MASON------	0	0
KITSAP-----	0	0
Totals---	5	15

Other medical resources

Ambulance services

Since 1973 emergency medical services, first aid, and ambulance services in the State of Washington have been required to meet the standards established that year by Senate Bill 2365 and administered by the Secretary of the Department of Social and Health Services. This legislation defines types of services, the minimum requirements for vehicles and communication equipment, the licensing of vehicles, the certification and licensure of prehospital emergency medical services personnel.

Ground equipment for ambulance services includes any motor vehicle constructed, arranged, and operated for transporting ill, injured, infirm, or otherwise incapacitated persons. The term "air equipment," for ambulance services, applies to aircraft (fixed wing or helicopter) used to transport patients for immediate medical attention or for emergency evacuation purposes. Most of the aircraft carry an attendant and first aid equipment, but few of the operators and their aircraft are employed exclusively in ambulance work. MAST (Military Assistance to Safety and Traffic) is the emergency medical helicopter service available to the six-county study area from McChord Air Force Base in Pierce County.

Traditionally, the responsibility of emergency medical vehicles was to transport patients from the scene of an accident to medical care. Implementation of the newer concept of stabilizing the patient before transport creates two orders of response: the first brings medical aid to the patient; the second transports the patient from the accident scene to the hospital. The State program to provide immediate prehospital treatment for victims of motor vehicle accidents, of suspected coronary attacks, and of trauma or other acute illnesses has reduced the response time to all State roads to fifteen minutes by an increase in number and better distribution of vehicles.

Data collection

Data collection included an inventory of the commercial ambulance companies and those special emergency services provided by fire departments and volunteer associations. Information was supplied by surveys undertaken in 1972 by the Department of Social and Health Services, State of Washington, and in 1974 by the Puget Sound Health Planning Council and the Health Care Study Center of the Battelle Memorial Institute. Data were not collected on "Cabulances" or other similar vehicular services employed to transfer the infirm or handicapped in nonemergency situations.

A fire department aid-car or rescue unit may transport in an emergency situation when an ambulance is not available. Nonacute calls are performed by commercial ambulance companies as reported in the 1974 survey made by the Puget Sound Health Planning Council. Three companies in Snohomish County estimated that 30-40 percent of their runs were nonemergency calls, such as transporting a patient from a hospital to a nursing home. At the same time in 1974, the Seattle Fire Department reported in the survey made by the Battelle Institute, that none of the 17,500 runs made by the Fire Department Medic I service were nonacute transfers.

Response to a medical emergency involves three elements of emergency communication: a means of requesting medical care, a means by which a vehicle can be dispatched to the location of the victim, and a means by which the emergency vehicle can communicate with the hospital emergency staff. Under the 1973 law, Senate Bill 2365, the Secretary of the Washington State Department of Social and Health Services is required to establish standards for emergency medical communications, including the requirement that each ambulance and first aid vehicle licensed in the state must be equipped with transmitting and receiving equipment. Commercial ambulance companies can finance the purchase of expensive communication systems with substantial assistance from National Highway Traffic Safety Funds, U.S. Department of Transportation.

Analysis

In the event of a major earthquake the functioning of emergency vehicles will be largely governed by the structure in which they are normally housed. If the structure collapses or the exit of the vehicle from the structure is blocked by debris from an adjacent building, or if it cannot traverse a street because of debris, it cannot serve as an emergency vehicle. This is just as true for a Medic I vehicle housed at a fire station as it is for a commercial ambulance. Figure 30 shows the disposition of medical-emergency vehicle services in the Puget Sound Basin. Field inspections of 12 ambulance services in 3 counties supplied data on the type and date of construction for ambulance shelter and methods of parking vehicles. It was observed that the majority of the field-inspected services housed vehicles in one-story earthquake-resistive structures, or parked them in open areas where access would not be restricted.

The summary of services shown in table 32 relates to a survey made in 1972--the latest comparable information available for each of the six counties. A similar inventory will be undertaken by the Department of Social and Health Services in July 1975 that will document the effect of the 1973 legislation establishing standards for vehicles, communications, and personnel. Because field surveys determined that the majority of emergency medical vehicles are housed in earthquake-resistive structures or in open areas, impairment to structures was considered negligible.

TABLE 32.--DISTRIBUTION OF EMERGENCY MEDICAL SERVICES BY COUNTY
(Developed from an inventory taken in Auguest 1972 by the State of Washington, Department of Social and Health Services)

	Number by County			
County	Services surveyed	Vehicles	Two-way hospital communications	Services not contacted
SNOHOMISH--	11	17	4	7
KING-------	37	78	21	11
PIERCE-----	17	28	9	3
THURSTON---	4	6	0	1
MASON------	4	3	0	1
KITSAP-----	5	11	0	4
Totals	78	143	34	27

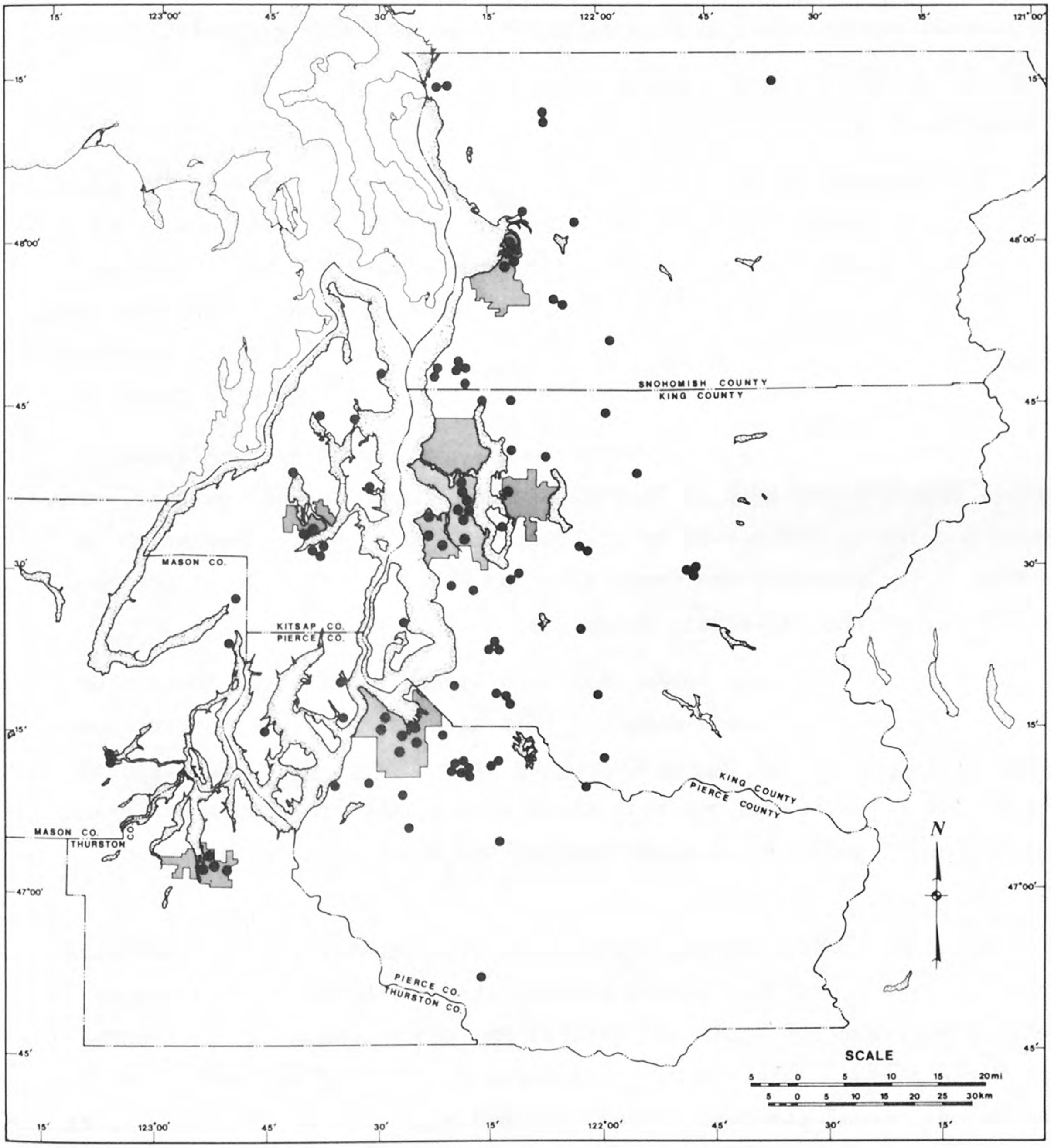


Figure 30.--Location of medical emergency vehicle services in the six-county study area. One dot may represent more than one facility.

Blood banks

A review of medical resources includes the region's blood collection and distribution systems. There are three blood banks located in the six-county study area, as shown in figure 31. They also serve four other counties--a total of 10 Washington counties with a population of 2,196,400 persons.

Data collection

The recognition of "blood" as a national resource created the need for regional blood centers large enough to provide all services. The Puget Sound Blood Center in Seattle--formerly the King County Central Blood Bank--is the regional center in western Washington. With its satellite facility at Tukwila, the center serves 35 hospitals and 7 counties: Whatcom, Skagit, Jefferson, Kitsap, Mason, Thurston, and King Counties.

All of the hospitals in Pierce County are served by the Tacoma-Pierce County Blood Bank in Tacoma. Snohomish and Island Counties, with seven hospitals, are served by the Snohomish Blood Bank Association in Everett. The American Red Cross does not maintain a blood collection center within the six-county study area.

Basically the blood banks utilize a direct call to the donor from a master file of volunteer donors. This assures the proper collection, laboratory identification, and matching procedures. Centralization of the facility, including centralization of all laboratory work necessary for transfusing blood, is essential for the control of inventory and utilization.

The laboratories of the Puget Sound Blood Center are open 24 hours per day. The Center has direct communication with the Hospital Emergency Administrative Radio and the 911 emergency communication system in the Metropolitan Seattle area. A laboratory staff of six medical doctors and an additional staff of 30 well-trained personnel do all the patient typing, cross-matching, and donor compatibility for the area. The donated blood may be separated into components so that, when called for, the patient is provided with only the part that is needed. This policy has provided great benefits to the general community, lowering the cost of

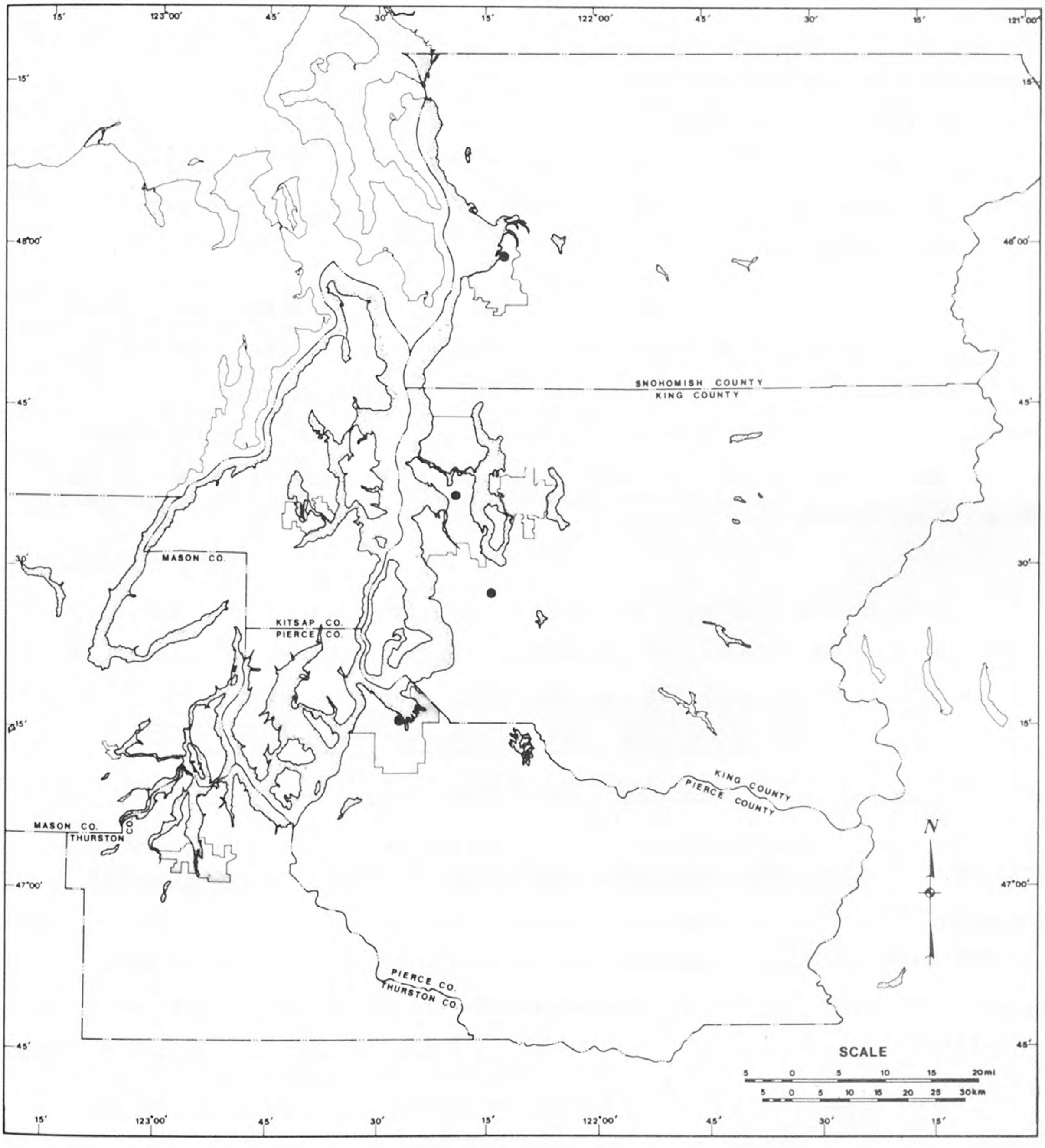


Figure 31.--Location of buildings housing blood banks serving the six-county study area.

one pint of whole blood (in 1975 about $100) by almost 90 percent and reducing the rate of hepatitis infection to the lowest in the United States.

Analysis

Authoritative information concerning the blood banks in the study area was supplied by the administrators of individual blood banks. Information reviewed by the analysts included building construction data: construction type, type of foundation, size of building, number of stories, year built and dates of additional construction, earthquake-resistive system, emergency systems, number of mobile units, and street accessibility for all vehicles.

All four of the buildings housing blood banks have emergency generators to maintain operation of refrigeration units in the event of electric power failure. Mobile units can store substantial quantities of blood units in styrofoam boxes. At least one mobile unit at the Puget Sound Blood Center is self-contained and has a refrigeration capacity of 100 units of blood.

TABLE 33.--DATES OF CONSTRUCTION OF ORIGINAL PART OF BUILDING FOR BLOOD BANKS SERVING THE PUGET SOUND BASIN

Location	Constructed pre-1950	Constructed 1950-74	Height of building (stories)	Emergency power available
SNOHOMISH:				
Everett--	1		1	Yes.
KING:				
Seattle--	1		1-3	Do.
Tukwila--		1	3	Do.
PIERCE:				
Tacoma---		1	1	Do.

In the postulated earthquakes, blood bank structures will be subjected to intensities varying from MMI VII to MMI IX. As shown in table 33, the structures vary in age from 1946 construction to 1970, with additions of facilities varying from dates of original construction. The response of several structural types, based on location and anticipated intensities, indicates a possibility that 20 percent of the structures will be nonfunctional as a result of damage from either postulated earthquake. Damage to equipment, laboratory facilities, and reserve stocks can be severe.

The blood banks, as a matter of policy, participate in disaster exercises staged by civil preparedness agencies. The directors of the blood banks express confidence that their services can meet the needs of the area in the event of a major disaster. However, the demands imposed by a major disaster producing hundreds of casualties could exceed this capability and require additional blood services from the nearest regional centers--Yakima, Portland, Spokane, or Boise.

Clinical laboratories

Clinical laboratories provide services to hospitals and to doctors in the performance of tests, investigation of specimens, and performance of many other functions vital to hospitalized and some non-hospitalized patients in diagnosis and treatment control. Loss of laboratory functions could adversely affect patient treatment, leading to possible earthquake-related loss of life.

Earthquake victims who are actual physical casualties, requiring treatment for breaks, bruises, and similar injuries, are not immediately affected by nonfunctioning of clinical laboratories. The long-term loss of such facilities for hospitalized earthquake casualties might have some later impact on their treatment.

Assignment of possible values to such losses, in an effort to establish numerical values, is beyond the scope of this report.

Data collection

A listing of non-hospital laboratories was prepared from those listed as "Independent Laboratories Participating in the Medicare Program" by the Washington State Department of Social and Health Services, and from listings in telephone directories. Clinical laboratories are not licensed by the State of Washington for certification.

On-site inspection was made of 22 of the total of 85 non-hospital clinical laboratories in the six counties of the study area. The following information was obtained for the buildings housing the laboratories (some buildings house more than one): location, type and year of construction, number of stories, and accessibility. The number and distribution by county is given in table 34 and figure 32, respectively. Table 35 gives a summary of data on construction types and dates.

Analysis

The location of the laboratory within a hospital will have a bearing on the nature and extent of damage to the equipment and material therein, because the laboratory will be affected by the performance of the hospital structure during a severe earthquake.

Of the 22 non-hospital sites inspected, 12 were housed in one-story wood-frame structures; 5 in concrete or mixed construction, two stories in height; and 5 in steel-frame buildings, more than two stories in height. The newer hospitals, Valley General in Renton, Evergreen in Kirkland, Harrison in Bremerton, Mason General in Shelton, and St. Peter in Olympia, have created medical complexes contiguous with the hospital campus. These new one-story structures house physicians' offices, clinical laboratories, convalescent centers, and nursing homes. Almost all are of wood-frame construction.

TABLE 34.--CLINICAL LABORATORIES IN SIX-COUNTY AREA

(Taken from "Directory of Licensed Hospitals" and "Independent Laboratories Participating in the Medicare Program", submitted by Washington State Department of Social and Health Services, written commun., 1975)

County	Hospital laboratories	Non-hospital laboratories		Clinical laboratories
	Number	Number	Field inspected	Total number
SNOHOMISH---	4	6	2	10
KING				
Area:				
1-----	6	7	7	13
2-----	8	9	7	17
3-----	4	4	4	8
4-----	2	5	2	7
Remainder--	2	3	2	5
PIERCE------	8	10	3	18
THURSTON----	1	3	1	4
MASON-------	1	1	1	2
KITSAP------	1	2	1	3
Totals--	37	50	30	87

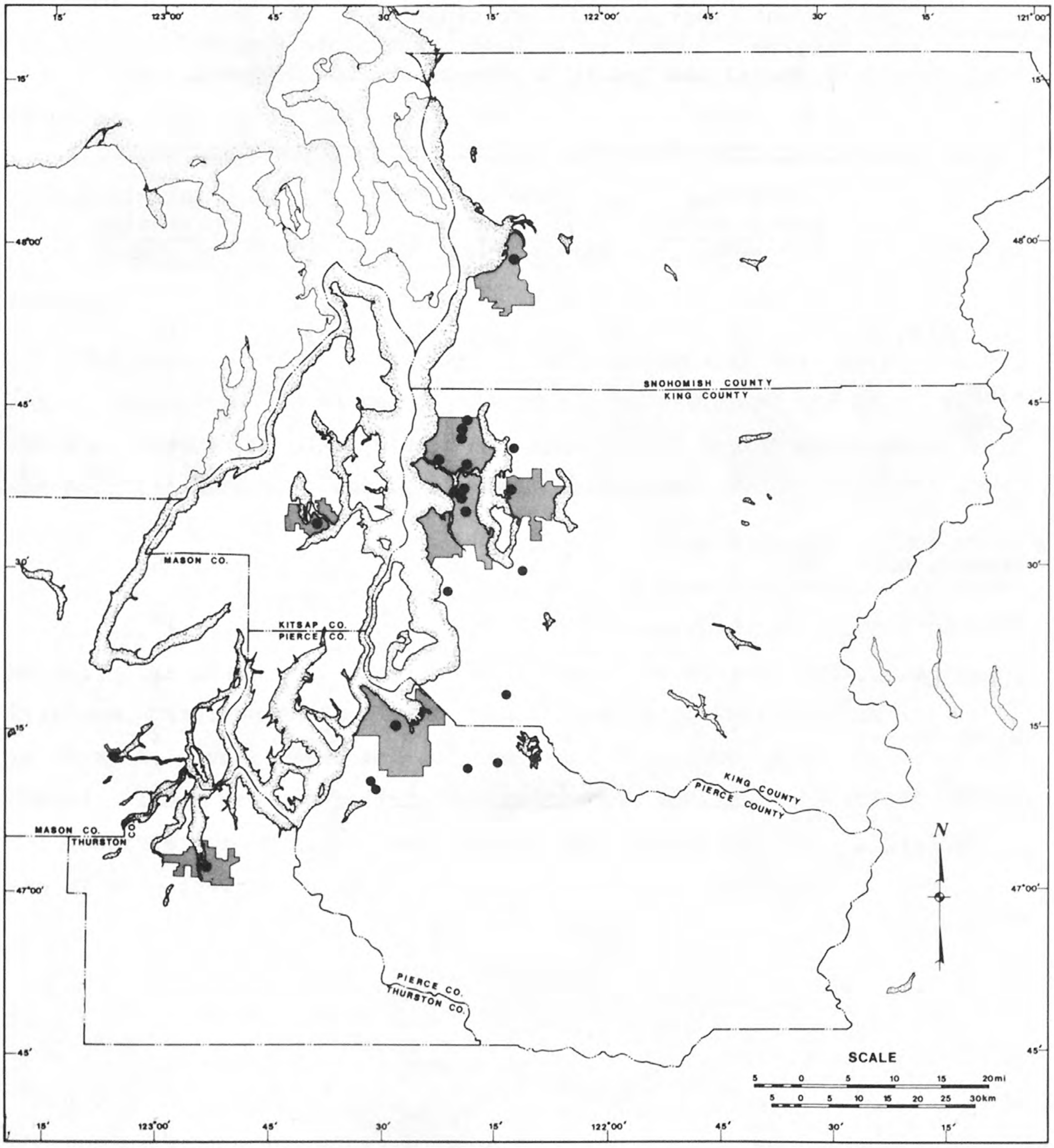


Figure 32.--Clinical laboratories. Dots represent facilities inspected in field. One dot may represent more than one facility.

TABLE 35.--NON-HOSPITAL CLINICAL LABORATORIES IN SIX-COUNTY AREA

(Includes only those structures that were field inspected by consultant staff)

County	Type of construction				Year of construction		Total buildings
	Wood frame	Steel	Concrete	Mixed	Pre-1950	1950 to 1975	
SNOHOMISH--	0	0	1	1	1	1	2
KING							
Area:							
1----	6	0	1	0	0	7	7
2----	1	2	2	2	5	2	7
3----	3	0	1	0	1	3	4
4----	2	0	0	0	0	2	2
Remainder-	2	0	0	0	0	2	2
PIERCE-----	0	3	0	0	0	3	3
THURSTON---	1	0	0	0	0	1	1
MASON------	1	0	0	0	0	1	1
KITSAP-----	1	0	0	0	0	1	1

Medical supplies

Practice may vary among hospitals with regard to the level of medical supplies maintained. In general, supplies are sufficient to accommodate continued operation of the normal practice of the hospital for a period of days, or even weeks, without resupply from wholesale houses. These supplies include normal housekeeping needs, laboratory and drug supplies, surgical materials, anaesthetics and gases, and other normal needs. Demands created in the event of a severe earthquake might vary sufficiently from the normal supply requirements to cause shortages in orthopedic and fracture materials, requiring resupply from outside sources much sooner than normal practice would foresee. Such resupply might come from unaffected wholesalers or from hospitals outside the affected area.

The Emergency Services Division of the Department of Social and Health Services, State of Washington, advises that there is just one type of prepositioned medical supply available to the study area as of March 1975. Five PDH (Packaged Disaster Hospital), a 200-bed unit with a 30-day supply of medical-surgical supplies stored in boxes, are positioned as follows: two in Snohomish County and one each in King, Pierce, and Mason Counties. The Hospital Reserve Disaster Inventory (HRDI Modules), a 30-day supply of critical medical-surgical items, previously placed in the community hospitals, have been purchased by the hospitals, and the stocks assimilated into the hospital stock. HRDI Modules, as independent modules, are no longer an emergency medical resource.

Hospitals are normally supplied by wholesalers of drug and hospital equipment from service areas near the medical facility. If the buildings and warehouses of these medical supply companies were damaged or destroyed, supplies would have to be sought in an outlying area or be brought in from distant sources. The disruption of local transportation routes could also effectively reduce delivery of supplies at a time of extreme need.

Data collection

The listings in the yellow pages of telephone directories were the principal source of data for this section, subsequently confirmed by administrative staff of the Seattle Area Hospital Council.

The locations of the major wholesale suppliers were tabulated and localized in relation to the respective zones of the study area. Table 36 indicates the number, and fig. 33, the geographical distribution of wholesale drug and hospital-equipment suppliers reviewed in this report. Table 37 lists the number of retail drug and pharmacy outlets in each of the six counties of the Puget Sound Basin.

Analysis

The losses to medical supplies for hospital use and for direct public use may be considered as the losses to supplies stocked by wholesale and by retail facilities. For study purposes, retail medical supplies are restricted to those contained in the 17 drug-wholesaler locations and to the 23 suppliers of hospital equipment in the six-county area.

The losses of medical supplies require the analysis of two factors:

1. Loss as the result of drugs falling from shelves used for storage; and
2. Building collapse on drug stocks (or buildings damaged to the extent that use and occupancy of the facilities are seriously restricted).

Retail medical supplies

Reliable loss data from 90 pharmacies experiencing the 1971 San Fernando shock are available. These losses included the results of rare instances of building damage to drug stocks, plus the usual losses of stock falling from shelves. From these data it was possible to develop a relationship between Modified Mercalli Intensity and the dollar loss to drug stocks as follows:

MMI	Percent loss (in dollars) to drug stock
IX	23
VIII	12
VII	7

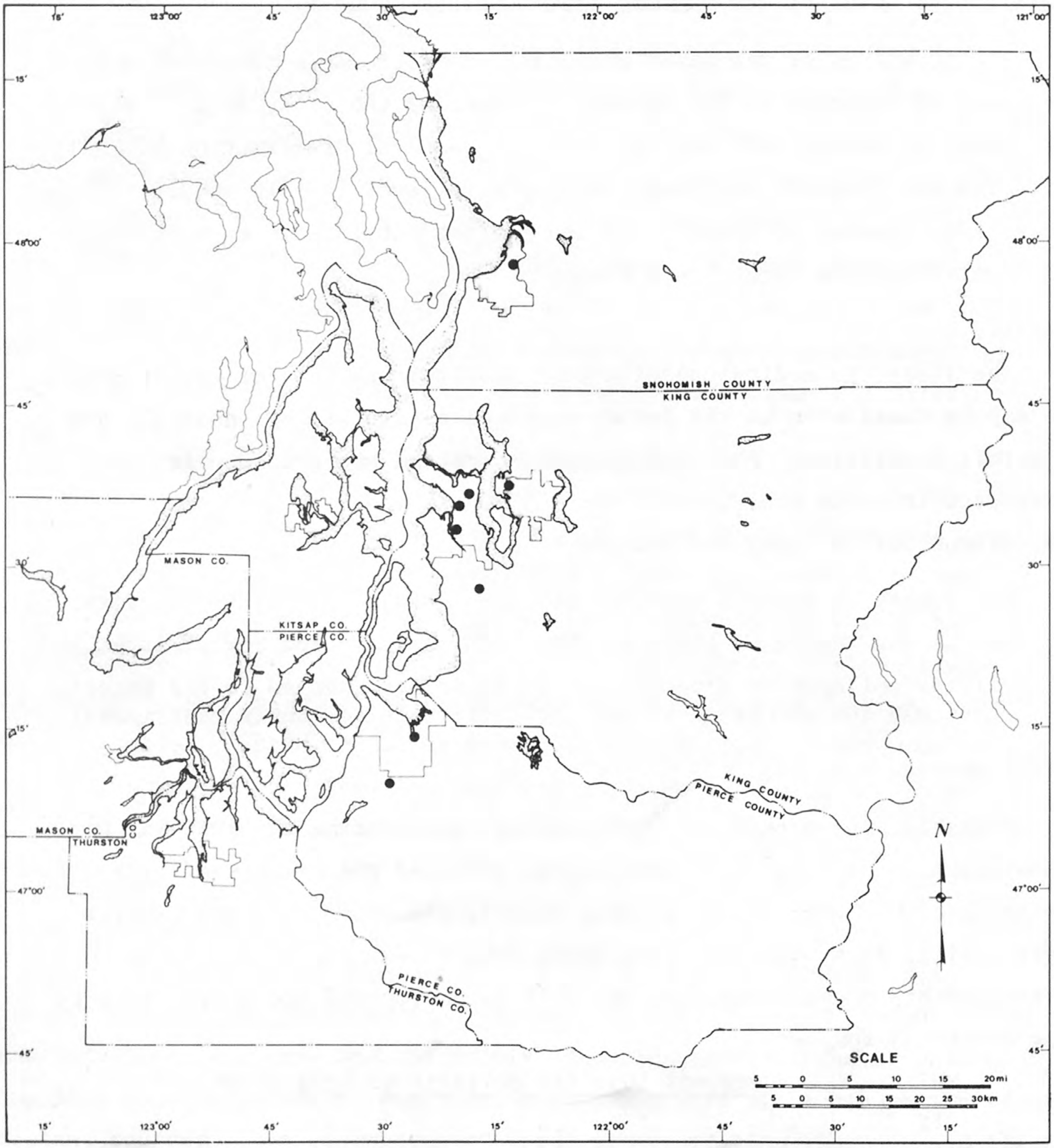


Figure 33.--Location of wholesale drug and hospital suppliers in the six-county study area. One dot may represent more than one supplier.

TABLE 36.--MAJOR DRUG AND HOSPITAL SUPPLIERS IN SIX-COUNTY AREA

(Taken from Seattle Area Hospital Council, written commun., 1975; telephone directory, 1974)

County	Number of suppliers	
	Drugs	Hospital equipment
SNOHOMISH--------	2	0
KING		
Area: 1-------	0	2
2-------	1	4
3-------	5	8
4-------	2	5
Remainder----	4	1
Subtotal-----	12	20
PIERCE-----------	3	3
THURSTON---------	0	0
MASON------------	0	0
KITSAP-----------	0	0
Totals-	17	23

TABLE 37.--RETAIL DRUGSTORES AND PHARMACIES IN SIX-COUNTY AREA

(Taken from Washington State Board of Pharmacy, Olympia, Wash.)

County	Number
SNOHOMISH------------------	65
KING-----------------------	318
PIERCE---------------------	87
THURSTON-------------------	21
MASON----------------------	8
KITSAP---------------------	29
Total--------	528

The relation expressed in the preceding paragraph can be used directly in the study areas having the same Modified Mercalli intensities, based upon the reasonable assumption that the average construction of buildings housing pharmacies will not differ greatly in the six-county study area from that in San Fernando.

The 1971 San Fernando shock occurred before pharmacies were open, and personnel had opportunities to take care of personal problems before reporting for work. In many cases, the delay in opening pharmacies located in the lower intensity zones appeared to be a result of the general confusion and the delayed arrival of personnel as much as the cleaning up of fallen shelf stock. Several downtown stores delayed opening for a number of hours, even though reported stock losses were zero and the buildings were not damaged.

In the analysis summarized in table 38, the percentages of MMI VIII and IX, shown in table 39, in the various urban areas, and the estimated percentages of MMI VII for the postulated earthquake were multiplied by the loss percentages given above.

The percentage losses in table 38 do not reflect additional losses due to inclement weather, when water will leak through damaged roofs, walls, and windows. Losses in table 38 should be increased by 5 percent if inclement weather is encountered (that is, 20 percent becomes 25 percent).

The occurrence of earthquake "A" will result in higher-than-average drug losses in the Olympia area of Thurston County. Because this area also serves a good portion of Mason County, transportation facilities could be critical if rerouting of traffic or temporary repairs require a time period of more than a few days.

In the assumed condition of earthquake "B", with the epicenter nearer Seattle than Olympia, the highest average loss to drugs will be in the Seattle area, particularly in the older areas with multistory buildings.

Wholesale drug and hospital equipment suppliers

The percentage-loss figures for the dollar loss sustained by 90 pharmacies in the 1971 San Fernando earthquake were also used as a basis

TABLE 38.--PERCENTAGE OF STOCK LOSSES TO RETAIL DRUGS AND PHARMACIES, BY COUNTY IN SIX-COUNTY AREA [1/]

County	Stock losses to retail drugs and pharmacies (in percent)	
	Earthquake "A" Olympia-Tacoma epicenter	Earthquake "B" Seattle epicenter
SNOHOMISH---------	6	11
KING--------------	8	17
PIERCE------------	15	10
THURSTON----------	17	10
MASON-------------	15	10
KITSAP------------	12	12

TABLE 39.--PERCENTAGE OF STOCK LOSSES TO WHOLESALE DRUGS AND HOSPITAL SUPPLIES, BY COUNTY IN SIX-COUNTY AREA [1/]

County	Stock losses to wholesale drugs and hospital supplies (in percent)	
	Earthquake "A" Olympia-Tacoma epicenter	Earthquake "B" Seattle epicenter
SNOHOMISH---------	7	12
KING--------------	12	16
PIERCE------------	12	9
THURSTON----------	0	0
MASON-------------	0	0
KITSAP------------	0	0

[1/] Increase all percentages by 5 percent during inclement weather.

upon which to estimate losses to wholesale drug and hospital supplies. The susceptibility of retail drugs to earthquake losses is considered to be greater than that of wholesale drugs, due to the fact that large portions (50-90 percent) of the wholesale drugs are stored in original cartons. However, this is partially offset by the storage of wholesale drugs in relatively high stacks and unbraced racks, and also by storage in larger warehouse-type structures, more subject to roof collapse as a result of earthquake.

The percentage losses shown in table 39 were computed by applying the loss experience on retail drugs for various intensities to the postulated earthquake intensities at the various building locations, using a modified basis to adjust for storage methods. The percentage loss figures for the various areas in King County were weighted with the total number of drug and hospital-equipment supply houses in each area to arrive at the average percentage-loss figure for King County. These losses should be increased by 5 percent in the event of inclement weather (that is, 25 percent becomes 30 percent).

The concern for damage to wholesale supplies of drugs and hospital equipment, caused by earthquake "A", is essentially limited to the three counties, Snohomish, King, and Pierce. King County will experience the greatest dollar loss to wholesale stocks, particularly in the downtown industrial area. However, suppliers in Pierce County will suffer the same 12-percent loss, as shown in table 39.

In the case of earthquake "B", the damage to wholesale medical supplies will increase in all three counties with an earthquake of 7.5 intensity at this epicenter. Again, downtown locations in Seattle and Tacoma will experience the greatest dollar loss to stocks. Transportation for these supplies will therefore be more acute, as will be the disruption of communications and utility systems.

Mortuary services

In a major disaster private mortuary companies are called upon to provide emergency services. Cooperative agreements have been established between the companies and the local Offices of Emergency Services to provide adequate care for the large number of fatalities that may be anticipated in a major disaster. A temporary morgue would be established and transportation furnished by members of the Funeral Directors Association cooperating with agencies of local government, such as a department of local works. Some mortuary companies also maintain ambulance service, which is discussed in that section of this study.

Data collection

Identification and geographical location of mortuary services have been made through the 1974 Directory of the Washington State Funeral Directors Association, and the yellow pages of the telephone directories. The same conditions apply to mortician services as to ambulance services for serviceability following severe earthquake. A vehicle will be nonfunctioning if housed in a building which collapses, or where its exit is blocked in any way. Data collection included field inspection of eight services to determine, in addition to its access from arterial street, the type and construction of the building housing vehicles; age of the building; and the vulnerability of vehicles housed there, either from damage to the structure or to adjacent structures. Approximately one-half of the services are located in densely populated areas where street access would be restricted at a time of disaster; the other half are located in residential or suburban areas with easy access. The distribution of mortuary services is indicated in table 40.

Analysis

In King County, a Natural Disaster Plan has been prepared by the Office of Emergency Services. The plan establishes a cooperative agreement with mortician services to provide adequate burial services for a large number of people at a time of disaster. Temporary morgues would be established and transportation to these would be accomplished by private companies. This plan necessitates availability of men and vehicles but only a minimum access to mortuaries. It is possible that a vehicle might serve as an ambulance as well as a hearse if that were the need at the time of an actual disaster. On the basis of information provided by the Funeral Directors Association, modified to reflect unavailable equipment and manpower owing to earthquake losses, it is estimated that 33 vehicles and 66 men would be available in King County to respond to a major disaster. Other counties should note that King County's Disaster Plan calls for mutual assistance between law enforcement agencies, the American Red Cross, the Funeral Director's Association, the Public Works Department, and the Emergency Medical Coordinator.

TABLE 40.--DISTRIBUTION OF MORTUARIES IN THE SIX-COUNTY AREA OF THE PUGET SOUND BASIN
(From city directories and telephone directories)

County		Number
SNOHOMISH		12
KING		33
PIERCE		18
THURSTON		3
MASON		1
KITSAP		5
	Total	72

A major disaster could draw heavily upon the mortuary vehicles and personnel for services in a particular area. In a disaster involving numerous fatalities, the establishment of a temporary morgue would be required, and local mortuary capacities would not be of immediate concern. In an earthquake where the number of deaths is limited, local mortuary facilities combined with hospital morgues could accommodate immediate needs. To undertake an inventory of the mortuaries' capabilities, county by county, was beyond the scope of this report. Such a study was made for the King County Office of Emergency Services by the 365th Army Reserve Unit, in 1974, with inconclusive results.

Nursing homes

Nursing homes are not considered a resource category in terms of medical resources. Surveys made by the Office of Emergency Services for the various counties have concluded that nursing homes are almost always full. Such facilities would be unavailable in the event of a disaster, and, in any event, lack suitable emergency medical facilities or personnel.

Data collection

There are 156 licensed nursing homes in the six-county study area. The Washington State Department of Social and Health Services is charged with the responsibility of licensing nursing homes in accordance with rules and regulations established by the State Board of Health. In addition to meeting health and sanitation requirements, nursing homes must also meet fire safety requirements established by the State Fire Marshal.

Because nursing home occupants lack the mobility of the general populace, data were collected for large nursing homes, with bed capacities exceeding 200 beds, as follows: location, type of construction, number of stories, materials of construction, year built. Table 41 shows the distribution of nursing homes throughout the six-county area according to bed capacities.

Analysis

Nursing homes, while they do not constitute a resource, may become potential problems as their occupancy status remains essentially the same regardless of the hour of a disaster, and they house many incapacitated people. Damage to the structures might lead to a higher percentage of casualties among frail individuals than would be experienced among occupants of apartment buildings or offices.

TABLE 41.--NURSING HOMES IN THE SIX-COUNTY AREA, PUGET SOUND BASIN
(Data from Directory of Licensed Nursing Homes, January 1975, Washington State Department of Social and Health Services)

County	Number of nursing homes: Under 40 beds	40-99 beds	100-199 beds	200-299 beds	Total number of beds
SNOHOMISH--------	3	10	3	2	1,764
KING					
Area:					
1----------	1	7	5	4	1,929
2----------	7	5	3	2	1,256
3----------	3	11	6	2	2,016
4----------	2	2	6	1	1,235
Remainder-------	2	5	8	0	1,539
Subtotals-----	15	30	28	9	7,975
PIERCE-----------	10	15	9	2	2,804
THURSTON---------	2	2	4	0	571
MASON------------	0	0	1	0	1,000
KITSAP-----------	0	7	4	0	1,018
Totals--------	30	64	49	13	14,232

ESTIMATED CASUALTIES AND HOMELESS

Losses from causes other than dam failure

Deaths and injuries resulting from the postulated earthquakes in the six-county study area of the Puget Sound Basin will be due principally to the failures of manmade facilities, such as buildings. While earthquake-induced landslides may cause loss of life during the wet season, the type of landslide that led to the loss of 25,000-30,000 lives after the Peruvian earthquake of 1970 is not possible. Tsunamis, or seismic sea waves, have not been experienced in the study area and have very low probability because of the nature of the terrain; therefore, they will not be included in the analyses for this report.

Data collection

Historical record

Table 14 of this report is a listing of earthquakes in the United States having relevance to this study. Excluded was the 1872 Owens Valley earthquake in which 23 persons out of a population of 250-300 were killed in Lone Pine, Calif. This exclusion was based on nonrelevant construction --adobe and stone houses, usually without any kind of mortar. Foreign earthquakes normally have minimal relevance, due to construction or other differences, and were therefore also excluded from the list, although specific events are considered elsewhere in the text.

Documentation of death and injuries is less clearly stated in earthquake reports than is the damage to buildings and other property. Heart attack deaths may or may not be included, and texts leave the matter unclear in most cases. Injuries leading to deaths may be included under injuries or under deaths. The dividing line between "serious injury" and "injury" is rarely stated in reports, and the given data are often incomplete. Whether or not emotional cases were included is usually not stated, although some of these cases would have required medical attention.

Table 42 is a listing of deaths and injuries per 100,000 population

TABLE 42.--DEATH AND INJURY RATIOS, SELECTED UNITED STATES EARTHQUAKES
(Modified from "A Study of Earthquake Losses in the Los Angeles, California area", 1973)

Earthquake	Date	Time of Occurrence	Deaths per 100,000 Population	Injuries per 100,000 Population
Charleston, S. C.	Aug. 31, 1886	9:51 p.m.	45 outright; 113 total	----no record-----
San Francisco, Calif.	April 18, 1906	5:12 a.m.	124	104 serious
Santa Rosa, Calif.	April 18, 1906	5:12 a.m.	116	69 serious
San Jose, Calif.	April 18, 1906	5:12 a.m.	80	38 serious
Santa Barbara, Calif.	June 29, 1925	6:42 a.m.	45	119
Long Beach, Calif.	March 10, 1933	5:54 p.m.	26	1,300
Imperial Valley, Calif.	May 18, 1940	8:37 p.m.	18	40
Olympia, Wash.	April 13, 1949	11:56 a.m.	1	5 serious
Kern County, Calif.	July 21, 1952	4:52 a.m.	500	----no record-----
Bakersfield, Calif.	Aug. 22, 1952	3:41 p.m.	3	47
Anchorage, Alaska	March 27, 1964	5:36 p.m.	9	315
Seattle-Tacoma, Wash.	April 29, 1965	7:29 a.m.	1.5	3
San Fernando, Calif.	Feb. 9, 1971	6:01 a.m.	1/ 64 total	180 serious

1/ 52 deaths in V.A. Hospital.

for selected American earthquakes. Earthquakes with life loss of less than eight were excluded from the listing, and the 1872 Owens Valley earthquake was omitted for reasons already stated. Possibly the cutoff figure should be much larger than eight to provide an acceptable base for extrapolation; however, this casualty level matches prior experience in the study area. Furthermore, Puget Sound earthquakes have much deeper focal depths than do those in southern California; as a result, the damage and life-loss patterns are distinctly different. Similar variations apply to the Charleston shock of 1886. Also, the effect of a single major collapse can strongly affect the losses per 100,000 population; see, for example, the variations in table 42 when the deaths at the Veterans Administration Hospital from the 1971 San Fernando shock were included.

Table 42 is a useful guideline when applied with judgment and in the context of the time of day, appropriate comparative construction, and appropriate Modified Mercalli intensities. It must be clearly understood that information contained in this table cannot be used directly without consideration of the foregoing qualifications. For one example, the hazardous unreinforced brick-bearing-wall buildings are slowly being phased out in the study area, although large numbers of them still exist. This means that data from past earthquakes (such as 1933, Long Beach) may be of decreasing importance. However, the current trend to rehabilitate and reoccupy older buildings has, in the past 5 years, slowed the removal rate of this building type, and has, at the same time, increased the occupancy.

Building inventory

For realistic usage, the death and injury ratios in table 42 must be modified on the basis of a hazard evaluation of the construction types found in the study area. In turn, these modified ratios must be multiplied by the daytime and also the nighttime populations in the areas being examined.

Data on multistory construction were gathered for portions of Seattle and Tacoma and listed in table 43 by number of buildings and by story-height groupings. The areas within each city were selected on the basis of their relatively high population concentrations, relatively congested building areas, and potentially higher-than-average disaster effects; the

TABLE 43.--MULTISTORY BUILDING INVENTORY FOR SELECTED CONGESTED AREAS (Inventories furnished by Seattle and Tacoma Building Departments, current to, but not including, year indicated for each city.)

Construction material	Number of stories	Number of buildings Seattle (1974)	Tacoma (1975)
Concrete----------	4-8	8	7
	9-13	17	4
	14 up	12	7
Steel frame-------	4-8	no record	2
	9-13	5	no record
	14 up	10	0
Brick[1/]-------------	4-8	75	4
	9-13	0	0
	14 up	0	0
Mixed construction	4-8	2	3
	9-13	2	1
	14 up	6	1
	Totals	132	30

[1/] Reinforced and non-reinforced brick walls.

boundaries of these areas are shown in figure 34. The selected construction types of multistory buildings were concrete, steel frame, brick, and mixed construction.

The basic data were obtained from Sanborn map volumes. This material is proprietary and is used principally by the insurance industry. Access to the volumes was provided by the Washington Surveying and Rating Bureau. Updating was accomplished through data obtained from the Research and Evaluation Section, city of Seattle, and its counterpart in the city of Tacoma.

Heavy loss of life from earthquakes in the United States is usually associated with brick buildings, and therefore special attention has been paid to this construction type in the building inventory.

In the study area, 1950 is the dividing line between earthquake-resistive reinforced brick structures and nonresistive brick structures. This year was selected because of a virtual cessation of unreinforced masonry construction after 1950, partly due to failures experienced in the 1949 earthquake, but largely due to changes in current architectural and structural treatment. These latter changes include tilt-up concrete, curtain-wall facings, and precast facings. Additionally, life-loss statistics may be segregated into those related to building collapse (deaths within the building) and those related to parapet and appendage failure (deaths on sidewalks, on roadways, in alleys).

Table 44 is a listing of all non-earthquake-resistive brick masonry buildings, regardless of height, in the selected congested areas of the cities of Seattle and Tacoma; also included is the total lineal footage of street frontage, not including alleys, for this building type. This lineal footage becomes the basis for estimates of the number of casualties from parapets and other masonry appendages that may fall on sidewalks and streets, adjusted with consideration to the number of parapets that have been strengthened in recent years.

The count of brick buildings within the selected congested areas of the cities of Seattle and Tacoma may vary substantially, depending upon the building definition that is used. Numerous structures in the old central city areas are a series of interconnected "party wall" buildings;

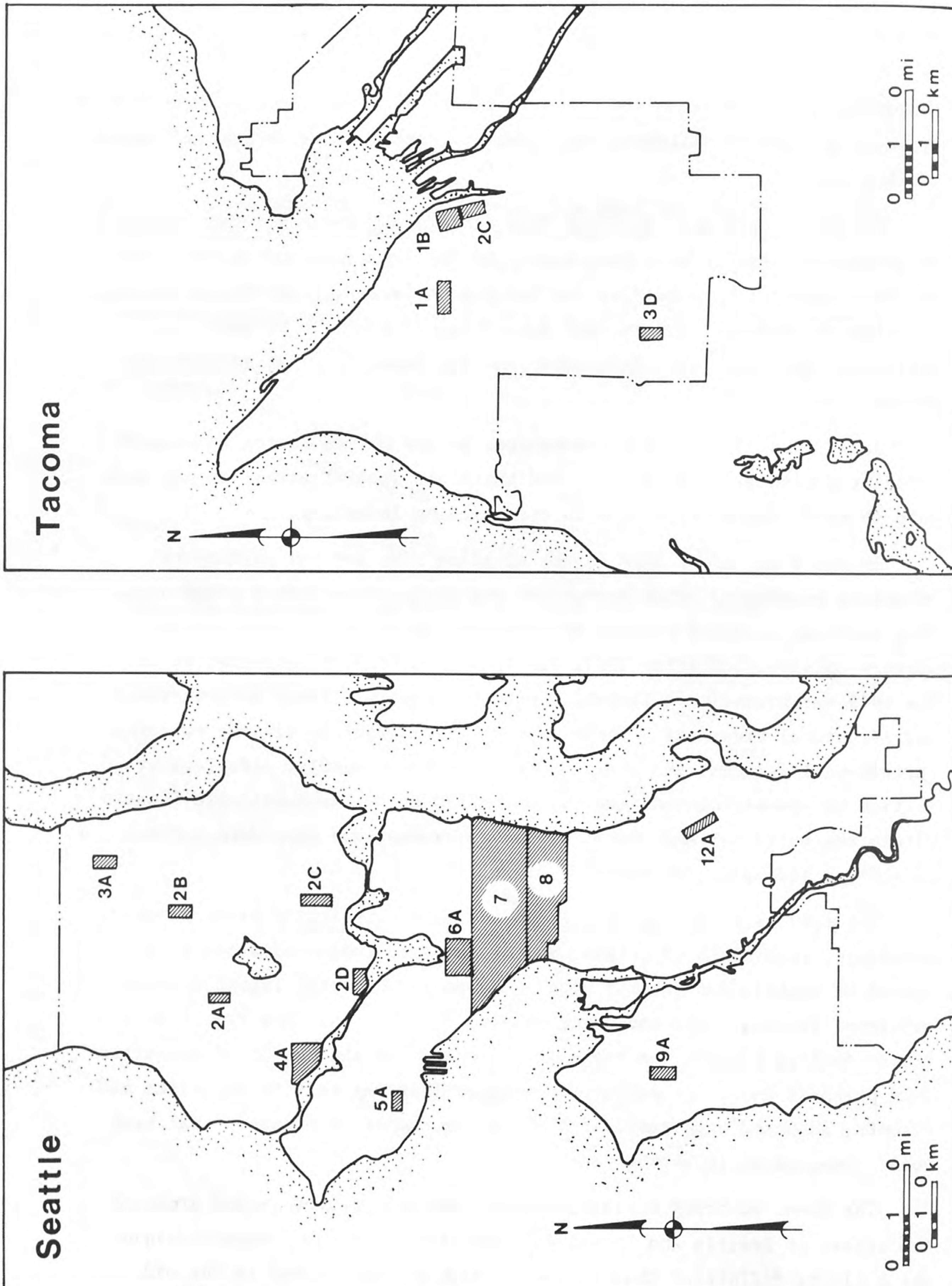


Figure 34.--Selected areas of non-earthquake resistive buildings located in the congested sections of Seattle and Tacoma. Numerals refer to areas listed in table 45.

TABLE 44.--NON-EARTHQUAKE-RESISTIVE BRICK MASONRY BUILDINGS AND THEIR STREET FRONTAGE IN SELECTED CONGESTED AREAS OF SEATTLE AND TACOMA. (NONREINFORCED BRICK BUILDINGS CONSTRUCTED PRIOR TO 1950).
(Data from Sanborn Map volumes, Washington Surveying and Rating Bureau)

City	Sanborn Map vol.	Number of buildings	Street Frontage (lineal feet)
Seattle---	1	56	4,360
	2	131	12,800
	3	40	3,200
	4	75	8,000
	5	38	3,600
	6	70	4,700
	9	23	1,600
	14	13	1,100
	15	9	590
	16	12	650
	Total-	467	Total--- 40,600
Tacoma----	1	85	9,200
	2	54	4,680
	3	27	2,800
	Total-	166	Total--- 16,680

in such cases, multiple-occupancy and separately designated buildings were counted as one in table 44, unless the party wall was parapeted above the roof line. Table 45 shows population in congested areas.

In 1949, no major community in the Puget Sound Basin had ordinances covering parapet removal. As a result, the "Unsafe Building" portion of the applicable building codes was used to force the removal of parapets and some building modification immediately following the earthquake. In 1956, both the city of Tacoma and the city of Seattle enacted ordinances with respect to unsafe buildings, relating to anchorage of parapets and strengthening of construction. The city of Seattle has subsequently adopted Ordinance 162219, dated June 4, 1973, relating to alterations and repairs of existing buildings, reducing the seismic requirements for older buildings. In the years following 1949, a number of older buildings damaged in that earthquake were demolished, while others were reduced to a safer total height.

Dwelling data

Within the six-county study area, single-family dwellings of wood construction far outnumber those of brick or masonry. This construction is inherently safe. Buildings containing many housing units, such as apartment buildings, are often of fire-resistive construction or of mixed construction using either unit masonry or reinforced concrete. These multiple-unit structures are often much more vulnerable to earthquake damage than is a single-family wood-frame dwelling.

The 1970 census provides, in a generalized way, one convenient method for relating the population to the type of housing in the urbanized areas of the six counties. Table 46 shows dwelling and population data for all urbanized areas in the six-county study area, outlined in figure 35.

According to the 1970 census, the population of the urbanized area is 1,171,428, while the total population of the entire six-county study area is 2,019,600. Although some of the suburban areas may not be accurately represented through the use of these urbanized-area data, the error is not significant in number and not otherwise significant because suburban and rural areas tend to have fewer earthquake problems.

TABLE 45.--POPULATION IN SELECTED CONGESTED AREAS
(Data from Block Statistics, Bureau of the Census, 1970)

City	Area	Sanborn Map vol.	Population
Seattle			
North----	2A	15	324
	2B	15	464
	2C	6	1,725
	2D	6	883
	3A	14	1,711
	4A	5	873
	Subtotal----------		5,980
Central--	5A	16	172
	6A	4	390
	7	2	41,029
	8	1	31,905
	Subtotal----------		73,496
South----	9A	3	690
	12A	9	2,068
	Subtotal----------		2,758
	Total Population-----		82,234
Tacoma-----	1A	1	2,656
	1B	1	1,418
	2C	2	708
	3D	3	432
	Total Population-----		5,214
Everett----	A	1	2,730
	Total Population-----		2,730
Olympia----	A	1	727
	B	1	3,699
	Total Population-----		4,426
Bremerton--	A	1	1,257
	Total Population-----		1,257

TABLE 46.--SELECTED DWELLING AND POPULATION DATA FOR URBANIZED AREAS IN SIX-COUNTY STUDY AREA
(Data from Block Statistics, Bureau of the Census, 1970)

		Year-round dwellings by number of units				
County	Area 1/	One Unit	Two-Nine Units	Ten or more Units	Total Units	Population in urbanized areas
SNOHOMISH	Everett--	14,090	3,870	2,516	20,476	53,622
	Other----	17,769	2,168	3,313	23,250	75,173
	Totals---	31,859	6,038	5,829	43,726	128,795
KING-----	Seattle--	132,783	39,906	49,206	221,895	530,831
	Other----	50,617	9,258	10,754	70,629	209,460
	Totals---	183,400	49,164	59,960	292,524	740,291
PIERCE---	Tacoma---	43,281	7,644	7,725	58,650	154,581
	Other----	31,588	8,422	4,290	44,300	2/ 162,949
	Totals---	74,869	16,066	12,015	102,950	317,530
THURSTON-	Olympia--	6,725	1,555	896	9,176	23,111
	Other----	3,887	691	813	5,391	15,069
	Totals	10,612	2,246	1,709	14,567	38,180
MASON----	Shelton--	1,951	262	131	2,344	6,515
KITSAP---	Bremerton	7,627	3,749	828	12,204	35,307
	Other----	1,139	219	34	1,392	3,904
	Totals---	8,766	3,968	862	13,596	39,211

1/ Other denotes urbanized communities of more than 2,500 population.

2/ Includes Fort Lewis and McChord AFB.

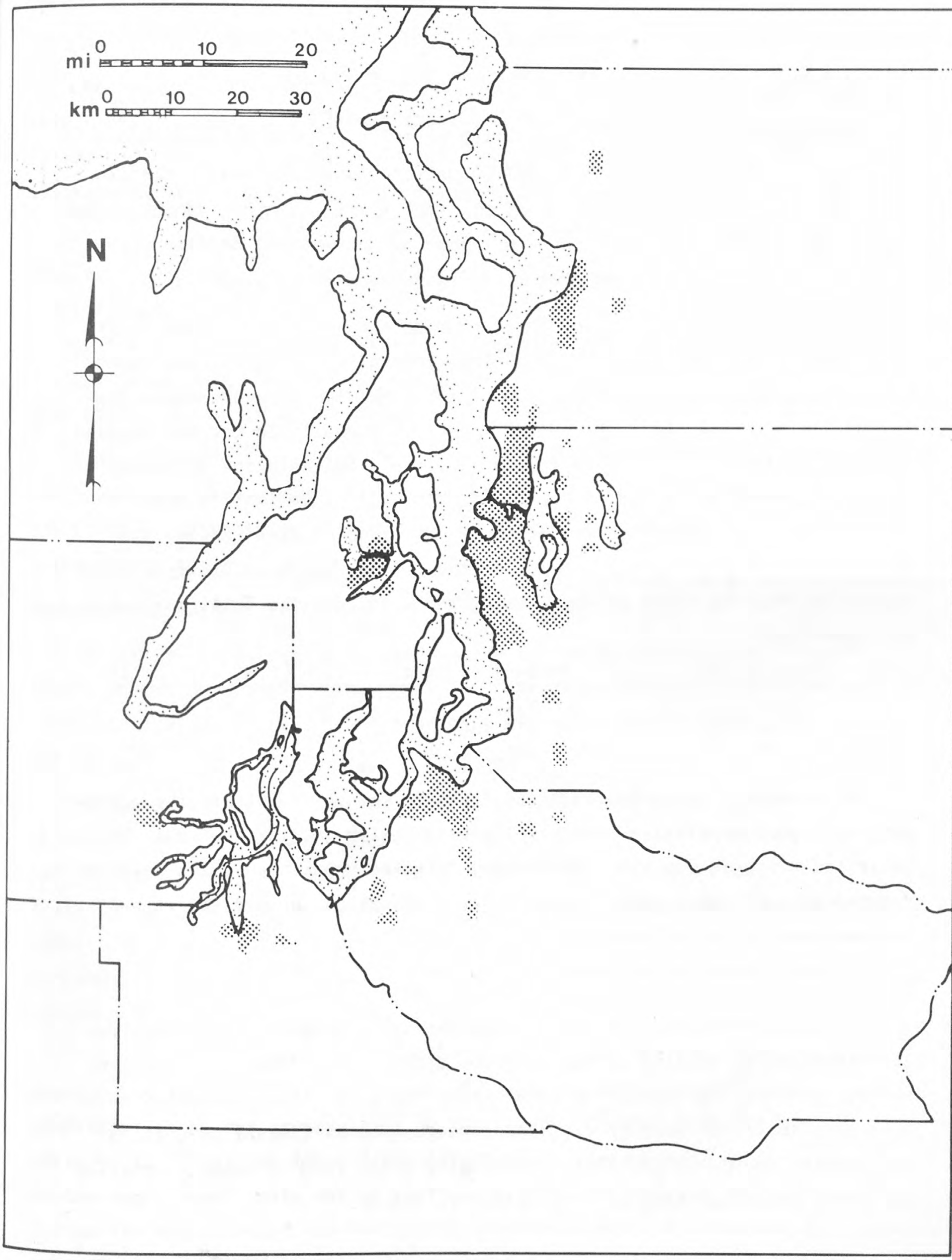


Figure 35.--Shaded areas indicate urbanized communities discussed in text.

Day-night population shifts

Information on day-night population distributions is of substantial importance with respect to potential casualties, and accurate statistics for analysis purposes are most difficult to obtain. At night, much of the population has shifted from the higher-than-average hazard usually found in the congested areas to the relatively safe wood-frame dwellings.

The authors are not aware of detailed data on peak population shifts with respect to time of day for any urban community within the six-county area. Employment estimates compiled by the Puget Sound Governmental Conference in 1970 and the 1970 Housing Census were available for the central business district of Seattle. This area closely approximates the total of areas designated as 5A, 6A, 7, and 8 in figure 34. The traffic department of the city of Seattle furnished records of cordon studies showing the movement of the populace in and out of the central business district of Seattle at various times of day. Using these sources the following table was developed:

Time of day	Persons in area	Ratio (2:30 a.m. as 1)
2:30 a.m.	124,766	1.00
2:00 p.m.	214,166	1.72
4:30 p.m.	165,166	1.32

With respect to other urbanized areas in the six counties, the aggregate day-night population shifts are substantially smaller than for the congested areas in Seattle. Therefore, detailed population-shift data for those areas will have comparatively little effect on the overall casualty calculations.

Analysis

As has been stated, casualty estimates are determined by population distributions as related to construction types, earthquake intensity, and special geologic or foundation conditions. In turn, these overall figures must be adjusted to suit specialized factors such as freeway casualties and special occupancy casualties, including those from schools, hospitals, and other buildings with high occupancy ratios.

Because the population spends much of its time in dwellings, a desirable starting point is the determination of the relationship between population and dwelling-construction type. Short of making field surveys, relevant information can be derived from the census figures and table 46.

The population in the one-unit structures is principally housed in wood-frame dwellings, which have had a minimum of earthquake casualties and for which substantial favorable-experience data exist. The population in the two- to nine-unit structures will have a somewhat higher risk, while a significant portion of the population in the structures having more than nine units will be in multistory apartment buildings.

In all of the discussion that follows, casualty figures are restricted to the six-county study area. In the event postulated earthquake "A" should occur, casualties will also occur outside the six-county area, particularly in Lewis and Cowlitz Counties.

Nighttime casualties (2:30 a.m.)

Nighttime casualties are based on the fact that the populace is essentailly in its dwellings at that hour. A reasonable death ratio for persons in single-family dwellings in the hardest hit areas (MMI IX) is 12 deaths per 100,000.

Often structures containing two to nine units are more than one story in height, and frequently they are of a construction type that is not as safe as wood frame; as a result a higher death ratio is expected. The death ratio for structures with ten or more units includes the long-period effects on high-rise structures, namely, that high-rise buildings are proportionately more affected at larger distances from the epicenter than are low structures.

In general, the calculation methodology for the San Francisco and Los Angeles studies was followed, except that details were adjusted to local conditions of no surface faulting in the six-county area. An average ratio of 12 deaths per 100,000 population was assumed for urbanized areas in the Puget Sound Basin for an earthquake with a postulated magnitude of 7.5 at the epicenter of the April 1949 earthquake near Olympia, and 12 per 100,000 for an earthquake with a postulated magnitude of 7.5 at the epicenter of the April 1965 earthquake between Seattle and Tacoma. Obviously, the average death ratio for any area within the six-county area varies as functions of the construction types, foundation conditions, and distance from the epicenter.

The many uncertainties regarding the number of casualties and the nature and gravity of injuries made the development of statistics from previous records of very doubtful value. A ratio of four serious injuries to one death was assumed for planning purposes, with serious injuries defined as those requiring hospitalization, however brief. The ratio of 30 injuries to one death was assumed for nonserious injuries. The summary results of the calculations are shown in table 47.

Daytime casualties (2:00 p.m.)

The life-hazard problem is more complicated and less subject to reliable analysis for daytime earthquakes than for those occurring at night. Many of the 2,019,600 persons in the six-county area will be at work in structures that are not as safe as their wood-frame residences. The others will still be at home, in shopping areas of not much greater hazard than their single-family homes, in safe schools, in moderately safe industrial plants, in office buildings of various quality, and the like. Some will be on the streets in the more hazardous areas. At 2:00 p.m., the streets will not be as crowded as during the commuting hours.

The daytime casualty calculations may be broken into the following categories:

1. Persons experiencing no more than average nighttime earthquake hazards;
2. Persons in the congested areas where the hazard is the highest;
3. Persons in intermediate hazard areas; and
4. Special hazards (schools, freeways, hospitals, fire).

For the six-county study area, 40 percent of the population, or about 808,000 persons, may reasonably be estimated to have about the same general hazard as that of the nighttime population. The process of determining the geographic distribution of deaths by proportion from the nighttime figures then becomes simple.

TABLE 47.--DEATHS AT THREE TIMES OF DAY IN THE SIX-COUNTY AREA FOR TWO POSTULATED EARTHQUAKES 1/

County	Earthquake "A"--Olympia-Tacoma epicenter		
	2:30 a.m.	2:00 p.m.	4:30 p.m.
SNOHOMISH	10	80	90
KING:			
Area 1	13	167	184
2	11	935	1043
3	15	101	111
4	9	15	17
Remainder	12	132	145
Subtotals	60	1350	1500
PIERCE	30	300	320
THURSTON	4	70	70
MASON	1	10	10
KITSAP	5	40	40
Totals	110	1850	2030

County	Earthquake "B"--Seattle epicenter		
	2:30 a.m.	2:00 p.m.	4:30 p.m.
SNOHOMISH	10	100	100
KING:			
Area 1	17	183	201
2	15	1035	1140
3	17	106	116
4	14	24	26
Remainder	17	152	167
Subtotals	80	1500	1650
PIERCE	20	270	300
THURSTON	4	60	70
MASON	1	10	10
KITSAP	5	40	40
Totals	120	1980	2170

1/ For planning purposes, a ratio of 4 injuries to 1 death was assumed with serious injuries defined as those requiring hospitalization, however brief. The ratio of 30 injuries to 1 death was assumed for nonserious injuries.

Data on selected congested areas are given in tables 43-45, and some of their geographic locations are shown in figure 34. By no means do the foregoing include all of the congested areas, but they do place the necessary emphasis on the older business areas where construction is poorer and resulting loss of life will be heaviest. Clearly, the city of Seattle dominates the multistory-building categories and congested-population figures.

As one basis for analysis, the death ratio in Anchorage in the 1964 Alaskan earthquake can be used. Table 42 indicates that the ratio was 9:100,000 for this earthquake, which occurred late in the day on Good Friday. Based on extensive building investigations made by the authors after the 1964 shock, 100 deaths would have been reasonable if the hour had been earlier and if the buildings under construction had been completed. Metropolitan Anchorage had a population of 100,000 at the time of the earthquake, with about 50,000 within the city limits. If the population in homes, in schools, and in low wood-frame buildings were discounted, then the downtown population at the time of the estimated 100 deaths would be estimated to have been not more than about 20,000. This would give a death ratio of 500:100,000.

Another approach may be used. Using the ratio of three major building collapses in Anchorage per 20,000 congested-area population, a proportional figure developed for Seattle would be $3 \times \frac{82,234}{20,000}$, or 12 equivalent major building collapses.

A death ratio of 480 deaths to 100,000 population at MMI IX, the experience of Caracas, Venezuela, was reviewed. Most of the 12 high-rise buildings that collapsed there in the 1967 earthquake were modern earthquake-resistive structures designed to meet one-half the standards required for Seattle buildings. The average death rate was roughly 40 deaths per building, or 480 deaths, at earthquake forces possibly equal to those expected at maximum conditions in Seattle.

Deaths from unanchored parapets and building appendages must be added to deaths from the collapse of buildings to determine the total estimated deaths in a congested area. One death per unbraced building was considered to be a reasonable upper limit for planning purposes.

Last, the figures in table 47 for 2:00 p.m. include special factors such as freeway collapse, high-rise building fires, school and hospital collapses, and similar items not covered by the death-ratio figures.

Daytime casualties (4:30 p.m.)

The deaths at 4:30 p.m. will be similar in number to those at 2:00 p.m., except that many of the persons who were in offices and in other places of employment will now be on the streets. The total population in the congested areas at 4:30 p.m. may be substantially less than that at 2:00 p.m.; however, the street population will be greater, resulting in increased possibility of casualties from parapet and appendage hazard, and freeway collapse. One mitigating factor on overall casualties is the fact that schools are generally closed before 4:30 p.m. and most children have returned to single-unit dwellings.

Homeless

Data on the past performance of single-family wood-frame dwellings in earthquakes are summarized in Algermissen and others (1969). In addition, a detailed study on dwelling performance in the 1971 San Fernando shock is available (Steinbrugge and others, 1971). These sources identify the dollar losses to wood-frame dwellings but do not state at what damage level the houses were evacuated. Indeed, there probably was no consistent practice in this regard; in some earthquakes, social needs were sometimes confused with safety requirements when it came to building condemnations. For the purposes of this report, wood-frame dwellings suffering 50 percent or greater loss are considered to be uninhabitable, as the utilities are usually inoperative, doors will not open or close, and the buildings often have substantial structural damage. On this basis, the backup data used from the detailed study of the San Fernando earthquake may be summarized as follows:

1. For pre-1940 dwellings in MMI IX zones, 2 percent of the wood-frame dwellings had 50 percent loss or more; and
2. For post-1940 dwellings in MMI IX zones, 0.3 percent of the wood-frame dwellings had 50 percent loss or greater.

In the 1933 Long Beach earthquake, 1 percent of the wood-frame dwellings in the city of Compton had 50 percent loss or greater.

Wood-frame single-family dwelling construction in the Puget Sound Basin is probably inherently stronger than that in California because of the preponderant use of plywood sheathing on walls, roofs, and floors, and the limited use of exterior gypsum sheathing or stucco in the past. On the other hand, most houses have brick chimneys, frequently on one exterior wall.

The data for the 1971 San Fernando earthquake and for the 1933 Long Beach earthquake provide conservative upper limits for the analyses in this study. Lower intensity values were determined by interpolation. In San Fernando a portion of the damage to structures was related to surface rupture. The Puget Sound Basin has not experienced surface rupture, thus making it necessary to use the California statistics even more conservtively.

Multiple-unit dwellings, such as apartment houses, vary in kind of construction materials, often depending upon location within a fire zone. Construction also varies by occupancy and building type as defined by respective municipal agencies. Multiple-unit structures located in the high density, urbanized sections are often multistory and are constructed of heavier mass materials than wood frame. On the other hand, wood-frame multiple units are more common elsewhere, in the areas characterized as lower density zones (both urban and suburban). This follows from building code provisions that commonly limit wood-frame construction to three stories in height; any structure with a greater number of stories may generally be classified as having a structural system of heavy timber, masonry, concrete, or steel. Multiple-unit structures constitute an average of 34 percent of dwelling units in the six-county study area. Puget Sound Basin communities lack large areas of high-density, high-rise multiple-unit dwellings, but have a large proportion of wood-frame multiple units, many built as speculative ventures, with limited quality control in construction.

The calculations used to derive the values shown in table 48 include the comparative numbers of single-family wood-frame dwellings and multi-unit structures of various construction types. The geologic hazards of landslide and poor ground conditions were included as factors in the analysis. Extensive areas of steep sidehills having weak clay lenses, related to the glaciation, and alternating periods of sedimentation create much landslide potential. These factors have not affected large numbers of homes or people in the past, but may become more of an exposure element with future population growth.

"Long-term homeless" is defined as being homeless for one week or longer. "Long-term homeless" also includes families remaining on the premises (indoors or out), but with loss of public utilities and (or) building damage to make the structures uninhabitable under nonemergency conditions.

TABLE 48.--POPULATION MADE HOMELESS BY POSTULATED EARTHQUAKE DISASTER EXCLUSIVE OF LOSSES FROM DAM FAILURE OR FIRE

	Earthquake "A" Olympia-Tacoma epicenter			Earthquake "B" Seattle epicenter		
	Population			Population		
County	Urban	Rural	Total	Urban	Rural	Total
SNOHOMISH--	770	60	830	1,190	260	1,450
KING						
Area						
1----	690	0	690	6,050	0	6,050
2----	650	0	650	2,370	0	2,370
3----	2,050	0	2,050	4,280	0	4,280
4----	390	0	390	1,380	0	1,380
Remainder-	2,840	510	3,350	3,660	890	4,550
Subtotals	6,620	510	7,130	17,740	890	18,630
PIERCE-----	7,820	190	8,010	2,300	190	2,490
THURSTON---	300	110	410	300	50	350
MASON------	160	30	190	58	30	88
KITSAP-----	380	140	520	380	160	540
Totals---	16,050	1,040	17,090	21,968	1,580	23,548

Losses from dam failure

The near catastrophic failure of the Lower Van Norman Dam in the 1971 San Fernando, Calif., earthquake pointed up the need for reviewing the earthquake-design criteria for dams in seismic areas, and for evaluating the potential effects of failure of any of these structures. Although it is very reasonable to assume that recently constructed major dams have incorporated adequate earthquake-resistive criteria in their designs, the consequences of error in these criteria may be enormous. The San Fernando earthquake demonstrated that ground accelerations can occur which are significantly higher than most engineers, seismologists, or geologists would have anticipated, and which are considerably in excess of those customarily used for the design of dams. This section of the report is limited to a review of the dams, reservoirs, and locks in the six-county study area, and to an estimation of the potential life loss and extent of damage to these structures that might occur during a major earthquake.

Background information, number and capacity of dams

A total of 174 dams exist in the study area, distributed among the counties as shown in table 49. Many of these dams are small, and consequently their failures as a result of an earthquake would not be catastrophic. In addition, the failure of many of these dams would result in flood routes that would not involve highly populated areas. The failure of any of these dams, however, might be critical from the standpoint of secondary effects. A loss of water supply endangers fire protection necessary for numerous residential areas and causes the disruption of other vital public needs.

Table 50 lists some of the characteristics of the 15 storage dams and locks in the study area that have capacities greater than 4,000 acre-feet (4,900,000 m^3); their locations are shown on figure 36. Although the failure of small dams and reservoirs can cause substantial life loss, it is the sudden release of large quantities of water that can reasonably be expected to result in the largest life loss for downstream populations. It should be pointed out, however, that two of the dams are for flood control, and that normally these dams do not contain significant amounts of stored water. The earthquake hazard for these flood control dams, therefore, is negligible.

TABLE 49.--NUMBER AND LOCATION OF DAMS IN THE STUDY AREA[1/]
(Taken from Corps of Engineers, 1974, Inventory of Dams in Washington State)

County	Number of dams
SNOHOMISH----------------	34
KING---------------------	49
PIERCE-------------------	37
THURSTON-----------------	18
MASON--------------------	15
KITSAP-------------------	21
Total---------------	174

[1/]Includes all dams 25 feet (7.6 m) or more in height that impound more than 15 acre-feet (18,502 m^3) of water, and all dams more than 6 feet (1.8 m) high that impound 50 or more acre-feet (61,675 m^3) of water.

Summary of dam experience

Dams in many parts of the world have failed during earthquakes. In the United States, the earthen Sheffield Dam failed in the 1925 Santa Barbara, Calif., earthquake. In the Montana earthquake, August 17, 1959, the earthen Hebgen Dam was damaged but remained serviceable, despite being overtopped several times and despite a major fault scarp being located less than 1,000 feet (305 m) from the spillway. The partial failure of the Lower Van Norman Dam, in the 1971 San Fernando, Calif., earthquake, required the evacuation of 80,000 inhabitants.

On the other hand, several dams performed quite well in the 1906 San Francisco, Calif., earthquake. The 95-foot (29-m)-high Pilarcitos Dam, located less than 2 miles (3 km) from the San Andreas fault, was constructed in 1864-66 with an earthen puddle core; it was not damaged. In 1906, a 7-foot (2-m), right-lateral offset on the San Andreas fault passed through a knoll that formed an abutment for the two sections of the San Andreas Dam. This 93-foot (28-m)-high, earthen-puddle-core dam, constructed in 1868-70, was undamaged. The Lower Crystal Springs Dam is a concrete

TABLE 50.--CHARACTERISTICS OF SELECTED DAMS, CAPACITY OVER 4,000 ACRE-FEET (Taken from Corps of Engineers, 1974, Inventory of Dams in Washington State, written commun., 1975)

County	Name	Ownership/Purpose	Max. storage (acre-feet)	Height (feet)	Crest length (feet)	Type	Year completed
SNOHOMISH	Lake Chaplain Dam	City of Everett, Water Supply	13,200	60	940	Earth fill dikes	1944
	George Culmback Dam and Reservoir	Snohomish County, PUD No. 1, Power	48,000	203	240	Rock fill	1965
KING	Tolt Dam and Reservoir	City of Seattle, Water Supply	57,900	213	987	Earth fill	1963
	Lake Chester Morse (Crib Dam)	Seattle Water Dept., Water Supply	55,500	18	200	Timber crib; rock fill	1904
	Hiram Chittenden Locks and Dam	U.S. Corps of Engineers, Navigation	458,000	63	240	Concrete	1916
	Howard A. Hanson Dam and Reservoir	U. S. Corps of Engineers, Flood Control	106,000	235	675	Rock fill	1962
	Masonry Dam and Pool	Seattle Water Dept., Water Supply & Power	105,440	207	980	Concrete arch	1914
	Lake Youngs Reservoir	Seattle Water Dept., Water Supply	33,764	28	1,065	Earth fill dikes	1926 (height increased 5 ft in 1960)

TABLE 50.--CHARACTERISTICS OF SELECTED DAMS, CAPACITY OVER 4,000 ACRE-FEET--Continued

County	Name	Ownership/Purpose	Max. storage (acre-feet)	Height (feet)	Crest length (feet)	Type	Year completed
PIERCE	Alder Dam	Tacoma City Light, Power	231,936	320	1,600	Concrete	1945
	Mud Mountain Dam	U.S. Corps of Eng., Flood Control	106,000	425	700	Earth fill	1948
	Lake Tapps Reservoir	Puget Sound Power and Light, Power	65,000	45	4,800	Earth fill dikes	1913
THURSTON	Skookumchuck Dam and Reservoir	Pacific Power and Light, Reservoir	42,000	182	1,300	Earth fill	1971
MASON	Cushman Dam 1	Tacoma City Light, Power	478,000	280	980	Concrete arch	1926
	Cushman Dam 2	-------do--------	8,000	230	550	---do--------	1930
KITSAP	Casad Dam and Reservoir	Bremerton Water Dept., Water Supply	4,419	202	400	---do--------	1956

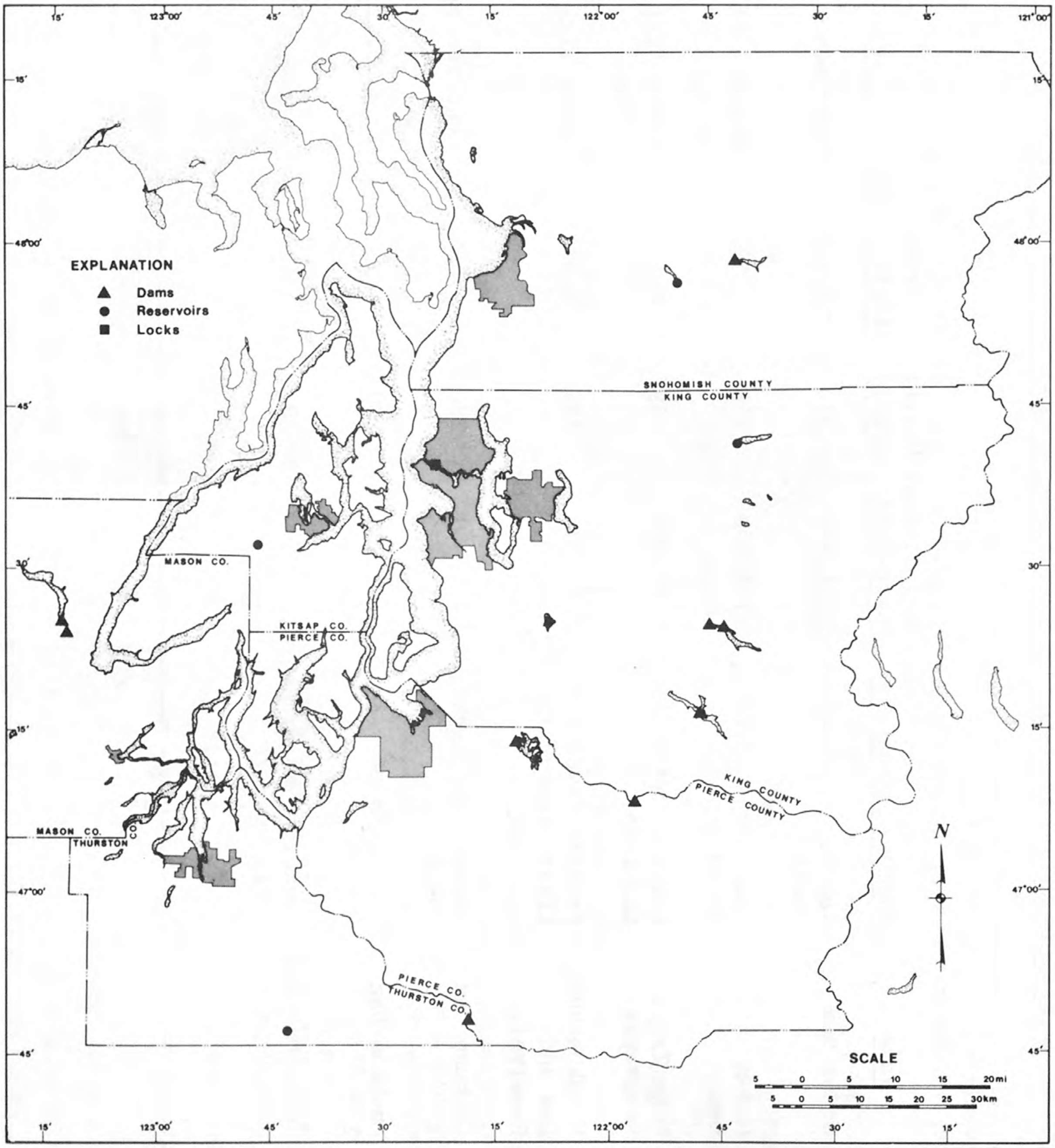


Figure 36.--Principal dams and reservoirs in the six-county study area.

dam located within a few hundred feet (70 m, more or less) of the 1906 fault breakage; it survived the 1906 earthquake without damage.

None of the dams in the State of Washington is known to have suffered any damage as a result of an earthquake.

Analysis

Although the number of major dams is small compared to the number of buildings in the study area, the rapid or almost instantaneous failure of any of the dams, listed in table 50, during a major earthquake would lead to catastrophic results for downstream populations. The lack of any known active major faults in the study area, however, largely precludes failure of this type for any of the dams listed. It is more likely that damage to one or more of the dams, which might occur during a major earthquake, would result in leakage problems and potentially require population evacuations below them. These conclusions are based on an evaluation of each of the dams listed with respect to the geologic conditions at the dam site and the type of dam construction. The intensities that might be expected from the two postulated earthquakes, at each dam site located in figure 36, are shown in figures 19 and 20.

The Lake Tapps reservoir, constructed as a series of dikes in 1913, is a hydraulic power source. Its age and construction make it suspect; however, it is habitually held at a level only 75 percent its limited capacity. No additional technical information is available regarding this dam.

Assumed failures for planning purposes

Because of the need for effective disaster-response planning, the failure of one of the major dams listed in table 50 is assumed for the purpose of this report. The dam selected for this purpose is the Howard A. Hanson Dam on the Green River, because, while failure is considered unlikely, failure of this dam is believed to be potentially the most hazardous to downstream populations. Another dam, the Crib Dam, a low, rock-filled timber crib structure, completed on the Cedar River in 1904, might be assumed to be the most likely dam to fail in the event of a large earthquake in the area. However, for planning purposes, the consequences of failure of this dam were considered to be much less than for the Howard A. Hanson Dam. The estimated number of probable deaths and homeless from failure of this dam are given below:

Dam	Homeless	Deaths
Howard A. Hanson	1,500	750

The figures shown represent the worst possible conditions, which, for planning purposes, assume both sudden failure and reservoirs that are filled to their maximum storage capacities. The estimated number of deaths are based on generalized assumptions regarding inundation areas. Numbers developed as a result of other disaster-response planning may vary considerably, due to differences in assumptions or to improvements in analysis methodology.

An assumed failure of the Hiram Chittenden Dam, or serious damage to one or both of the Locks would result in only a relatively few downstream deaths and persons made homeless, largely because the flood route is short and does not involve a highly populated area. However, the secondary effects could be significant. Not only would a vital transportation artery connecting Lake Washington and the Puget Sound be disrupted, but also, possible damage and concomitant disruption of major arterial traffic on the two Lake Washington Floating Bridges might occur. In addition, a number of homeless victims would be expected from the foundering and disabling of numerous houseboats and their sewer and water lines, and of boats, ships, and other floating structures in Lake Union and Portage Bay. Bridge closures and waterfront problems resulting from the sharp reduction in water level would last for months.

EFFECTS ON VITAL PUBLIC NEEDS

In order to function after a major earthquake, communities must provide for the supply and flow of information, people, energy, water, and goods by means of established communication, transportation, and water- and energy-distribution systems. The failure of one or more of these facilities contributes to the death and injury of inhabitants and damage to the region. The purpose of this section is to analyze, for potential hazard, those existing systems that must remain operative during and following an earthquake. Destruction or damage to any of these systems greatly affects public safety and welfare. Further, the period of time required to restore such services is difficult to estimate.

Public structures

Those buildings under the jurisdiction of city, county, state, and federal government, serving as administration and communication centers, are second only to hospitals as a class of vital public facilities. The function of these public structures, more critical than that of the average commercial building, is needed for communication, firefighting, and law enforcement, not only for disaster relief but also for post-disaster recovery.

In the event of disaster, the following agencies are considered to be most essential: communication facilities, police and fire departments, medical services, and county administration. Disaster adds to the regular duties and responsibilities of law enforcement agencies. In order to insure their ability to respond, police officers and equipment must be located in safe buildings that are of earthquake-resistive construction. Most of these structures have emergency electric generators; however, experience has shown that, although the structure may withstand the earthquake, much standby equipment may be inoperable due to damage from inadequate anchorage or to fuel supplies.

Data collection

Wherever possible, pertinent data were collected as follows: location, type of facility, year built, site description, type of construction, number of stories, area or size of building in square feet, foundation type, materials, emergency power, occupancy capacity, and cost of original building.

Data on municipal and county-owned buildings were available from the plan files of the respective city and county building departments, and from the files of the Civil Defense Support unit of Naval Facilities Engineering Command, who had made field surveys of most facilities in the six counties. In addition, several facilities in Everett, Seattle, Tacoma, Bellevue, Olympia, Bremerton, and Shelton were field inspected by consultant staff.

Most police facilities are housed in city and county administration buildings, and the consultants have some personal knowledge of other police buildings. Fire departments of Seattle, Bellevue, Everett, Tacoma, and Olympia provided information as to the number of stations, general type of construction, and the year built. Additional construction data were obtained for fire stations--seven in Seattle, two in Bellevue, three in Tacoma, and one in Everett. Figure 37 shows the location of municipal-owned facilities and figure 38 shows the location of county-owned facilities for which data were received. Tables 51 and 52 are summaries related to the municipal- and county-owned buildings covered in this report.

Data on state buildings were obtained from the plan files of the Division of Engineering and Architecture, Olympia, Wash., and from field inspections by the consultant staff. Figure 39 shows the locations of major state buildings considered in this report, and table 53 is a summary of state facilities.

Data collection and damage analysis for the state institutions providing food and shelter to the residents of mental hospitals, prisons, and special schools is beyond the scope of this study. They are a concern at a time of disaster because they house a large number of people restricted to specific buildings. The number of these multi-building complexes is shown in table 53 for information only.

Data on major, federally-owned facilities were obtained from the Construction Management Division of the General Services Administration. Figure 40 shows the locations of major federal buildings in the six-county area and table 54 is a summary of them.

Analysis

Municipal buildings

Earthquake-related problems are generally more critical in larger cities than in smaller ones; therefore, this report focuses on the cities of Seattle, Bellevue, Tacoma, Everett, and Olympia.

In the six-county area, major police departments and the communication systems are housed either in a municipal administration building or in a combined city-county administration building. Thus, the communication centers serve both the police and administrators responding to disaster. All municipal buildings have generators for emergency power.

Major municipal fire departments have communication centers with emergency power. Fire departments in smaller communities that do not have emergency power for communication purposes use an emergency-fire-radio system. The Seattle Fire Department reports that four of their fire stations have emergency power, and that the department has mobile generators that can, if necessary, be taken to a site such as the Harborview Medical Center to supplement power for emergency lighting or for elevators.

Past performance of all of the city buildings has apparently been satisfactory, because no mention of them is included in the published reports on damages caused by the 1949 and 1965 earthquakes.

As may be seen in table 55, the cities have a relatively large number of pre-1950 buildings. These include the Public Safety and City

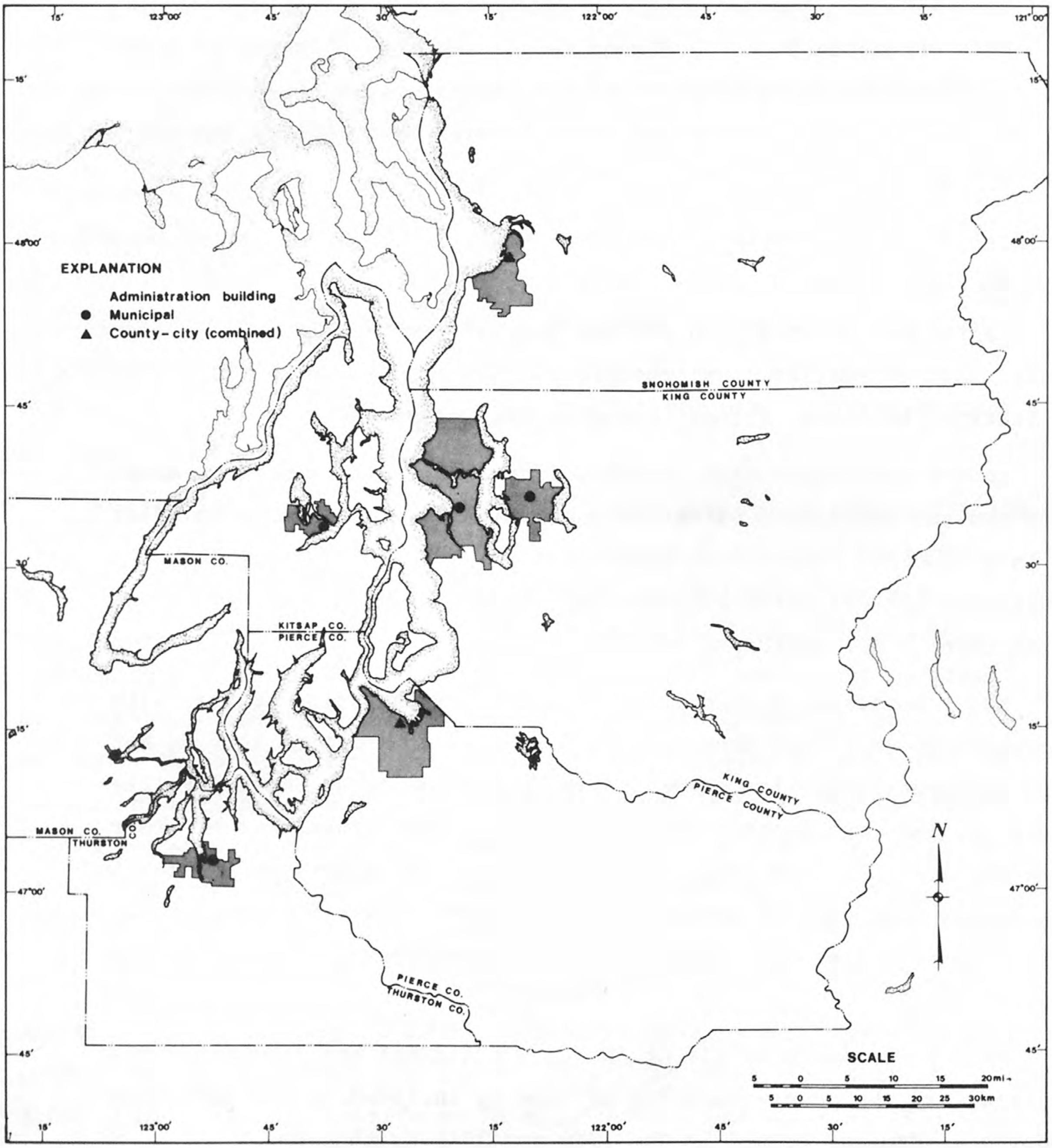


Figure 37.--Location of municipal administration buildings of essential need in each of the six counties of the Puget Sound Basin. One dot may represent more than one facility.

TABLE 51.--MUNICIPAL BUILDINGS OF ESSENTIAL PUBLIC NEED IN PRINCIPAL CITIES IN THE PUGET SOUND BASIN

Location	Administration buildings 1/	Police facilities	Fire stations	Communication centers
SNOHOMISH:				
Everett----	1	1	5	2
KING:				
Bellevue---	2	1	5	2
Seattle----	3	5	36	2
PIERCE:				
Tacoma-----	2/ 1	1	18	2
THURSTON:				
Olympia----	1	1	3	2

1/ Each administration building houses a communication center and a police facility, and is equipped with emergency power.

2/ This facility houses both city and county administrative offices.

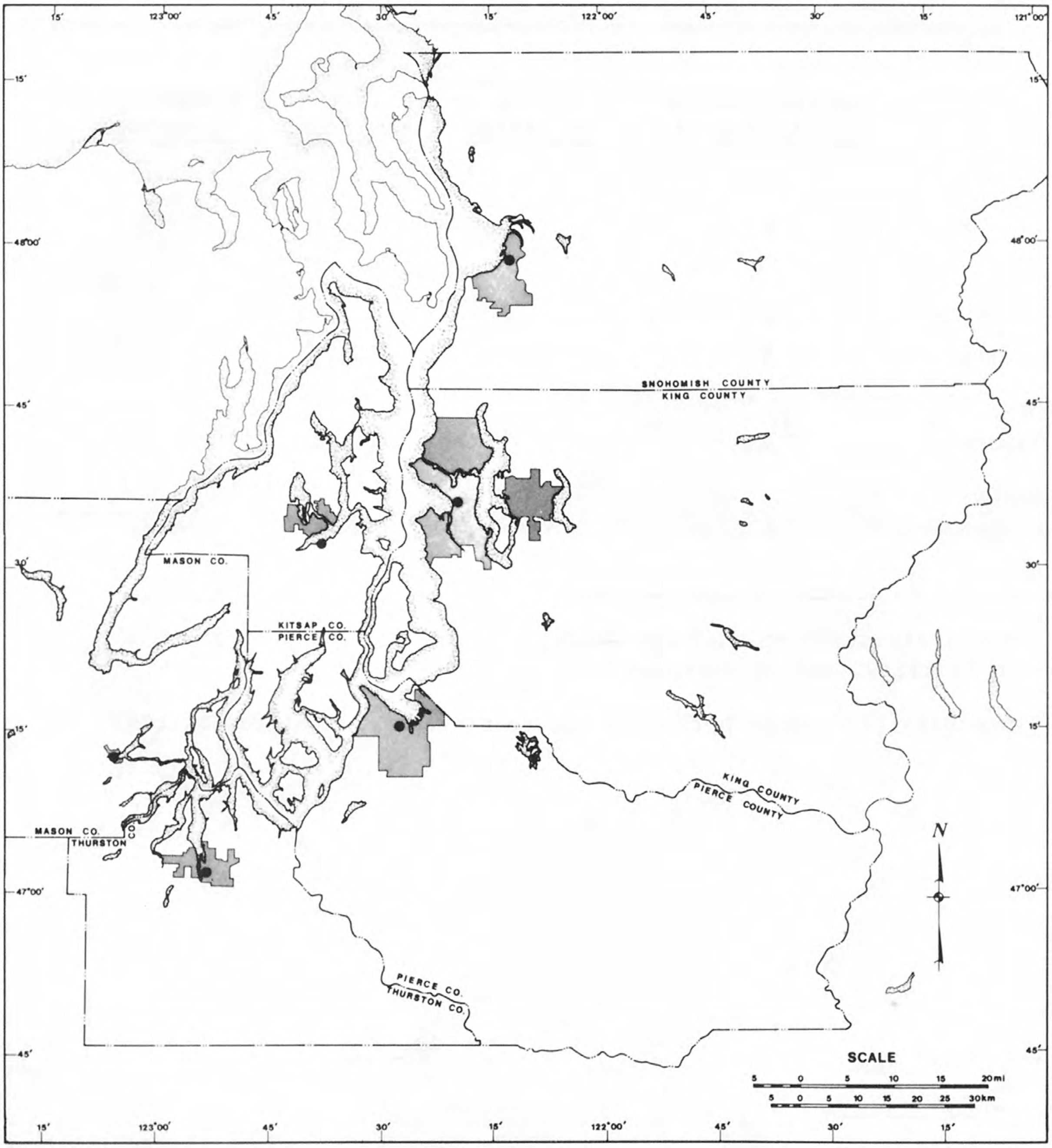


Figure 38.--Location of county buildings of essential need in the six-county study area. One dot may represent more than one facility.

TABLE 52.--COUNTY ADMINISTRATION BUILDINGS REVIEWED IN THE TEXT

County	Dates of construction of selected county buildings								
	Administration			Police			Fire		
	Pre-1950	1950-1974	Total number	Pre-1950	1950-1974	Total number	Pre-1950	1950-1974	Total number
SNOHOMISH--	1	2	3	0	1	1	Not available.		43
KING-------	1	1	2	1	0	1	Do.		119
PIERCE-----	0	1	1	0	1	2	Do.		46
THURSTON---	1	0	1	1	0	2	Do.		37
MASON------	1	0	1	1	0	1	Do.		10
KITSAP-----	1	0	1	1	0	1	Do.		24
Totals---	5	4	9	4	2	8			279

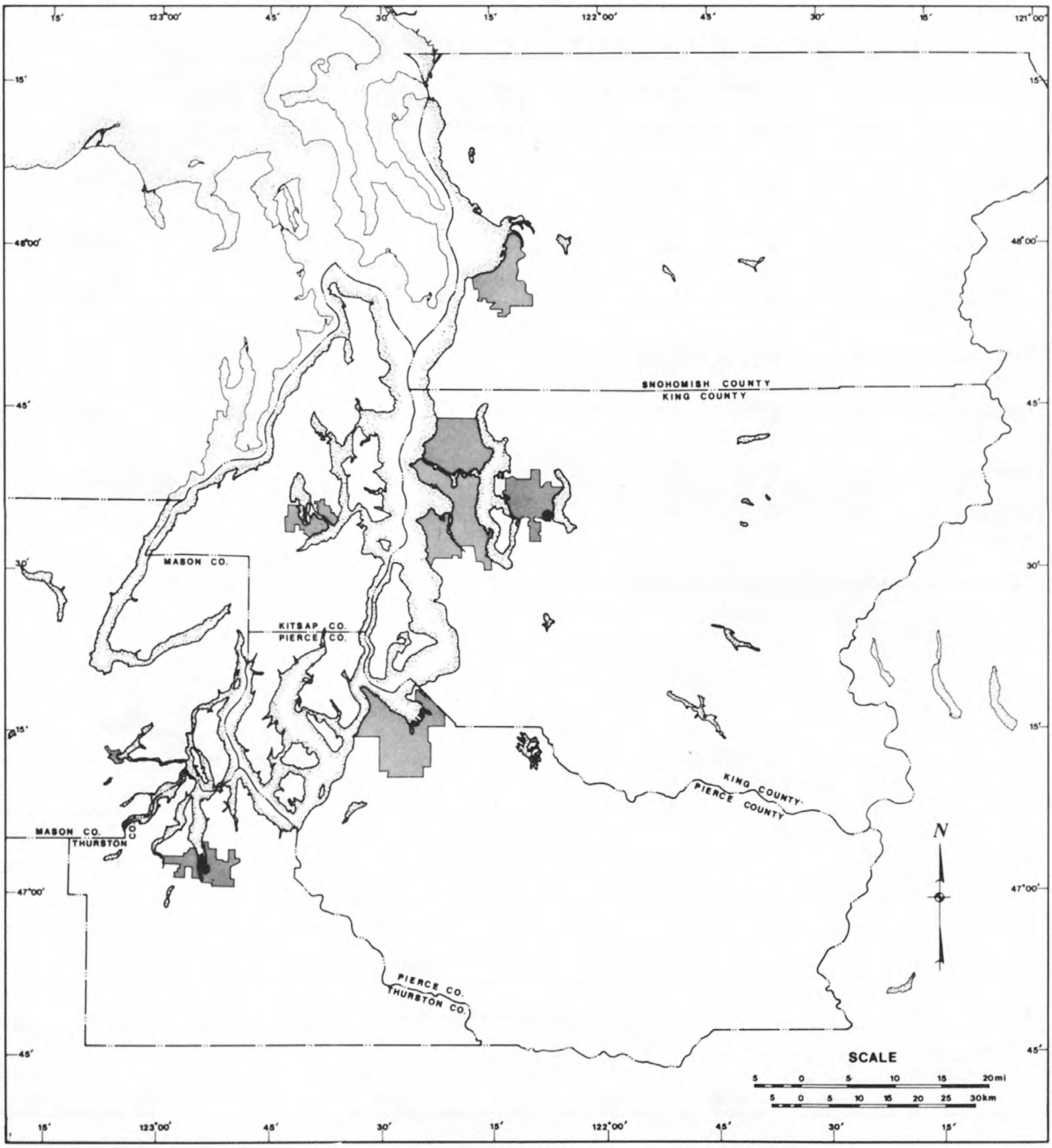


Figure 39.--Location of major State buildings of essential need. One dot may represent more than one facility.

TABLE 53.--DISTRIBUTION OF MAJOR AND ESSENTIAL STATE BUILDINGS, AND FACILITIES DISCUSSED IN TEXT

(Number in parentheses indicates number of buildings with emergency power)

County	Major and essential buildings	Washington State Patrol	Construction data collected: Administration building	Construction data collected: State Patrol	State institutions
SNOHOMISH--	0	1	0	0	1
KING-------	0	4	0	1 (1)	4
PIERCE-----	0	1	0	0	4
THURSTON---	18	1	3 (1)	1 (1)	0
MASON------	0	1	0	0	1
KITSAP-----	0	1	0	0	1
Totals---	18	9	3	2	11

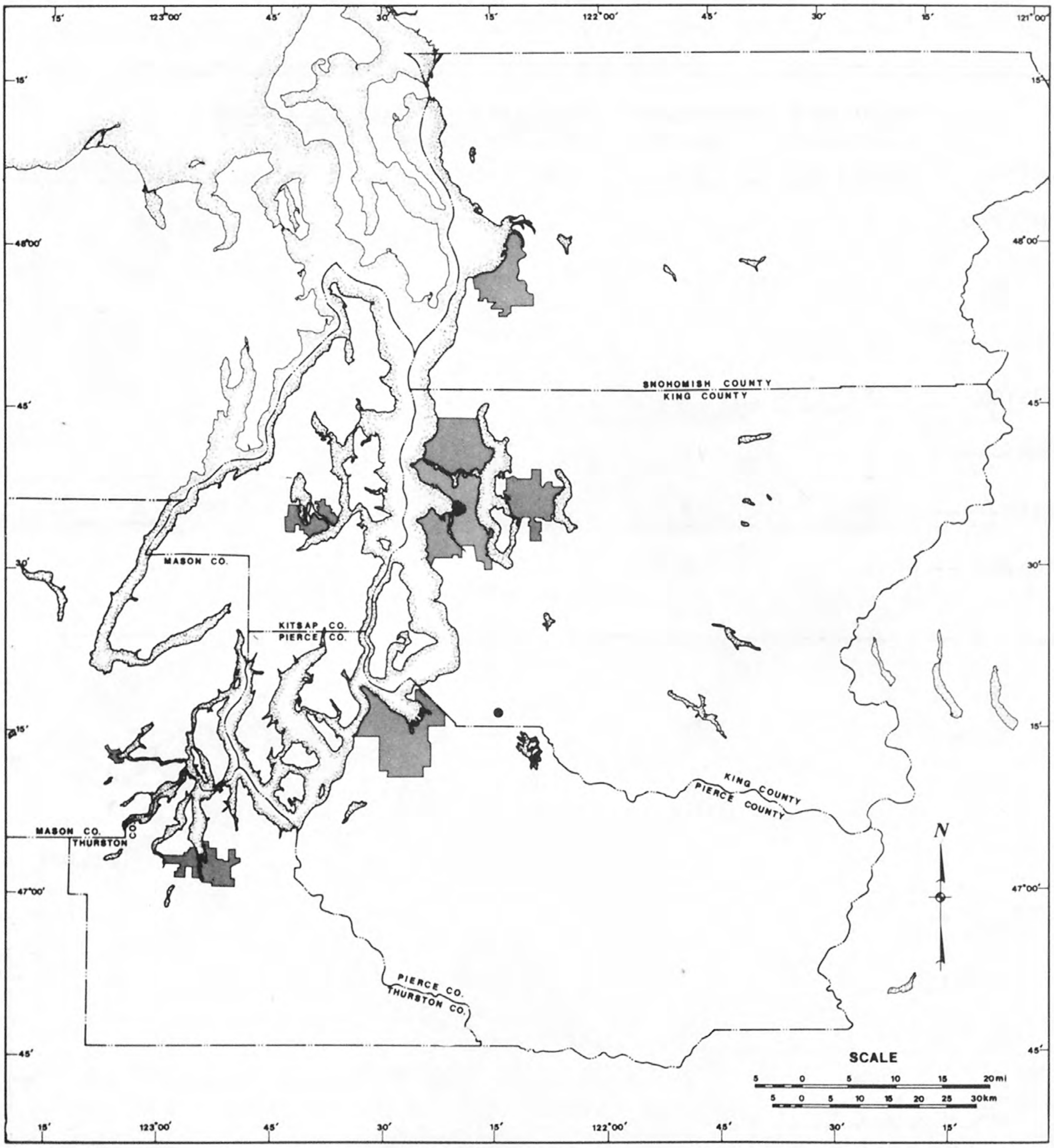


Figure 40.--Major federal buildings of essential need in the six-county study area. Dots represent several facilities.

TABLE 54.--ESSENTIAL FEDERAL BUILDINGS AND FACILITIES, EXCLUDING POST OFFICES, REVIEWED IN THE SIX-COUNTY STUDY AREA

Location	Type of structural frame	Number of stories	Year built
KING COUNTY:			
Seattle-----	steel	6	1915
	--do--	6	1927
	concrete	9	1931
	steel	2	1934
	concrete	9	1939
	steel	37	1974
Auburn------	concrete [1/]	2	1954

[1/] Complex of 12 1- and 2-story buildings, including 8 warehouses, shop, fire station, and a general administration and the Federal Aviation Administration building.

Light buildings in the City of Seattle and approximately one-half of the fire stations in the cities. This is particularly serious because the main communication facility for the Seattle Police Department is located in the Public Safety Building. Nonfunction of this building, therefore, could seriously hamper emergency operations.

Tables 55 and 56, show that the functional losses to Seattle administration buildings in earthquake "A" will be due mainly to the presence of a pre-1950, 15-story reinforced-concrete building and a pre-1950, 8-story reinforced-concrete building with a more recent 7-story tower addition. Both buildings are located in a high intensity area. The high functional loss to the Seattle police and fire buildings and to the Tacoma fire buildings will be due to the presence of many pre-1950 buildings and to the relatively high intensities induced by the postulated earthquakes in those areas.

The Bellevue administration buildings and the Tacoma administration building (which also houses the Tacoma police) are expected to have relatively minor functional losses, in spite of high intensities, because all of the buildings have been constructed recently. Expected functional losses to the Everett administration building are due primarily to the pre-1950 construction.

Table 56 indicates that postulated earthquake "B" will have a more serious effect than earthquake "A" on the buildings in Seattle, Everett, and Bellevue, and a slightly less serious effect on buildings in Tacoma and Olympia. For planning purposes, impaired use is expected to last for at least 1 month for 50 percent of the damaged buildings listed in table 56.

County buildings

The county administration buildings are listed in tables 52 and 57. Emergency power is available in each administration building and thus to sheriff facilities located therein. The locations of fire stations in the counties were determined, but other construction data were not obtained. Assumptions made about their construction types and dates of construction were based on consultants' knowledge of the local practice.

TABLE 55.--MUNICIPAL BUILDINGS REVIEWED IN THE TEXT

Location	Dates of construction of selected municipal buildings											
	Administration			Police			Fire			Communication centers		
	Pre-1950	1950-1974	Total number	Pre-1950	1950-1974	Total number	Pre-1950	1950-1974	Total number	Pre-1950	1950-1974	Total number
SNOHOMISH:												
Everett----	1	0	1	0	1	1	3	2	5	2	0	2
KING:												
Bellevue---	0	2	2	0	1	1	0	5	5	0	2	2
Seattle----	2	1	3	4	1	5	17	19	36	1	1	2
PIERCE:												
Tacoma-----	0	1	[1/] 1	0	1	1	12	6	18	1	1	2
THURSTON:												
Olympia----	0	1	1	0	1	1	2	1	3	1	1	2
Totals---	3	5	8	4	5	9	34	33	67	5	5	10

[1/] Combined county-city building.

TABLE 56.--NUMBER OF MUNICIPAL BUILDINGS DAMAGED AND PERCENTAGE OF LOSS OF FUNCTION DUE TO EARTHQUAKE DAMAGE

	Earthquake "A"							
	Administration buildings		Police buildings		Fire stations		Communication centers	
Location	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent
SNOHOMISH:								
Everett---	1	25	0	5	1	20	0	15
KING:								
Bellevue--	1	5	1	5	1	5	1	5
Seattle---	2	75	1	25	9	25	1	45
PIERCE:								
Tacoma----	1	15	1	10	9	50	1	35
THURSTON:								
Olympia---	1	35	1	25	1	25	1	30

	Earthquake "B"							
	Administration buildings		Police buildings		Fire stations		Communication centers	
Location	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent
SNOHOMISH:								
Everett---	1	45	1	10	2	40	1	25
KING:								
Bellevue--	1	5	1	5	1	10	1	10
Seattle---	2	75	1	25	15	40	1	45
PIERCE:								
Tacoma----	1	10	1	10	6	40	1	35
THURSTON:								
Olympia---	1	35	1	25	1	25	1	30

TABLE 57.--NONFUNCTIONING COUNTY BUILDINGS, OWING TO DAMAGE FROM POSTULATED EARTHQUAKES "A" AND "B", MAGNITUDE 7.5

County	Earthquake "A"--Olympia-Tacoma epicenter						Earthquake "B"--Seattle epicenter					
	Administration buildings		Sheriff buildings		Fire stations		Administration buildings		Sheriff buildings		Fire stations	
	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent	No.	Impairment percent
SNOHOMISH--	1	15	1	15	2	10	1	30	1	35	5	25
KING-------	1	50	1	80	14	20	1	50	1	80	20	30
PIERCE-----	1	15	1	15	9	30	1	10	1	10	8	25
THURSTON---	1	45	1	45	4	25	1	45	1	45	2	15
MASON------	1	45	1	45	3	25	1	25	1	25	2	20
KITSAP-----	1	5	1	5	6	25	1	5	1	5	6	25

Relatively high damage is expected to the King County administrative buildings in earthquake "A" due to the high intensity (IX) and the presence of a 1917, 10-story reinforced-concrete-frame building. Similarly high damage is expected in the Mason and Thurston County buildings, due to age and construction types of the buildings.

It is apparent from table 57 that postulated earthquake "B" will have a somewhat greater effect than earthquake "A" on buildings in King and Snohomish Counties, and a slightly less or the same effect as earthquake "A" in the other counties.

For planning purposes in the case of either postulated earthquake, impaired use is expected to last for at least 1 month for 50 percent of the damaged buildings listed in table 57.

State buildings

In the event of a major disaster, the functioning of the following state agencies is most vital: State Patrol, Administration, Communications, Highways, Public Health, and National Guard. Buildings considered essential to the functioning of these agencies are the State Patrol District Headquarters and the administration buildings, listed in table 53.

Construction data obtained for the state buildings are categorized in table 58. The consultants' knowledge of typical construction of State Patrol facilities was used to estimate the earthquake-damage susceptibility for those structures. No information was obtained on National Guard facilities.

Table 59 indicates that relatively intensive damage is expected in the old State administrative buildings, primarily because they have non-earthquake-resistive, unreinforced-masonry-bearing walls. The more recently constructed and smaller State Patrol facilities are expected to suffer relatively less damage.

Damage to the Legislative Building built in 1923 was reported after the 1949 and the 1965 earthquakes. The dome was damaged in 1949, but damage to the building below the roof line was reportedly minimal. The

TABLE 58.--BUILDING CONSTRUCTION INFORMATION FOR ESSENTIAL STATE BUILDINGS REVIEWED IN TEXT

Number of buildings	Location (county)	Construction date	Number of stories	Type of construction
1	Thurston	1923	2-5	Reinforced concrete with unreinforced stone-bearing walls.
1	---do---	1950	1	Reinforced concrete.
1	---do---	1953	3-5	Reinforced concrete frame.
1	---do---	1970	1-5	Reinforced concrete with shear walls.
1	King	1968	1	Pre-cast concrete walls; heavy timber roof.

TABLE 59.--MAJOR AND ESSENTIAL STATE BUILDINGS DAMAGED AND PERCENT OF IMPAIRMENT FOLLOWING POSTULATED EARTHQUAKES

	Earthquake "A"			
	Administration buildings		Police buildings	
County	Number damaged	Impairment percent	Number damaged	Impairment percent
SNOHOMISH----------	0	0	1	5
KING---------------	0	0	1	10
PIERCE-------------	0	0	1	10
THURSTON-----------	2	55	1	25
MASON--------------	0	0	1	15
KITSAP-------------	0	0	0	10

	Earthquake "B"			
	Administration buildings		Police buildings	
County	Number damaged	Impairment percent	Number damaged	Impairment percent
SNOHOMISH----------	0	0	1	10
KING---------------	0	0	1	25
PIERCE-------------	0	0	1	10
THURSTON-----------	2	55	1	10
MASON--------------	0	0	0	10
KITSAP-------------	0	0	1	10

1965 earthquake damage included a wide crack in the inner structure supporting the dome, a limited amount of structural damage to a few of the massive masonry piers, and extensive damage to the stone facing in the colonnade story supporting the dome. No damage to other state buildings reviewed in this study was mentioned in published reports.

The old State administration buildings are expected to suffer very heavy structural and nonstructural building and equipment damage from earthquake "A" and will probably have to be evacuated for many days, pending inspection and temporary repairs. These buildings are located in a high-intensity area, where damage is expected to be considerable even in specially designed earthquake-resistive structures. Damage is expected to be somewhat less in the two newer administration buildings, owing to their greater earthquake resistive type of construction and to location in a slightly lower intensity area.

The State Patrol buildings are also expected to suffer much less damage because of type of construction and location in a lower intensity area. The most significant damage to District offices is expected to occur in Thurston, Pierce, and Mason Counties.

The state administration buildings are expected to sustain the same damage from earthquake "B" as from earthquake "A," as they are located in the same intensity areas. The State Patrol buildings are expected to suffer the same relatively low damage as described for earthquake "A," but the damage is expected to be concentrated in King, Snohomish, and Kitsap Counties.

For planning purposes, impaired use in the event of either postulated earthquake is expected to last for at least a month for 50 percent of the buildings listed in table 59.

Federal buildings (excluding post offices)

The detailed information gathered from federal sources pertains only to larger federal buildings and excludes military, leased, and smaller buildings. The analysis of military structures is beyond the scope of this report, and leased building data could not be developed within the time available. All of the major federal facilities reviewed are located in King County, as shown on figure 40 and table 54.

As shown in table 54, construction data were gathered on the six buildings reviewed; sources were the General Services Administration, NAVFAC, and some field inspection by the consultant staff. With the exception of the 1974, 37-story Federal Office Building in Seattle and the complex of buildings in Auburn, the federal buildings are relatively old, non-earthquake-resistive, multistory construction. Emergency power is available for two of the federal buildings in Seattle, and presumably for the FAA communications building in Auburn.

The 1931, nine-story Federal Office Building in Seattle reportedly suffered extensive damage to the upper floors in the 1965 earthquake, but all damages were repaired quickly thereafter. No mention of damage to other federal buildings is made in the published reports of damage caused by the 1949 and 1965 earthquakes.

TABLE 60.--MAJOR FEDERAL BUILDINGS AND (OR) FACILITIES (EXCLUDING POST OFFICES) NONFUNCTIONING DUE TO EARTHQUAKE DAMAGE

County	Earthquake "A" Number	Earthquake "A" Percentage	Earthquake "B" Number	Earthquake "B" Percentage
KING-------	3	55	4	60

From table 60 it is readily apparent that rather extensive damage is expected to occur in federal buildings in the event of either postulated earthquake. All except one of these buildings are located in MMI IX areas. Damage to the 1974, 37-story office building in Seattle is expected to be primarily due to nonfunctioning elevators and equipment, with structural damage being relatively slight. It is anticipated that restoration of full service should be accomplished within 1 week.

The other four federal buildings in Seattle are expected to experience heavier structural and nonstructural damage, due to their non-earthquake-resistive construction. A longer period of time is expected to be required for inspection and repair of structural damage that may occur. For planning purposes, all of these buildings are expected to be closed for 1 day, 50 percent of the two buildings for 1 week, and 25 percent of one building for at least 1 month.

Of the twelve buildings in the complex at Auburn, any one may be inoperable initially, but it is expected to function again within 24 hours.

Post office buildings

Construction data were collected and tabulated for post office buildings in the six-county study area, based on an arbitrary size of 10,000 square feet (929 m^2) or more of floor area. The 24 post offices considered are shown in table 61 and figure 41. Most of these are one- or two-story buildings built since 1950 and reasonably earthquake resistive in construction.

No information was obtained regarding emergency power available to postal facilities. Major modern postal facilities contain extensive electric-powered mechanical processing systems and conveying equipment. Lack of electric power or misalignment of the equipment could seriously hamper operations by requiring a return to manual operations.

The greatest impairment to post offices is likely to occur in King and Pierce Counties. In King County, the higher expected damage percentage, shown on table 62, is primarily caused by the high intensities encountered at those post office locations. In Pierce County the higher percentage of expected damage results from older, less-resistive construction of the four-story masonry building built in 1909. For planning purposes, 50 percent of the inoperable services are expected to be at least partially functioning within 24 hours and the remainder within 30 days.

Table 62 also indicates the damage to post offices from postulated earthquake "A" and "B" will be essentially the same.

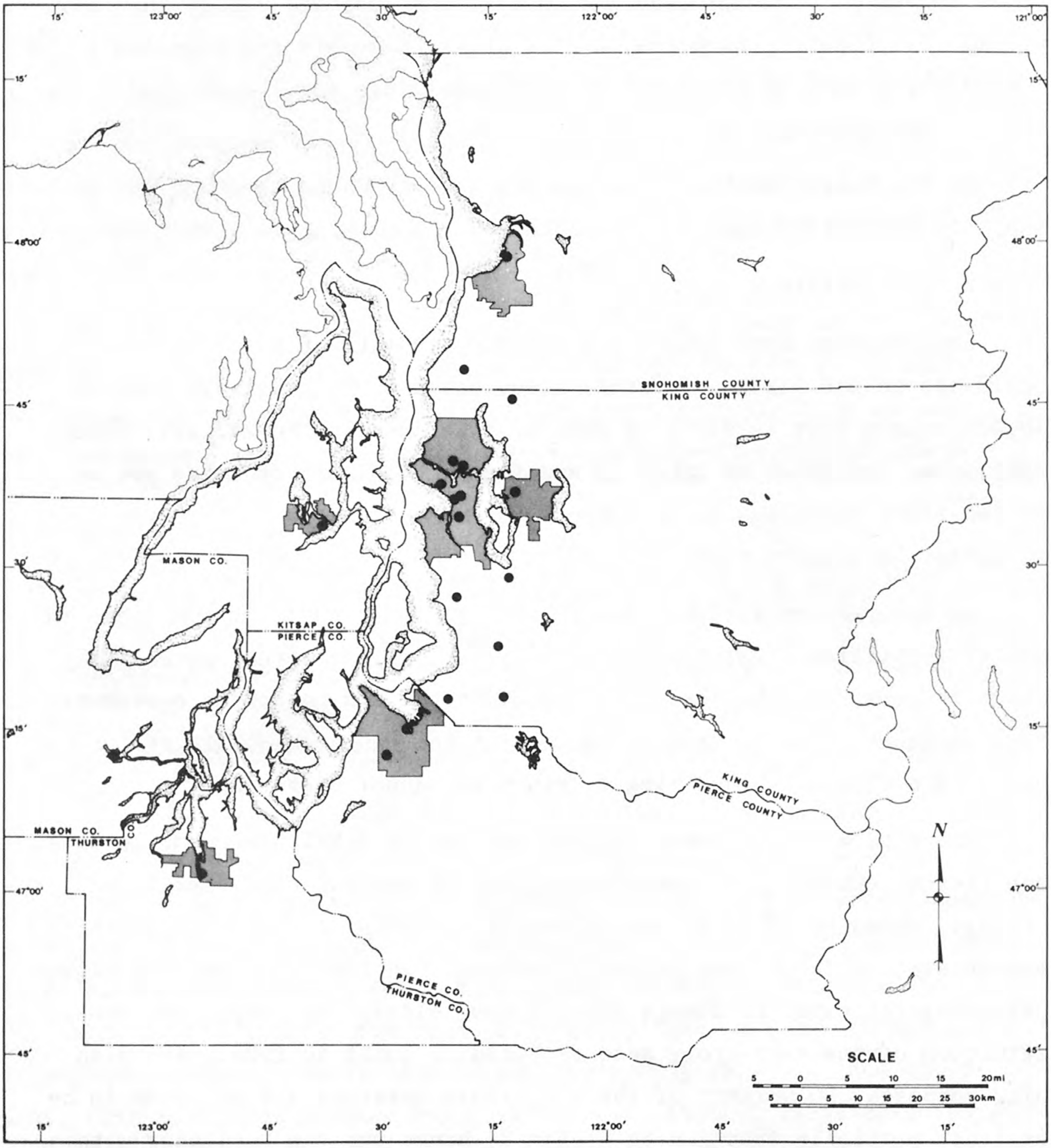


Figure 41.--Location of major postal facilities in the six-county study area.

TABLE 61.--LOCATION OF MAJOR FEDERAL FACILITIES AND U.S. POST OFFICE BUILDINGS REVIEWED IN THE TEXT

County	Number of buildings: Federal facility	Emergency power	Post offices
SNOHOMISH----	0	0	2
KING---------	1/6	2	15
PIERCE-------	0	0	4
THURSTON-----	0	0	1
MASON--------	0	0	1
KITSAP-------	0	0	1
Totals----	6	2	24

1/ Includes 1 12-building complex of 1- and 2-story buildings.

TABLE 62.--IMPAIRMENT OF MAJOR POST OFFICE FACILITIES OWING TO EARTHQUAKE DAMAGE

	Post Office buildings				
	Earthquake "A"		Earthquake "B"		
County	Number damaged	Impairment percent	Number damaged	Impairment percent	Total number
SNOHOMISH----	1	5	1	10	2
KING---------	2	15	2	15	15
PIERCE-------	1	30	1	15	4
THURSTON-----	1	10	1	10	1
MASON--------	1	10	1	5	1
KITSAP-------	1	10	1	10	1
Totals-----	7		7		24

Commercial, high-rise, and other buildings

Although this study is principally concerned with possible damage to public utilities and facilities, it is also appropriate to consider the effects of the postulated earthquakes upon other types of public structures in the Puget Sound region. High-rise and commercial buildings house large numbers of people at various times of day. During a working day, a large proportion of the area's population is concentrated in a relatively small area, such as the central business districts of Seattle and Tacoma.

Building-construction types in the downtown areas range from pre-1900 multistory structures of masonry construction to new high-rise (50-story) structures whose steel frames were specifically designed to resist substantial seismic forces. Many of the businesses housed in these downtown facilities, while not directly related to disaster relief, serve important functions in postearthquake recovery periods.

By enactment of Senate Bill 2634, the Washington State Legislature has established the Uniform Building Code as the guideline for the State of Washington, effective January 1, 1975. Thereafter, all communities are required to use this Code or a code that is not less restrictive. This formalizes a condition that has generally been followed in structural design throughout the study area. It does not, however, eliminate possible problems in many older buildings that are not in conformance with the Uniform Building Code. Many of these were constructed at a much earlier time, with no consideration for seismic requirements.

In Tacoma, the damages to commercial and high-rise buildings will be most severe at MMI IX in the poor-ground area, southeast of the port, for both postulated earthquakes "A" and "B". The central business district of Tacoma will experience MMI VIII under both seismic conditions and fortunately is not located on structurally poor ground.

Part of the central business district of Seattle is located in a poor-soil area that will be subjected to MMI IX in earthquake "A". Under the conditions of earthquake "B", almost all of the downtown area of Seattle will experience MMI IX. Extensive damage is expected to occur in many of the multistory buildings, particularly older structures.

Communications

Communication may take many forms: printed or written, verbal or visual, among many. Some, such as fire, police, and hospital communications, are emergency in nature, while others, such as magazines, may be weeks late and still fulfill their missions.

The San Fernando earthquake caused failure of communications which thus limited contact between some individuals and agencies responsible for emergency relief. This resulted in delays in assignment and use of available volunteers and materials, and in transmittal of adequate emergency information to the public. Emphasis in this report has been given to the types of communication that are vital to emergency services and to minimal maintenance of community life in the period immediately after the disaster, including radio, television, and telephone communications.

However, some attention must be given to the other means of communication. Any communication system located in an older non-earthquake-resistive structure or in a high intensity zone may be severely damaged. Postal facilities located in the congested areas of Seattle and Tacoma, for example, may be inoperative while the region is sealed off for damage evaluation. Postal facilities are discussed in the section on public buildings. Newspapers are important in giving the public much detail that cannot be carried effectively by radio or television. Electric power outages, misalignment of sophisticated printing equipment or direct damage to it, and transportation problems for employees will cause delay in the publishing process. Input to the paper through telegraphic and wire service systems may be temporarily reduced or suspended. It is reasonable to assume for planning purposes that newspapers will have to rely upon presses located outside of Seattle and Tacoma for at least 1 week.

Various agencies that provide emergency services have their own communication systems. Detailed analysis of these systems is beyond the scope of this report; however, some general comments will be based on the performance of various types of systems in past earthquakes.

Data collection

Because of the regional nature of commercial communication systems, data were collected from several sources rather than from one central agency. Among the major sources of information were the Pacific Northwest Bell Telephone Company, the Federal Communications Commission, and radio and television stations.

Data were collected for radio stations with power of 5 kw or greater. Smaller broadcasting stations have a limited range and, therefore, limited public function in the event of a disaster. Radio transmitting towers are frequently located on top of, or adjacent to, the buildings housing the stations. Data were collected for television stations with a visual power of 100 kw or greater. Television transmitting towers are usually situated on the top of a high hill, often separated from the site of the station. The following tower information was obtained: specific height of the tower above ground level, above average adjacent ground, and above sea level.

Figure 42 shows the location of major radio and television stations and transmission towers in the study area. Table 63 shows the number of stations above minimum power requirements and the number of stations that are part of the Emergency Broadcast System (EBS). Some of the radio and television stations also have mobile broadcasting units.

Data were obtained from the three telephone companies serving the six-county study area, permitting mapping of the 67 key telephone facilities included in table 64 and plotted on figure 43. Information on construction date, building type, and materials of construction was obtained for a significant number of facilities. A few of the facilities were field inspected by the consultant staff, and this inspection was augmented by applicable information developed from NAVFAC survey records.

Data were not collected for Western Union, ITT World Communications, RCA Corporation, and the many emergency communication systems. Analysis of the damage these might suffer in a major earthquake in the Puget Sound Basin is beyond the scope of this report.

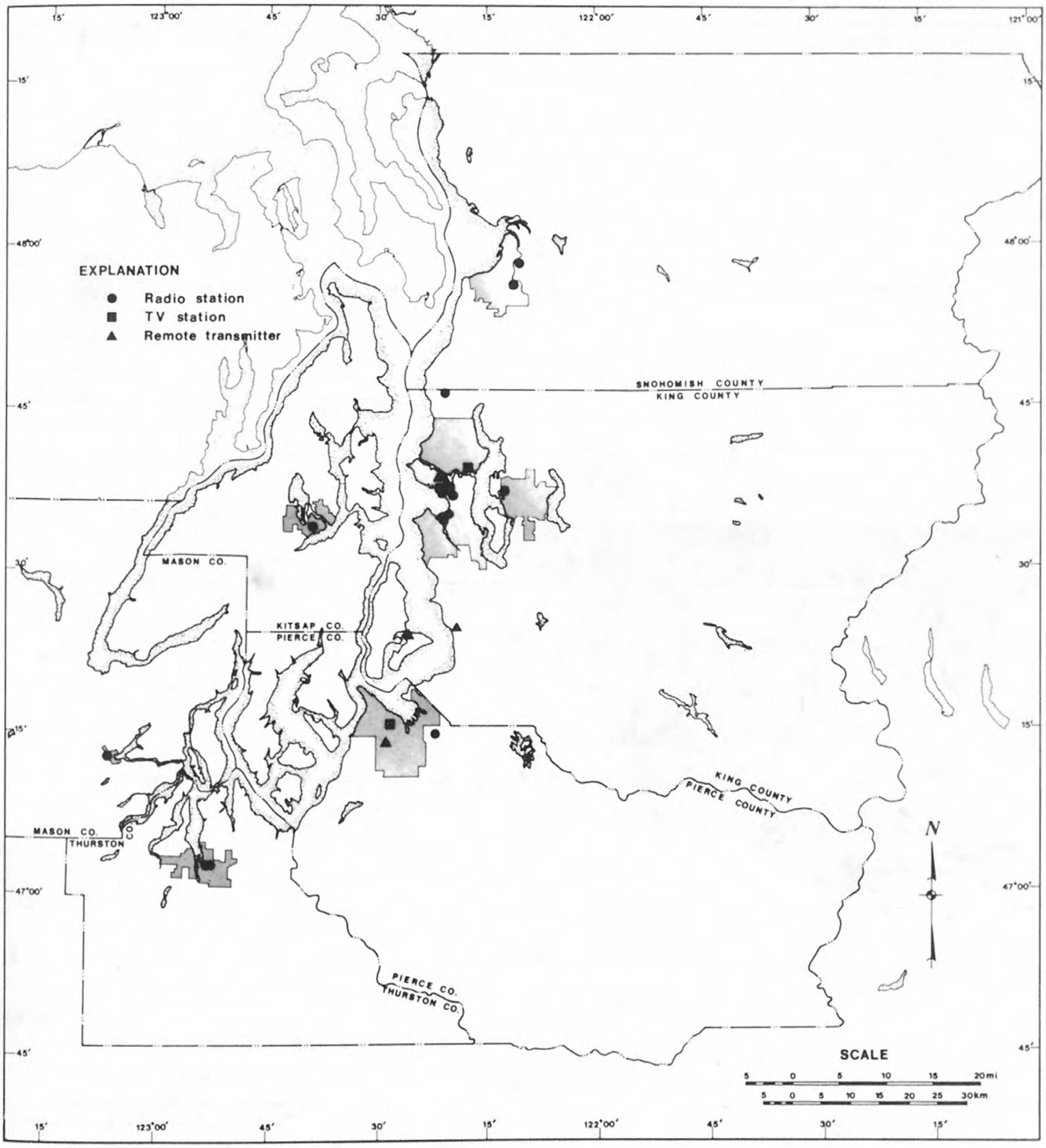


Figure 42.--Location of major radio and television stations and transmitter towers in the Puget Sound Basin. One dot may represent more than one facility.

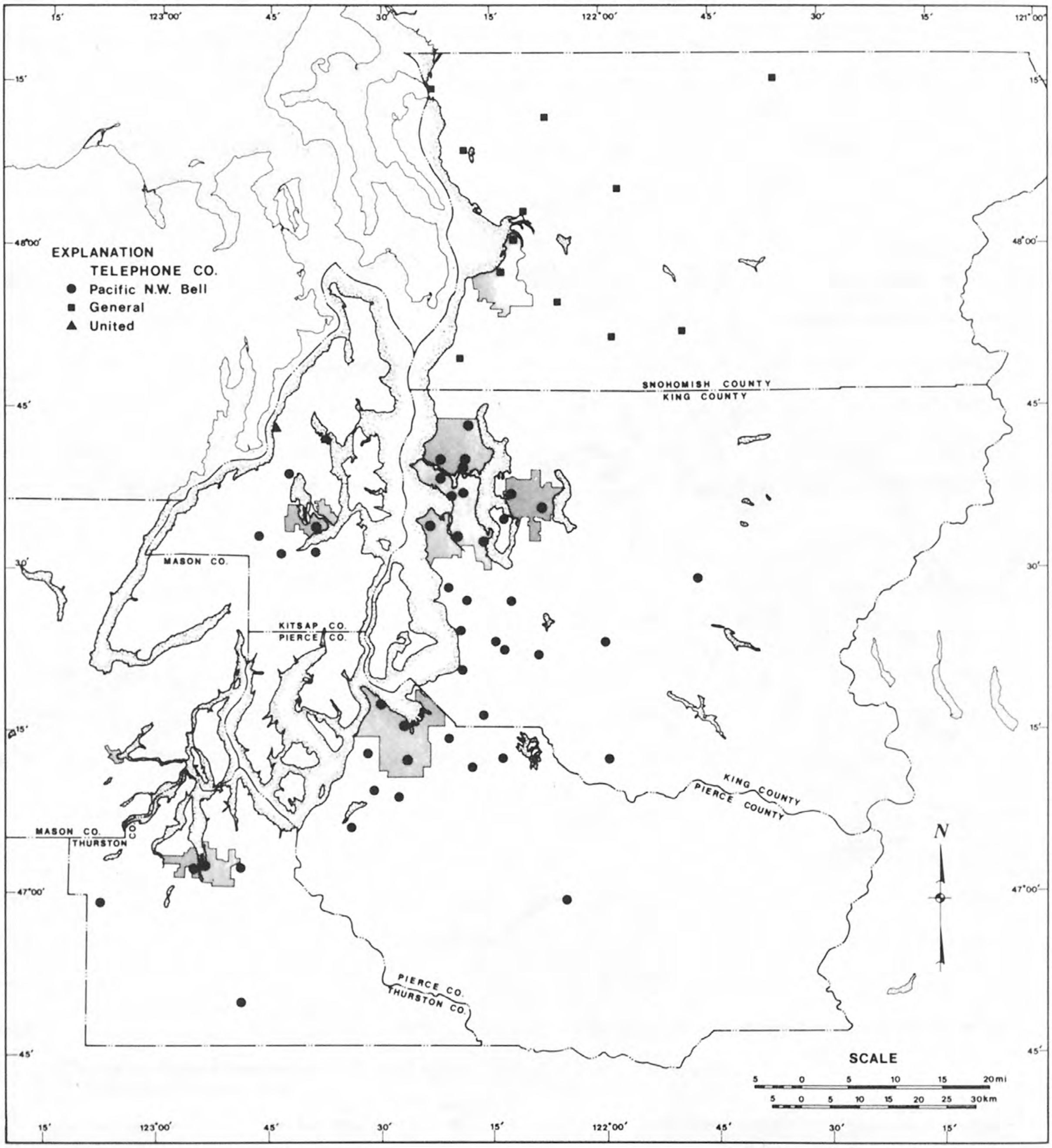


Figure 43.--Location of selected telephone buildings and key facilities in the Puget Sound Basin.

TABLE 63.--LOCATION OF MAJOR RADIO AND TELEVISION STATIONS AND TRANSMISSION TOWERS IN THE PUGET SOUND BASIN

	Distribution of radio and television stations		
	Radio--5 kw or over		Television--100 kw or over
County	Total number	Emergency broadcast	Total number
SNOHOMISH--	4	1	0
KING-------	17	6	4
PIERCE-----	3	2	1
THURSTON---	2	1	0
MASON------	1	1	0
KITSAP-----	1	1	0

TABLE 64.--TELEPHONE CENTRAL AND TRAFFIC OFFICES

		Percentage of impairment	
County	Total number	Earthquake "A"	Earthquake "B"
SNOHOMISH--	12	10	20
KING-------	27	15	20
PIERCE-----	15	15	15
THURSTON---	6	15	10
MASON------	0	0	0
KITSAP-----	7	15	15
TOTAL---	67		

Analysis

Radio and television

Damage to radio and television facilities may be divided into that which occurs to the studio building and equipment (station), to lines from the studio to the tower, and to the tower and appurtenant structures and facilities.

The geographic distribution of radio and television towers is shown in figure 42. Television towers are generally located on the tops of hills in order to obtain the best line-of-sight benefits for high frequency transmission. Radio is not as limited by line-of-sight transmission, due to the transmission characteristics of the frequencies used. Transmitters are located in much more diverse locations, including many with unfavorable foundation conditions.

Radio and television towers have other problems in addition to foundation conditions. The structural designs may be less conservative than those for buildings, inasmuch as life safety is not a consideration. Tower maintenance is difficult, and repainting is costly. Ceramic insulators used in both guyed and unguyed towers are strong and reliable for nonimpact loading conditions, but they may fail in a brittle manner under impact loads such as those that can be expected during a major earthquake. Transmitting equipment and standby power systems are not always braced to resist earthquake forces.

In the San Francisco earthquake of March 22, 1957, which had a magnitude of 5.3, radio towers survived quite well. Following the 1964 Prince William Sound earthquake, Alaskan stations were off the air due to power failures rather than to equipment or structural damage. The Puget Sound earthquake of April 13, 1949, caused a freestanding radio tower in Seattle to buckle. In the San Fernando earthquake of February 9, 1971, failure of electrical power to receivers caused communication blackouts in the heavily damaged area. In the same earthquake, a television station in Burbank was forced to use its truck-mounted auxiliary transmitter.

Damage-susceptibility factors for the stations and towers were determined on the basis of the consultant's knowledge of construction types of buildings in which the stations are located. A few of the radio stations are located in older, non-earthquake-resistive, multistory buildings in the downtown areas. The operations of these studios are expected to be hampered by building damage as well as by damage to their own equipment.

Television studios are generally located in fairly small and earthquake-resistive buildings. In the high intensity areas of an earthquake, the unanchored equipment in buildings will shift and overturn, and equipment will fall from the shelves. Because of the sensitive nature of the electronic equipment, it is estimated that damage to equipment in buildings subjected to large displacement will be twice as great as to equipment located in low, stiff, earthquake-resistive structures.

Special radio and television systems

Nationwide, "911" is the three-digit number reserved for calling for emergency assistance. In areas with a 911 capability, a telephone call serves all types of emergencies--fire, police, and medical emergencies. Areas outside the 911 service rely heavily on radio communication between police and fire departments. The Law Enforcement Administrative Radio Network (LEARN) can be a resource for ambulance companies that do not have access to other emergency medical communications. In southern Snohomish and King Counties, Hospital Emergency Administrative Radio (HEAR) is a direct, two-way radio communication between emergency medical vehicles, 28 hospitals, and the Puget Sound Blood Center.

Fire, police, public utility, and other special-service communication requirements were not field inspected, except when incidental to the inspection of those facilities for other purposes. The problems described for commercial radio and television facilities also apply in a general way to these facilities. Although emergency-service communications may be redundant to varying degrees, owing to multiple frequencies and alternate base stations, experience has shown that unpredicted trouble sources frequently develop during a disaster. As an example, according to press reports, a State Patrol radio tower in Everett toppled during the Puget Sound earthquake in 1965. Those services using multiple radio frequencies and having alternate base stations are less apt to experience overloading. Mobile transmitting and receiving equipment could substitute as a base station.

It is appropriate to consider the losses to radio and television communications as a group rather than by area, because most stations are located in the highly urban areas and serve the entire Puget Sound Basin. Impairment to radio and television communications above that shown in table 65 is expected, owing to damage to related vital systems of transportation, telephone communication, and public utilities. On the other hand, use of mobile ground and air units will help offset these problems, providing fuel supplies and alternate surface travel routes are available. For planning purposes, 25 percent of the impairment shown in table 65 is expected to be restored within 24 hours and the remainder within 30 days.

Earthquake "B" would have a slightly greater effect on broadcast communications than one at the Olympia-Tacoma epicenter, because of the large number of stations located in the Seattle area. Repair to stations located in the congested areas of Seattle might be hampered by other extensive damage to vital systems in the area.

TABLE 65.-- PERCENTAGE OF MAJOR RADIO AND TELEVISION STATIONS IN THE PUGET SOUND BASIN INOPERABLE BECAUSE OF DAMAGE TO BUILDINGS, EQUIPMENT, AND TOWERS

	Radio		Television	
	Impairment (percent)		Impairment (percent)	
Disaster	Studios	Towers	Studios	Towers
Earthquake "A"--	30	15	25	15
Earthquake "B"--	40	20	30	20

Telephone systems

The six-county Puget Sound Basin area is served by three principal companies--Pacific Northwest Bell Telephone, General Telephone, and United Telephone systems--and numerous smaller independent telephone companies. Figure 43 shows the location of the key facilities of the major companies.

Telephone buildings, in general, are more carefully and conservatively designed than conventional structures. Anchorage and bracing of telephone equipment to resist earthquake forces has been practiced by local telephone companies since 1949. Security rules limit inspections, however, and limited spot checks may pass over some problem conditions.

Disasters of any kind trigger a great number of calls, which could, if not controlled, exceed the communications network's capacity and hamper the work of emergency services. Under these conditions, the telephone companies automatically activate control measures giving priority to outgoing calls and prohibiting all but emergency calls into the disaster area.

Major loss of telephone communication has not been reported in Puget Sound earthquakes in the past. However, the postulated earthquakes are of significantly greater magnitude than recent damaging earthquakes. In the event of major equipment damage, telephone utilities have large reserves of manpower, equipment, and materials, and they are reasonably prepared for emergencies of disaster proportions.

The analysis of telephone systems was limited to central and traffic offices for the study area. Microwave stations and trunk lines were not evaluated, because data were not available.

Most of the telephone facilities are four stories or less in height, and most are reinforced-concrete frames with brick- or block-infill panels or pre-cast concrete wall panels. Results of the building analysis are shown in table 64. They are based on the known behavior of similar buildings in the various intensity zones of past earthquakes compared to the intensities at the specific telephone building site in the postulated earthquakes. Loss percentages were increased by 50 percent over the expected loss to a normal-occupancy building, to allow for increased impairment of telephone services because of displacement or damage to critical equipment.

Under normal conditions, restoration of individual high-density cables can be accomplished in a few hours. Service is rerouted over alternate facilities to prevent complete isolation of major communities. The practice of alternate routing is in daily use.

Local experience has shown that underground cables survive the property they serve, and, therefore, special earthquake-resistant design or construction measures are not used. Failure of these cables can be expected where major land displacements occur. Similar failures occur from disruption by construction accidents and penetration by water. Restoration techniques, under normal conditions, assure quick location of failure points and rapid repairs. Repair of breaks caused by an earthquake will depend upon interaction of several factors: access routes, availability of personnel and equipment, and effectiveness of emergency communications.

Table 64 summarizes the expected effects of the two postulated earthquakes. It may be seen that the overall extent of damage does not differ greatly for the two earthquakes and, predictably, that damage is higher near the epicenter in each case. For planning purposes, it is expected that 50 percent of the impaired service may be restored within 48 hours, but that the remainder could remain uncorrected for an indefinite period.

Transportation

This section of the report reviews all types of major transportation facilities considered vital to the efficient functioning of the six-county study area, as follows: railroads, major highways, bridges and interchanges, mass public transportation, major airports, and port facilities.

Data collection

Railroads

The Puget Sound Basin is served by three major rail systems: Union Pacific, Milwaukee Road, and Burlington Northern Railroads. There is no passenger service to Mason and Kitsap Counties. The freight service provided to those counties by Burlington Northern Railroad is critical, because it is the only rail system serving the Puget Sound Naval Shipyard and the other naval installations in Kitsap County.

Detailed information was obtained on bridges, tunnels, and routes for one of the railroad systems, and adequate information was obtained for the others. Wherever possible, the following specific information was collected on bridges and tunnels: identification and location of the facility, total length, materials of construction, number of tracks, and year put in use.

Field inspection of the lines, bridges, and tunnels was not necessary. Figure 44 shows the routes of the major rail lines and table 66 gives the distribution of major bridges and tunnels throughout the six-county study area.

Highways, freeways, and bridges and overpasses

The major highway and freeway routes selected for consideration in the study are shown in figure 45. A listing of bridges and overpasses on these routes was furnished by the Bridge and Structures Division of the Washington State Department of Highways. From a statistical printout, dated January 1, 1974, the following information was obtained for each structures over 500 feet (152 m) in length on the selected major routes within the six-county area: location, identification, route number, length, and type and materials of construction. Table 67 summarizes the number of major bridges and overpasses over 500 feet (152 m) in length. Data were also obtained for selected water crossings that are not on the selected routes, but whose continued function is considered important for post-earthquake recovery.

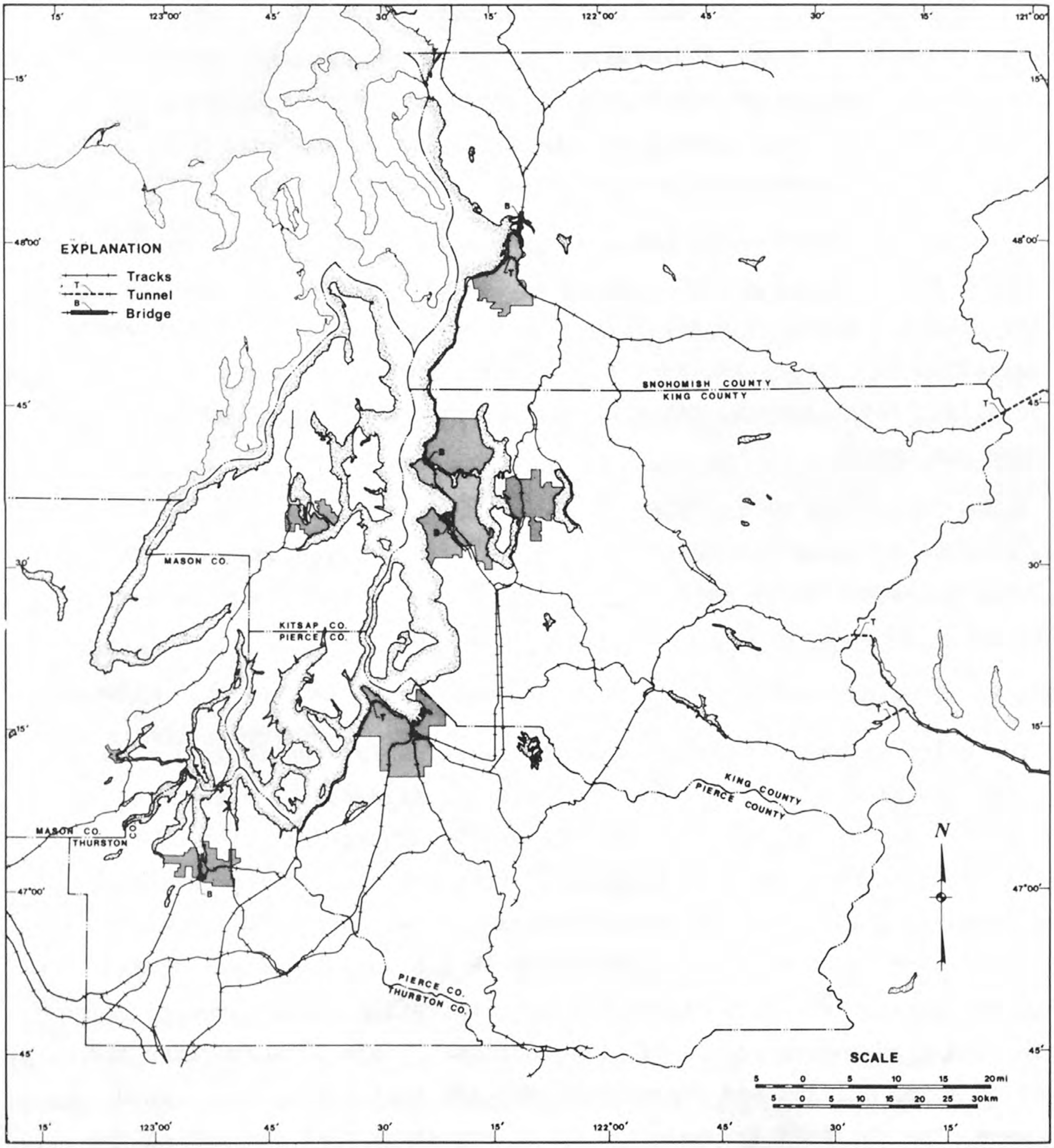


Figure 44.--Location of major railroad facilities in the Puget Sound Basin.

TABLE 66.--SELECTED RAILROAD BRIDGES AND TUNNELS LOCATED IN THE SIX-COUNTY STUDY AREA

(Data from Burlington Northern Railroad, and Engineering Operations Division, city of Seattle, written commun., 1975)

County	Major bridges	Tunnels	
		Number	Length
SNOHOMISH:			
Everett------	3	1	2,440 ft single track
KING:			
Seattle------	2	1	41,152 ft single track
		1	5,142 ft double track
PIERCE:			
Tacoma-------	2	1	324 ft double track
		1	5,142 ft double track
THURSTON:			
Olympia------	1	1	1,001 ft single track
MASON----------	1	0	
KITSAP---------	0	0	
Totals------	9	6	

TABLE 67.--NUMBER OF MAJOR HIGHWAY OVERPASSES AND BRIDGES OVER 500 FEET (152 M), IN LENGTH, IN SIX-COUNTY STUDY AREA

(Limited to routes shown on figure 45)

County	Number of overpasses and bridges
SNOHOMISH-------------	33
KING:	
Area:	
1------------	4
2------------	80
3------------	74
4------------	44
Remainder---------	13
Subtotal-----	215
PIERCE----------------	52
THURSTON--------------	1
MASON-----------------	
KITSAP----------------	4
Total --------	306

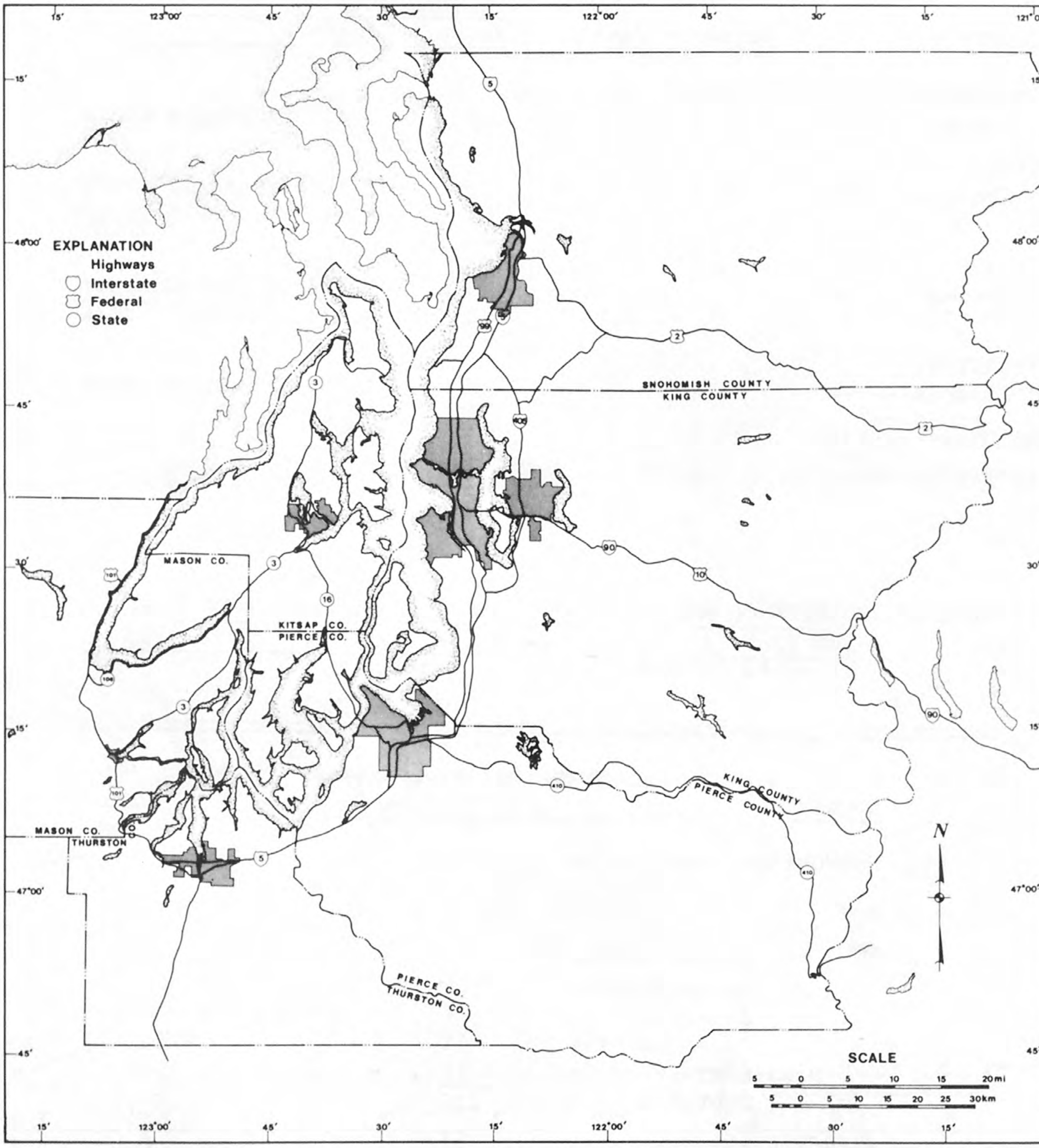


Figure 45.--Location of selected highway routes in the Puget Sound Basin.

Additional information on critical bridges in urban Seattle and Tacoma was obtained from the respective city engineering departments and the Building Department of King County.

Mass transportation

Statistics and other information specific to the operation of the METRO Transit System operated in King and Snohomish Counties was received from the Municipality of Metropolitan Seattle.

Airports

General information was obtained for all of the major airports in the study area, and an inventory was made of all airports from information supplied by the Director of the Washington State Aeronautics Commission. Table 68 is a summary of airfields by classification and location. Of particular concern are the major airports: Seattle-Tacoma International Airport, King County International Airport, McChord Air Force Base, and Paine Field.

Particular emphasis was placed on air control towers and public spaces in collecting the following data: location, year built, access to highway routes, maps, types and materials of construction, layout of runways and traffic statistics for cargo and passengers. Figure 46 indicates the location and distribution of selected airports in the six counties. Table 69 is a summary of the volume of cargo and passenger traffic at selected commercial airports. Frequently, general aviation flights are not recorded as passenger or air freight cargo flights, and so it is extremely difficult to place a numerical count on either the total tonnage or the passenger traffic volume.

Ports

Each of the six counties has a concern for its port facilities. However, major port facilities--docks or quays, cranes, and containerized-cargo staging areas--are concentrated in Tacoma and Seattle. The consultants' personal knowledge of the port areas obviated the need for field inspections. Military facilities were not included in this study.

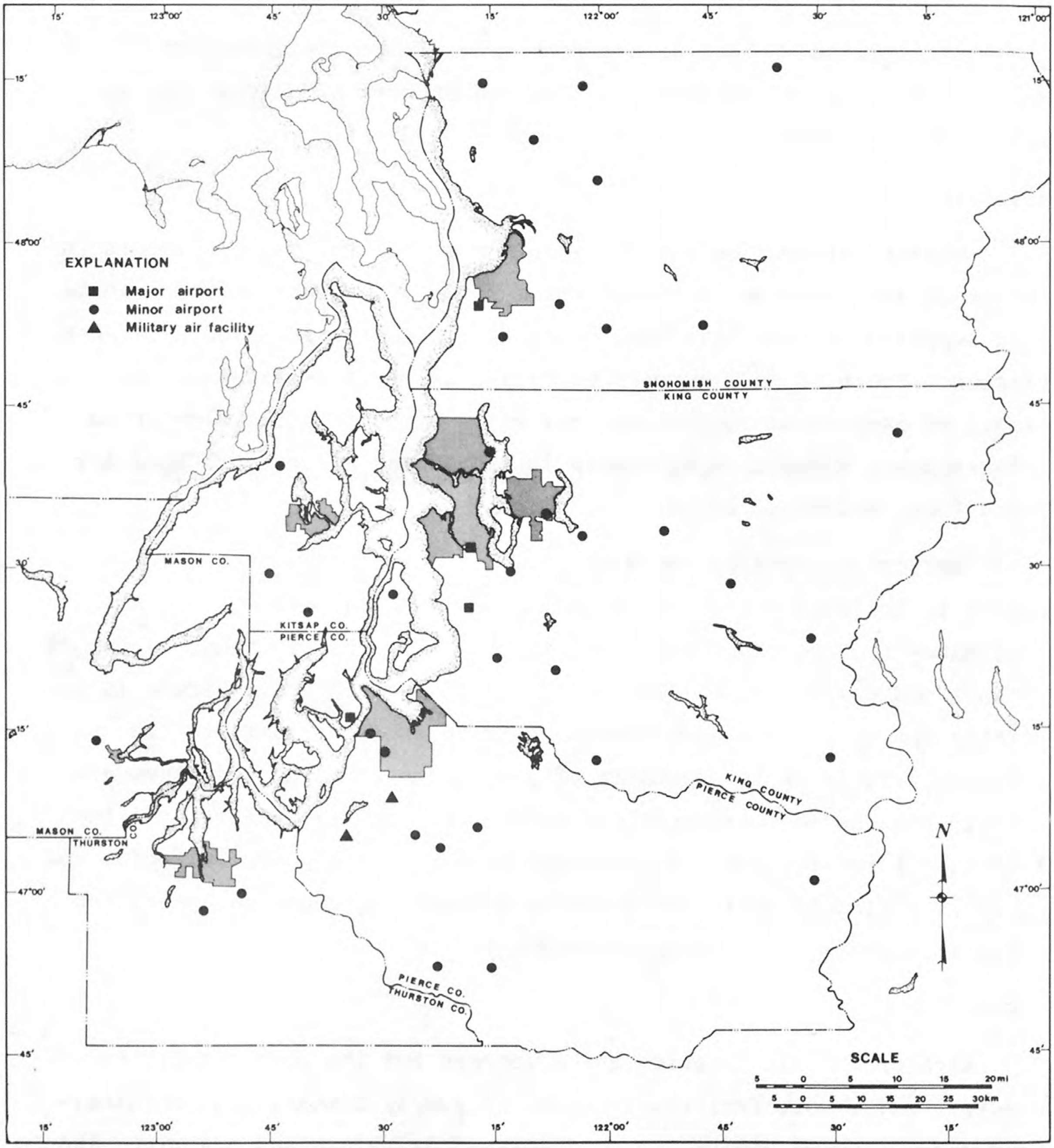


Figure 46.--Location of selected airports in the Puget Sound Basin.

TABLE 68.--INVENTORY OF AIRFIELDS IN THE SIX-COUNTY STUDY AREA (Washington State Aeronautics Commission, written commun., 1974)

County	General description						
	Major	Minor (commercial)	Municipal	Private	Military	State	Seaplane
SNOHOMISH--	0	1	2	7	0	0	0
KING-------	2	4	4	3	0	3	3
PIERCE-----	0	2	2	4	2	1	0
THURSTON---	0	1	1	3	0	0	0
MASON------	0	0	1	0	0	0	0
KITSAP-----	0	1	1	2	0	0	0
Totals---	2	9	11	19	2	4	3

TABLE 69.--TRAFFIC VOLUME OF SELECTED AIRPORTS (Developed from reports of the managers of airports, written commun., 1975)

Airport	Total for year 1974	
	Air freight cargo (in tons)	Passenger traffic volume
Seattle-Tacoma Int'l---	142,115	5,790,000
King County Int'l------	39	154,992
Olympia Airport--------	38	1,095
Kitsap Airport---------	78	10,230

Analysis

Railroads

Damage to railroads is expected to be heaviest in the structurally poor ground areas. The experience gained in the 1964 Alaska earthquake is excellent in regard to damage in areas of poor ground. Reference should be made to "Effects of the Earthquake of March 27, 1964, on the Alaska Railroad," by McCulloch and Bonilla (1970).

A significant amount of the railroad system in the Puget Sound Basin is located in areas of poor soil. Slide-prone areas are typically located along the east shoreline of Puget Sound. Slides can occur when soils are saturated with water, as they are during a major part of the year, or where steep cuts have left unstable conditions. In the 1965 earthquake, a hillside-fill near Olympia slid out from under 400 feet (122m) of track. An earthquake of the magnitude postulated may cause slides that result in damage and misalignment of tracks laid in areas of poor soil. Where tracks are located below slide areas, soil and debris will cause extensive blockage to tracks.

Historically, railway bridges have not generally suffered serious damage except in areas of poor soil or when affected by surface faulting. In the Puget Sound Basin, the railway bridges are frequently located in poor-soil areas. Movable bridges are especially vulnerable to earthquake damage. In the 1949 earthquake, the piers of a bascule railway bridge in Seattle shifted from 4 to 7 inches (10-18 cm). Although realignment of the tracks was the only required correction, the bridge was not open to traffic for several days. Some repair of fill at bridge approaches will be required in poor-soil areas following a major earthquake.

Table 66 summarizes the numbers and distribution of major railroad bridges and tunnels in the study area. Tunnels are rarely damaged internally by ground shaking; however, some impairment of use is expected from blockage by landslides and permanent ground movements in poor-soil areas.

The railroad passenger terminal in Seattle is located in an older building that has suffered damage in past earthquakes and is subject to severe damage and probable temporary closure. Railroad companies are well equipped to handle conventional emergencies, and the repair of their facilities is rapid. However, the collapse of freeway or highway overpasses, located in MMI IX area and blocking a railroad line, could cause problems beyond the direct control of the railroads.

Table 70 summarizes the expected damage to railroad bridges and tunnels in the six-county study area. King and Snohomish Counties will experience somewhat higher damage in earthquake "B" than in earthquake "A," but, in general, the railroads will suffer the same extent of damage in both postulated earthquakes.

Extensive blockage of tracks caused by slides is expected to occur along the east shore of Puget Sound. Based on experiences in past earthquakes, it may be assumed that this type of damage and impairment to movable bridges can be corrected within 1-2 weeks. Mainlines entering Seattle from the south, and branch lines in the main-rail terminal areas that experience high intensities will be subjected to permanent ground deformation, requiring extensive vertical and horizontal realignment, because they are located in areas of poor soil. Alternate north-south rail lines east of Seattle are capable of carrying freight past the city, but service to the city is expected to be very limited until repairs are made. In Tacoma, the port is located in an area of poor soil experiencing high MMI. Extensive damage to rail lines and bridges in this area would cause serious disruption of supply routes and problems in the terminal areas itself. In addition, lines south of Tacoma would be blocked by landslides.

The portion of the Burlington Northern Railroad serving Mason and Kitsap Counties is expected to experience only minor damage, because it is located on alignments falling in lower MMI categories and where poor soils are not a primary concern.

TABLE 70.--DAMAGE TO RAILROAD BRIDGES AND TUNNELS IN THE PUGET SOUND BASIN, OWING TO POSTULATED EARTHQUAKES

County	Facilities impaired: Bridges, Earthquake "A"	Bridges, Earthquake "B"	Tunnels, Earthquake "A"	Tunnels, Earthquake "B"
SNOHOMISH--	0	1	0	0
KING-------	0	1	1	1
PIERCE-----	1	1	0	0
THURSTON---	1	1	1	1
MASON------	0	0	--no facility--	
KITSAP-----	--no facility--		--no facility--	
Totals---	2	4	2	2

TABLE 71.--NUMBER AND LOCATION OF MAJOR FREEWAY OR HIGHWAY OVERPASSES AND BRIDGES SERIOUSLY DAMAGED IN THE EVENT OF TWO POSTULATED EARTHQUAKES IN THE PUGET SOUND BASIN

Location	Number seriously damaged: Earthquake "A"	Earthquake "B"
SNOHOMISH---------------	0	0
KING:		
Area 1-------------	0	0
2-------------	1	2
3-------------	1	2
4-------------	0	1
Remainder----------	0	0
PIERCE-----------------	4	3
THURSTON---------------	0	0
MASON------------------	0	0
KITSAP-----------------	0	0
Totals---------	6	8

Highways

Damage to the highway system may be placed in two categories: earth failure caused by landslide, movement of structurally poor ground, or surface evidence of fault movement; and damage to bridges and overpasses.

The Puget Sound earthquake in 1949 triggered minor landslides onto highways, causing temporary blockage, and also some minor settlement of fills that caused pavement to crack. After the Seattle earthquake in 1965, road settlement was reported at Three Tree Point, southwest of Seattle; slides onto roads were reported in Maple Valley, southeast of Seattle; and extensive slides were reported on the southwest slopes of Mount Si, near North Bend. In Pierce County, on the Nisqually River at LaGrande, earth cracks in the canyon wall and earthslides into the river and onto roads were reported.

Soils in the Puget Sound area are particularly susceptible to sliding when clays are saturated with water, which they are during a substantial part of the year. A large number of landslide blockages may occur as a result of either postulated earthquake. This type of damage may occur in the mountainous eastern portion of Snohomish, King, and Pierce Counties. It may also occur in urban areas, such as the western shore of Lake Union, where some substantial slides could block U. S. Highway 99 in Seattle. Although traffic may be disrupted for a long period due to the physical volume of a slide, ordinarily a good deal of slide material will be quickly removed by bulldozer, or a bypass will be constructed.

During an earthquake, manmade highway embankments and deep fills often settle in relation to nearby rock or firmer soils. This relative movement is called differential settlement. It may occur at approaches to bridges and overpasses, where the pavement on deep fills may settle, in terms of inches or feet, away from the surface of the bridge deck. These aggravated-nuisance problems can usually be temporarily repaired with little loss of use. Major slides also may occur in these fills and result in loss of traffic lanes or complete blockage of the highway.

Bridges and overpasses

Several bridges in the study area are considered important for quick recovery from earthquake damage. They are shown in figure 47. Damage was reported to bridges in the study area in the Puget Sound earthquakes of 1949 and 1965. In 1949, bascule bridges crossing the Duwamish Waterway at Spokane Street were closed. Displacement of the supporting abutments prevented opening of the lift span. Temporary repairs were quickly made, enabling automobile traffic to resume, but water traffic was limited to vessels capable of passing below the bridge until the operation of the lift span was restored 6 days later. In Tacoma, the Eleventh Street lift-bridges across the Puyallup and City Waterways were placed out of order by the earthquake.

In 1965 the Duwamish Waterway crossings were again damaged and inoperable for ship traffic on the Duwamish River; the Spokane Street Bridge and also the 14th Avenue South drawbridge were affected. All of the bridges mentioned above are located on structurally poor ground and subject to high MMI.

The structural integrity of many overpasses and similar structures in high-earthquake-intensity areas has come into sharp focus as a result of the 1971 San Fernando earthquake, in which freeway interchange and overpass structures were severely damaged and many of them collapsed. Almost all of this damage was confined to a relatively narrow zone along a fault. A total of 58 State Highway bridges were damaged and, of these, 7 either collapsed or were demolished. Design details and lateral-force design standards for California highway structures have now been revised. Most of the highway structures within this study area predate the San Fernando experience, and, while designed to AASHO standards, may not reflect concern for the seismic problem.

Based on the damage in San Fernando, it is reasonable to assume that 5 percent of the highway bridges and overpasses in an MMI IX and over will suffer serious damage due to ground shaking. (Serious damage is defined as at least partial collapse or other structural damage that puts

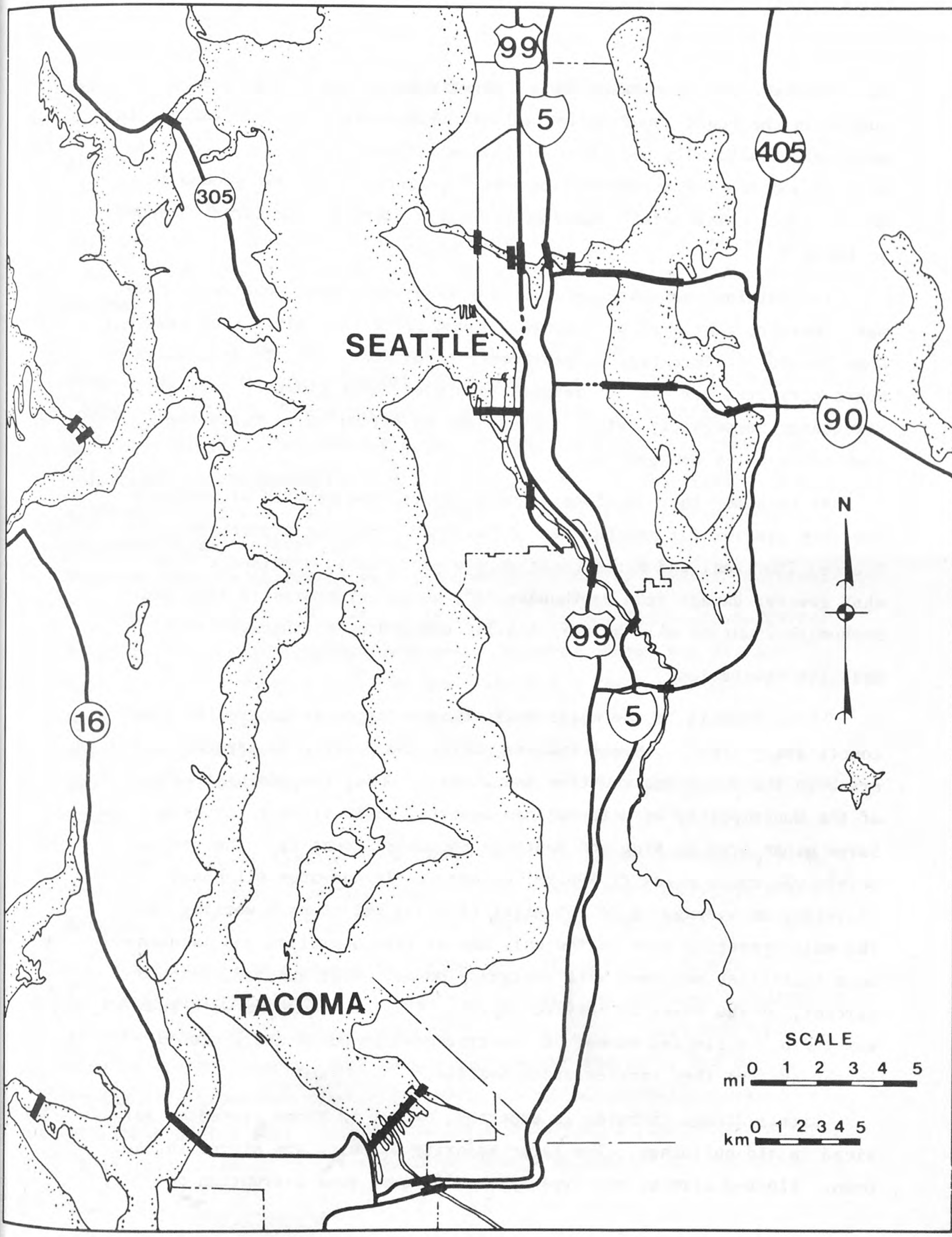


Figure 47.--Location of major water crossings in Seattle and Tacoma and on major highway routes.

the structure out of service for an indefinite period.) Past earthquakes in the Puget Sound Basin indicate that damage will be greatest in areas of structurally poor soil. It is estimated that the damage ratio will be doubled for structures located on structurally poor ground in MMI IX areas. The total number of seriously damaged structures is shown in table 71.

In addition, many bridges and overpasses will have repairable damage; however, they will be temporarily out of service until they have been shored, differential displacements resurfaced, movable span alignments corrected, or similar repairs completed. For planning purposes, structures temporarily out of service can be estimated as twice the number seriously damaged.

As in some other sections of this report, the results of analysis are very similar for earthquakes "A" and "B". Highway structures in Pierce, Thurston, and Mason Counties are expected to experience somewhat greater damage from earthquake "A", while structures in King and Snohomish Counties will be more heavily damaged by earthquake "B".

Mass transportation

METRO Transit is the major mass transportation system in the six-county study area. Several smaller public and private bus systems operate in the remaining counties and cities. Under the administration of the Municipality of Metropolitan Seattle, METRO Transit serves a large urban area in King and southern Snohomish Counties. The system covers 932 route miles (1,500 km) outbound. It operates 611 buses traveling an average of 74,165 miles (119,354 km) on each working day. The main operating base is the only one of five operation and maintenance facilities equipped with emergency power. Four hundred, or 65.5 percent, of the buses in service (April, 1975) are equipped with two-way radio. A limited number of electric-powered buses are included in the system; they service urban Seattle.

Little damage to buses is expected, except to those stored or serviced in old buildings. The large majority of buses are stored in the open. Blocked streets and freeways would cause some disruption of service in the event of a major earthquake. Both downed trolley wires and blocked streets can affect electric bus operation.

Airports

There are approximately 50 airports in the Puget Sound Basin area. The major airports are located as shown in figure 46. The Seattle-Tacoma Airport is by far the largest in terms of passenger and freight volume.

The great Alaska earthquake of 1964, with a magnitude of 8.4, provides a reasonable guideline for experience data. A total of 13 airports, out of 64 airports inspected, were found to have damage to runways or taxiways. Despite damage to runways and buildings, virtually all airports were operational within hours after the earthquake. Some resourcefulness was required to accomplish this. For example, the collapse of the control tower at the Anchorage International Airport required the use of radios in a grounded plane for air traffic control.

Runways remained functional at airports in the San Fernando Valley after the 1971 San Fernando earthquake. However, there was glass breakage in the control tower at the Burbank and Van Nuys airports. The most critical problem was the loss of commercial electric power, resulting in blackouts of terminal buildings and other buildings at several airports and lack of power to pump aircraft fuel out of underground storage.

The foregoing limited experience record is rather reassuring with respect to the most important function of an airport; namely, to allow airplanes to land and to take off with people and supplies.

Earthquake damage to airports can be divided into: damage to buildings and structures, and damage to runways and taxiways. Damage to structures can be subdivided into that vital to operational aspects, such as control towers, fuel tanks, and similar features, and damage to the less important service features. Detailed information was available on the construction of a large number of airport buildings. It is reasonable to expect structural damage to some of the buildings in the event of either postulated earthquake. Emphasis in the following paragraphs is on the damage to runways and taxiways that must remain functional after a disaster, despite other service inconveniences.

Some concern has been expressed about the extent of the existing civilian helicopter service within or near a possible disaster area. A review of the disaster plans prepared by the various counties' Offices of Emergency Services discloses many locations for emergency helicopter landings beyond those provided by the military, police, hospitals, or proprietary, such as radio-television stations. School playfields, large parking lots cleared of cars, or other large paved areas can serve as an emergency landing pad. Many of the hospitals in the six-county area have provided for helicopter service in the total hospital facility, particularly those in suburban areas where space is available. In more densely populated areas the hospital may use an adjacent parking lot and in highly congested areas, high rise buildings and power lines make helicopter landings impossible.

In earthquake "A," all major airports are located in MMI VIII areas except Paine Field in Snohomish County which would experience MMI VII. No serious runway damage is expected at any of the major airports. Some damage may be expected to glass in the control towers and to other buildings. However, the airports are expected to be functional within a few hours. Access to all major airports may be impeded by damaged freeways and other roads. Alternative access routes are generally available except for the Tacoma Industrial Airport which would be essentially isolated if the Tacoma Narrows Bridge were out of service.

Earthquake "B" is expected to cause more damage to airport facilities than earthquake "A". King County International and Seattle-Tacoma International, in Seattle, are both located in MMI IX areas and the other major airports are in MMI VIII areas. King County International Airport is located in a structurally poor soil area. Some significant runway damage is expected at the Seattle-Tacoma and King County fields.

Damage to control tower and some building damage is expected at the major airports in King County. Surface access to those airports may be restricted owing to highway damage but adequate alternate routes are available. Loss of commercial electrical power will require dependence upon emergency power for control tower operations and pumping of fuel. Those airports affected by runway damage should have temporary repairs completed within 48 hours and those suffering building damage only should return to limited operation within a few hours.

Ports

Analysis of port facilities will be limited to the Port of Seattle and the Port of Tacoma, because major port facilities for the Puget Sound Basin are concentrated there. Significant damage to port facilities in Seattle was reported in the 1965 earthquake. According to press reports, nearly every waterfront facility was damaged to some extent. Much of the damage occurred to facilities that were under construction. Behind one under construction, the bulkhead and fill material settled 6-24 inches (15-61 cm) for a width of 25-40 feet (8-12 m) and the bulkhead was reported to be 6-8 inches (15-20 cm) out of line. Several other facilities in Seattle suffered similar damage.

Both the Ports of Seattle and Tacoma are located in areas of structurally poor ground, which will experience MMI IX in either of the postulated earthquakes. Disaster planning should recognize that widespread and serious damage will occur. The older large buildings will suffer severe structural damage, particularly those damaged in past earthquakes. Many cranes will be thrown from their rails and some may fall. Pile-supported docks will not suffer serious damage, but access will be limited owing to settlement of approach fills and damage to access roads. Quay walls may be seriously damaged, owing to displacement by the retained soils. Cargo handling equipment will be damaged.

For disaster planning purposes, the port facilities should be considered 80 percent out of service for 2 days, 50 percent for 7 days, and 30 percent for an indefinite period.

Public utilities

The public utilities included in this section of the report are water supply, natural gas, electric power, sewage, and petroleum pipelines, and are generally restricted to those within the six-county study area. The purpose of this section is to evaluate the possible jeopardy caused by utilities that may be damaged or destroyed in a major earthquake. Failure of one or more of these facilities increases the magnitude of the disaster and decreases the functioning ability of other critical facilities. Damage to these public utilities will have varying impacts on human needs, depending on the product supplied or handled by the utility. Potable drinking water is a critical human need, and drinking water will be needed immediately following the earthquake. Natural gas is important for heating and cooking. Electrical power is a critical need affecting emergency services such as communications, medical services, refrigeration, and transportation. Untreated sewage might flow into storm drains and ditches and be discharged into the Sound; ruptured sewer lines and cesspools might contaminate water supplies. In any case, the availability of water for sanitary uses will be drastically curtailed in the heavily damaged areas. Damage to petroleum pipelines could create fire hazards and shortages of fuel for critical human needs.

The detailed studies of damage to public utilities caused by the San Fernando earthquake of February 9, 1971, have been extremely useful in estimating expected damages from the postulated Puget Sound earthquakes. However, it should be realized that the area affected by intense shaking was relatively small, and the available resources in material and manpower from the adjacent areas were immense.

Public utility systems, whether publicly or privately owned, generally are designed and operated in a manner intended to allow the systems to remain in a functioning condition after a disaster. All utilities are well prepared to act in emergencies, and they have considerable resources of manpower, equipment, and materials.

Experience from the 1971 San Fernando shock and other earthquakes has shown that the good construction and planning of public utilities reduce earthquake damage but certainly do not eliminate it. Earthquake forces and their effects are still imperfectly known. Certain geologic hazards can, at best, only be minimized. Facilities must sometimes be located in or across structurally poor ground areas, such as in potential landslide regions and deep alluvium.

Each type of utility has its own characteristic design, function, and vulnerability to earthquake. So severe was the damage suffered by utilities in the San Fernando earthquake of 1971, owing to failures of highway bridges, dams, aqueducts, and power, water, and gas facilities, that it amounted to approximately one-half the economic loss sustained. Subsequently the subcommittee, Earthquake Resistance of Public Utility Systems, of the newly appointed Earthquake Council for the State of California issued a report in 1974 concluding that all utilities shared the need for buildings that would meet the building code requirements for earthquake design; that would more adequately protect all fragile equipment; and that would protect transmission lines on, above, and in the ground. Elements of utility systems as diverse as bridges, pipelines, mechanical equipment, cables, railways, and dams obviously present special problems unique to the operation of each utility.

Special design criteria should be developed and used in the areas of known seismic risk to minimize damage and facilitate restoration of service. It is apparent that there should be adequate standby and storage facilities for water and fuel, and alternate routes for energy, communication, and transportation.

Data collection

Data, in most cases, were made available by the individual utilities for their own facilities. The Puget Sound Governmental Conference provided useful maps of some utility systems. The specific data collected are summarized in the following subsections.

No field inspections of the public utilities were made, because the collected data, plus the consultants' personal knowledge, were considered adequate.

Electric power

The principal sources of data were Seattle City Light, Tacoma City Light, and Puget Sound Power and Light. Information was also received on major substations and switching stations in the six-county study area. It should be noted that a large majority of the power for the study area is hydroelectric power generated outside the study area and furnished by the Bonneville Power Administration and Seattle City Light. The major electric-power generating facilities located within the six-county study area are shown in figures 48 and 49.

Water supply

Data collection consisted of a listing by county of water districts and water sources from information supplied by Water Supply Section, Department of Social and Health Services, and by the Washington State Association of Water Districts. Water systems for Mason and Thurston Counties were added to a map of water systems for Snohomish, King, Pierce, and Kitsap Counties, prepared earlier by the Puget Sound Governmental Conference. The major water supply lines in the Puget Sound Basin study area are shown in figure 50.

Sewage

Information regarding sewage collection and treatment facilities for Pierce and Thurston Counties, and planning for water quality in river basins was furnished by Washington State Department of Ecology. A map of major sewage facilities in King, Kitsap, Snohomish, and Pierce Counties was provided by the Puget Sound Governmental Conference. Additional information was obtained from the Directory of the Washington State Association of Sewer Districts. Major sewage lines, treatment plants, and pump stations are shown in figure 51.

Natural gas

Maps of natural-gas distribution systems were obtained from Cascade Natural Gas and Washington Natural Gas. The Puget Sound Governmental Conference provided a map of systems in Snohomish, King, Pierce, and Kitsap Counties. The major natural-gas transmission facilities are shown in figure 52.

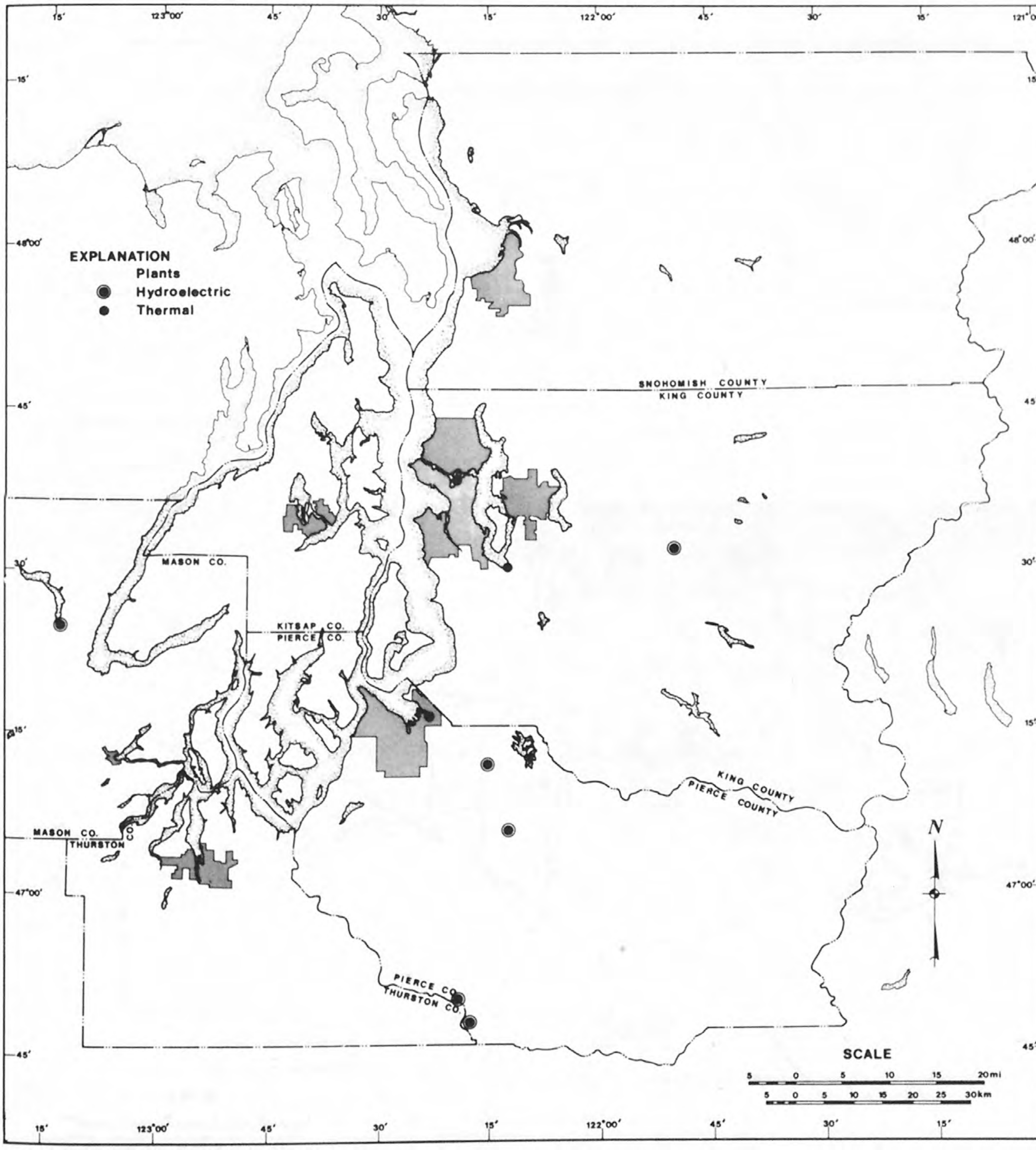


Figure 48.--Location of major electrical-power generating facilities in the six counties.

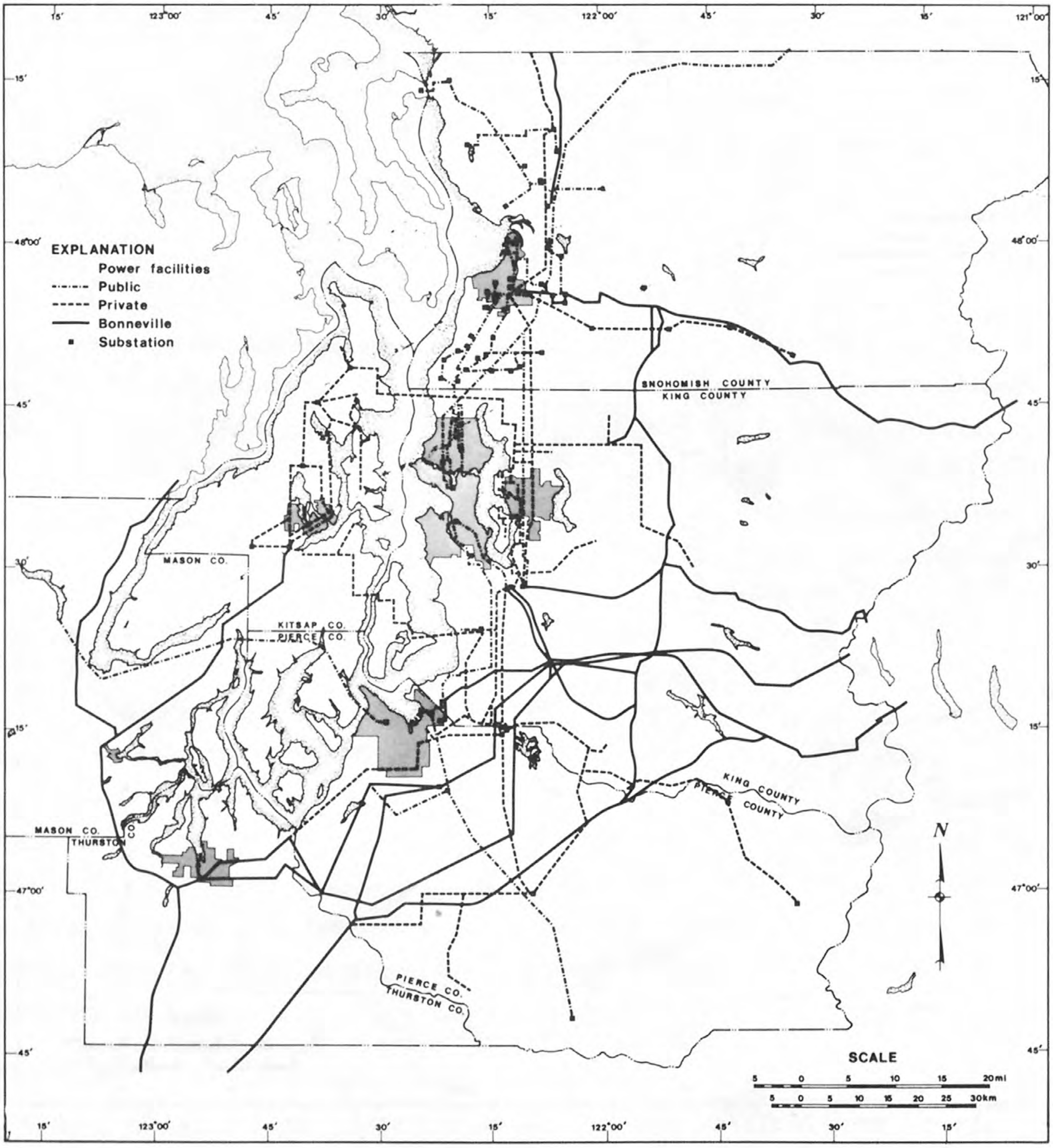


Figure 49.--Location of major power transmission lines within the six counties.

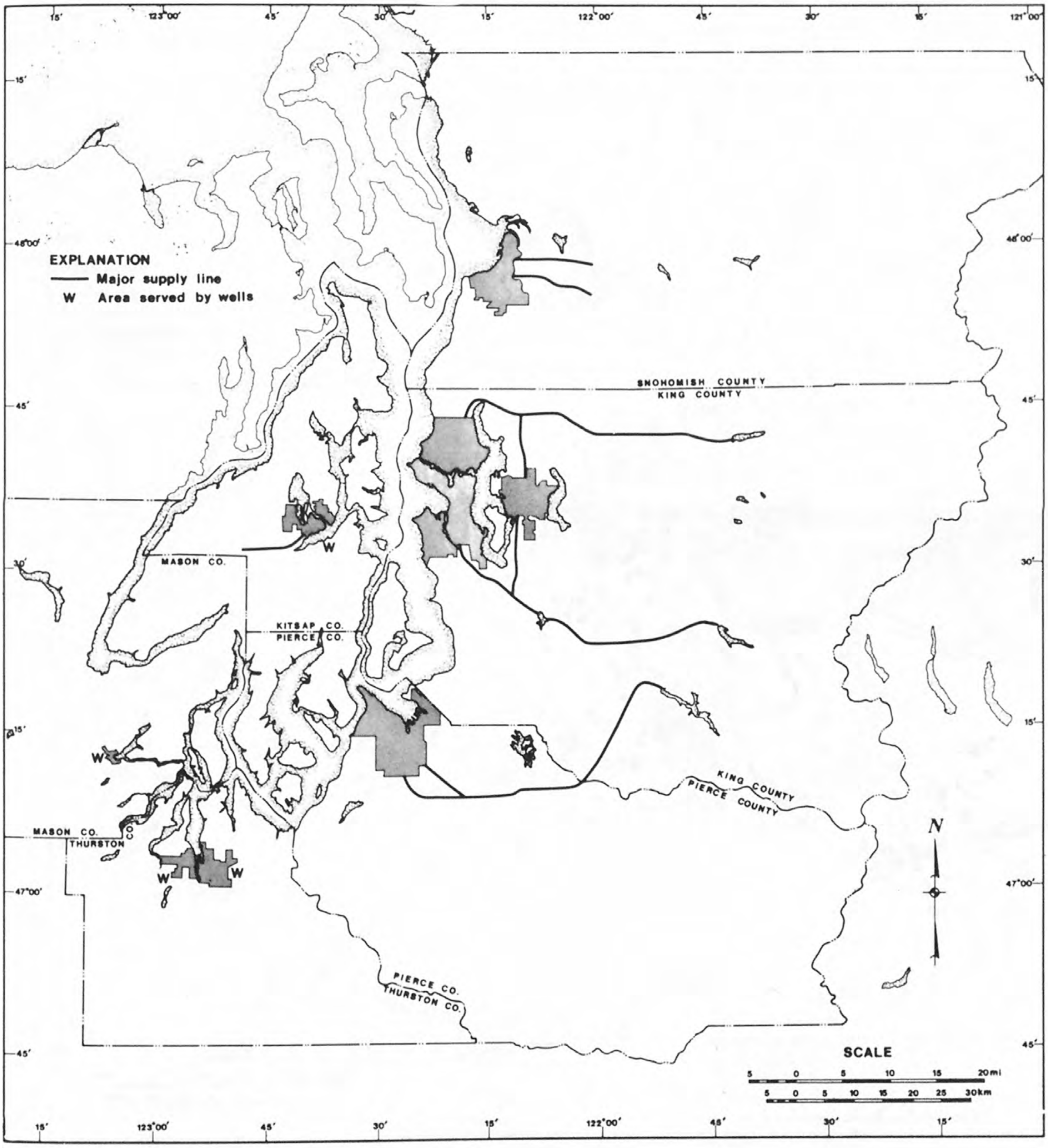


Figure 50.--Location of major sources of water supply in the six-county study area.

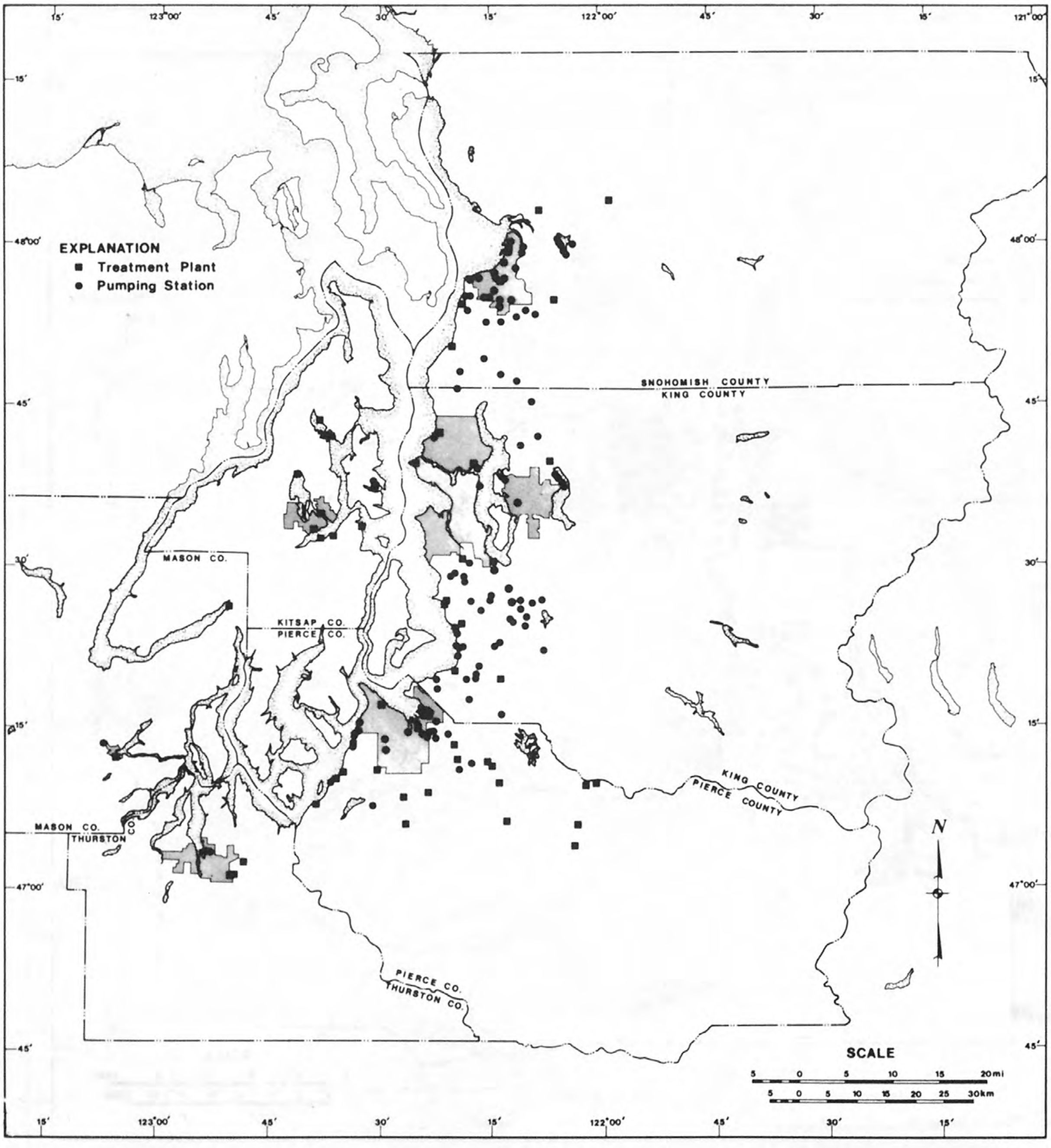


Figure 51.--Location of major sewage treatment plants and pumping stations in the six-county study area.

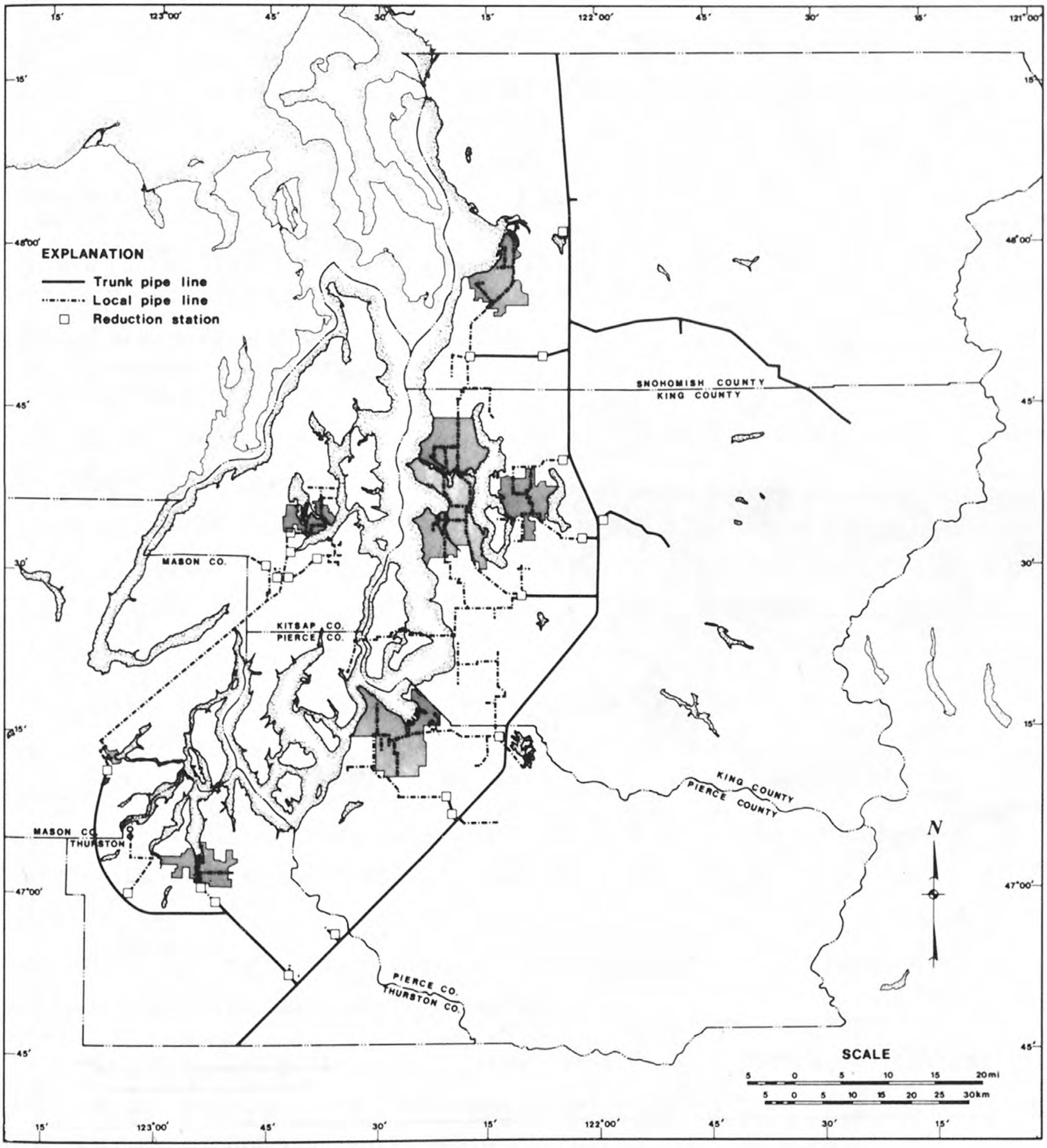


Figure 52.--Location of major natural gas transmission facilities in the six-county study area.

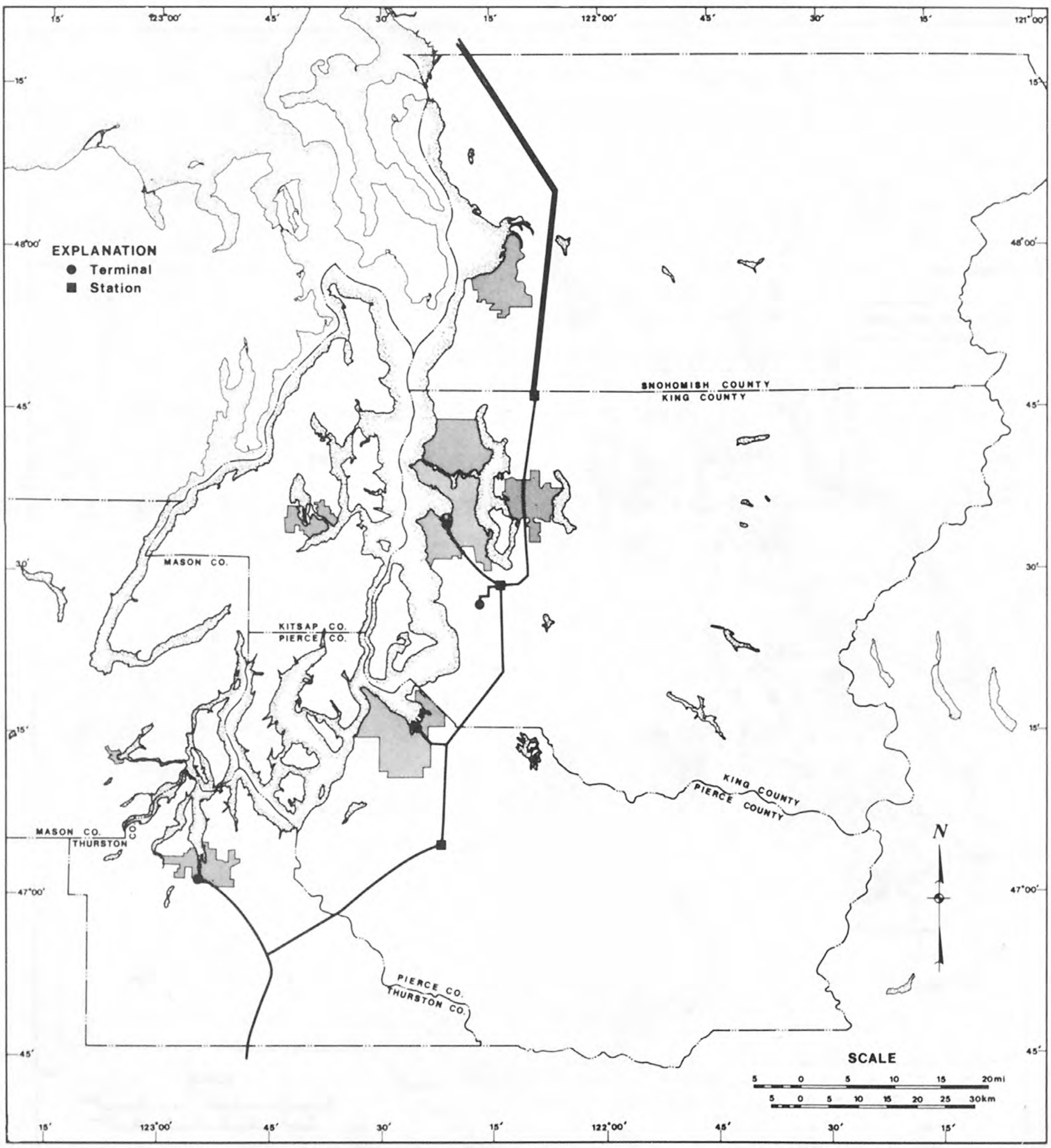


Figure 53.--Location of major pipelines for transport of crude petroleum and petroleum products to the six-county study area.

Petroleum pipelines

The Puget Sound Governmental Conference has prepared a map of the principal petroleum distribution pipelines in Snohomish, King, Pierce, and Kitsap Counties. Additional information was obtained from the Northwest office of the Western Oil and Gas Association. Figure 53 shows the major petroleum pipelines and delivery and terminal locations in the study area.

Damage calculations

Earthquake damage to utility distribution and collection systems is attributed to location in poor soil, ground shaking, and differential ground movement such as surface faulting, landslides, and subsidence.

Buried water lines, sewer lines, telephone cables, and power cables, as well as roadway and railroad alignments across poor soil, are subject to damage. Structurally poor ground may consist of loose, alluvial soils at stream estuaries, manmade land such as hydraulic fills, and areas in which landslides are incipient or a normal continuing problem. Magnification of soil response results in highest MMI values in the alluvial and manmade-fill areas.

In the six-county area, high bluffs are common along virtually the entire east shoreline of Puget Sound. Most of this alignment constitues a threat of potential landslide from normal seasonal changes in moisture content, and the same slide possibility exists from violent earthquake vibrations. Estuary areas of the Skykomish River near Everett, the Duwamish River in Seattle, the Puyallup River in Tacoma, and the port area in Olympia are all fundamentally softer materials, which may vibrate, displace, or settle.

Historically, utilities crossing these zones experienced problems both in the 1949 and 1965 earthquakes, and consideration is given in the current analysis to utility-loss potentials in these same areas. Where primary services cross these zones, a critical condition can exist, as in the case of water service to the city of Everett. Structurally poor ground conditions exist in the cases of some filled land areas where shopping centers or industrial parks have been developed. These are generally not related to primary public utility services.

Damage from ground shaking

In order to estimate the anticipated damage to utility systems from the postulated earthquakes, it was necessary to make assumptions based upon the damage experienced by utility systems in previous, strong earthquakes. Two earthquakes in California provide some data concerning breaks in utility lines, but this is insufficient for valid assumptions or meaningful calculations. The San Francisco earthquake of 1906 induced breaks in the water mains, located mostly in areas of structurally poor soil that averaged 59 breaks per square mile. In 1933, the Long Beach earthquake induced 500 main line breaks in water, gas, and oil lines in areas subject to the greatest intensities. Clearly, the greatest damage occurred in areas of structurally poor soil.

The 1971 San Fernando earthquake produced considerable amounts of useful data. In "A Study of Earthquake Losses in the Los Angeles, California, Area," (Algermissen and others, 1973), a detailed analysis was made of the damage to utility lines. It was assumed that the extent of damage was a function of the ground motion and that the most damage to underground utility collection and distribution systems in areas of MMI IX (and greater) was caused by ground shaking. In addition, it was assumed that the utility distribution and collection systems were uniformly distributed throughout the urban portion of the Los Angeles area in the same manner as the MMI IX zones of the San Fernando earthquake. These assumptions were limited by lack of complete information about the type of lines, line deterioration, and localized surficial geology. Indeed, many waterline outages will be caused by pressure surges finding weak spots in old or deteriorated lines. This results in immediate damage from ground shaking of an otherwise long-term maintenance problem.

The Los Angeles study determined that an urban area of about 12 square miles (31 km^2) suffered about 380 breaks in natural gas mains and services. It was estimated that 10 percent of these, or 38 breaks, were caused by ground shaking and the remaining 90 percent, or 342 breaks, by ground differential displacements. The distribution of pipeline breaks included the observation that the zone of deformation caused by surface faulting along the San Fernando thrust fault was extremely wide, ranging from a few hundred to several thousand feet. The size of the disturbed zone was due to the geometry of the faulting and the amount of displacement. In the Puget Sound Basin, the lack of evident surface faults in prior earthquakes makes direct comparison to the San Fernando experience extremely conservative.

Damage from geologic hazards

Damage from geologic hazards is considered to be due to differential ground movement such as surface faulting, landslides, and subsidence. Significant surface faulting has not occurred in the past in the Puget Sound region.

An assessment of the problems caused by subsidence can be made by examination of the areas of poor soil and landslides in the Puget Sound region. Seattle and Tacoma both have relatively large areas of poor soil that correspond, to a large extent, with the high intensity areas outlined on the isoseismal maps. Most of the waterfront facilities and large industrial developments in the study area are located in areas of poor soils subject to high intensities. The degree of hazard due to landslide depends upon the season of the year. It could be intensified by a rainy season and resulting saturation of soils.

An estimate of the influence of permanent ground displacement can be made by computing equivalent hazard areas. An equivalent hazard area herein is defined as the sum of 10 percent of the urban area subject to landslide and 50 percent of structurally poor soil in urban areas in zones of MMI IX. A summary of urban areas of landslide and poor soil subject to MMI IX and the equivalent hazard areas for the study area is given in table 72.

TABLE 72.--EQUIVALENT HAZARD AREAS FOR LANDSLIDE AND SETTLEMENT IN URBAN AREAS SUBJECTED TO MMI IX BY POSTULATED EARTHQUAKES

County	Earthquake "A" Olympia-Tacoma epicenter Areas in square miles	Earthquake "B" Seattle epicenter Areas in square miles
SNOHOMISH--	0	17.0
KING		
Area		
1----	0	0.13
2----	0.25	0.42
3----	1.82	2.02
4----	0	1.64
Remainder-	0	0
Subtotals-	2.07	4.21
PIERCE------	2.40	2.40
THURSTON----	0	0
MASON-------	0	0
KITSAP------	0	0
Totals----	4.47	23.61

Analysis

Electric power

A large proportion of the electric power used in the Puget Sound Basin is generated outside the study area as indicated in table 73. The amount generated within the study area is so small that even if the local facilities were extensively damaged, the overall effect on the total bulk power supply would be relatively slight. Damage to the incoming transmission lines of bulk power would have a much greater effect on electric power supply.

In the 1949 Puget Sound earthquake, some power outages were caused by power lines swinging and touching, and, as a result, tripping circuit breakers. In Tacoma and Olympia, equipment in substations moved a few inches, requiring realignment. In the 1965 earthquake, substation damage caused some minor outages in Seattle. At the same time the Bonneville Power administration reported the impairment, near Everett, of two 230,000 volt lines transmitting power from Chief Joseph Dam and of a 300,000 volt line from Grand Coulee Dam to Olympia.

Transmission towers are designed to withstand heavy lateral forces due to wind and conditions caused by broken conductors, and so they are inherently earthquake resistive. However, they are susceptible to damage caused by landslides and movement of supporting soils. Most of the transmission lines entering the Puget Sound Basin traverse mountainous terrain that could be subject to earthquake-induced landslides, particularly during the rainy season. Transmission lines can be out of service for a short period of time if shorting occurs from line swinging or if lines are broken due to tension from ground motion. Also, the shutdown of a switching station will put transmission lines out of service. Direct damage resulting from vibration might occur where transmission lines traverse alluvial soils in valleys and the vibration frequency of the tall towers might approach resonance with the soil.

Damage to distribution systems can be widespread and severe, requiring considerable time, manpower, equipment, and materials for

TABLE 73.--ELECTRICAL BULK POWER DELIVERED TO THE SIX-COUNTY STUDY AREA

Sources	Electrical bulk power (megawatts)		
	Power generation source		Total
	Outside study area	Inside study area	power
Seattle City Light:			
Hydro---------	736	23	759
Thermal-------	0	62	62
Tacoma City Light:			
Hydro---------	610	238	848
Thermal-------	0	65	65
Puget Sound Power & Light:			
Hydro---------	199	195	394
Thermal-------	0	89	89
Bonnevile Power Administration[1/]:			
Hydro:			
Snohomish----	768	0	768
King---------	1,573	0	1,573
Pierce-------	1,046	0	1,046
Thurston-----	0	0	0
Mason--------	81	0	81
Kitsap-------	33	0	33
Subtotals----	5,046	672	5,718
Percent of total	88	12	100

[1/]The Bonneville Power Administration supplies bulk power to the local electric power companies. The quantities shown are 1974 peak hour demands.

repairs. Underground distribution systems will be affected by landslide and earth settlement. Numerous transformers will fall to the ground or move from foundations, and pre-1950, or older, buildings will suffer considerable damage.

Assuming that all of the damage suffered by the electrical systems in the San Fernando earthquake in 1971 was due to ground shaking, losses to the electrical distribution system in the Puget Sound Basin were estimated and are summarized in table 74.

In the event of earthquake "A", it should be anticipated that 30 percent of the transmission lines entering the study area will be out of service due either to damage to the lines or to switching terminals. Extensive damage to distribution systems is likely to occur in urban sections of King and Pierce Counties.

Damage to the distribution systems in Pierce County will be about the same for earthquake "B", but the urban sections of King County will suffer more extensive damage due to the increase of the large areas in and near Seattle that would be subjected to MMI IX shaking.

Water supply systems

In any major disaster, disruption of the water supply threatens the health of the population and its ability to fight fire. The larger municipalities in the Puget Sound Basin--Everett, Seattle, and Tacoma--maintain water systems involving dams, aqueducts, reservoirs, storage tanks, buried mains, and pumping and treatment plants. Many of the smaller communities in the six-county area depend upon wells and springs for their source of water, with storage in reservoirs and tanks and pumping and treatment plants incorporated into the system. The nearly 25,000 inhabitants of Olympia use an average of 4,600,000 gallons (17,411 m^3) per day from the city's source of springs.

Following the earthquake of 1949, the Tacoma Water Department noted damage to its system as comparatively minor and took corrective measures. Pipelines were dislocated where landslides occurred and where lines crossed the tideflats. A secondary effect was noted: a surge similar

TABLE 74.--POSTULATED DAMAGE TO ELECTRICAL POWER DISTRIBUTION SYSTEMS IN URBAN AREAS SUBJECTED TO MMI IX

Location	Earthquake "A"		Earthquake "B"	
	Transformers damaged	Circuits interrupted	Transformers damaged	Circuits interrupted
SNOHOMISH--	0	0	0	0
KING-------	225	641	1,372	3,915
PIERCE-----	315	900	298	850
THURSTON---	85	242	29	83
MASON------	0	0	0	0
KITSAP-----	0	0	0	0
Totals--	625	1,783	1,699	4,848

TABLE 75.--DAMAGE TO NATURAL GAS DISTRIBUTION SYSTEMS IN URBAN AREAS SUBJECTED TO MMI IX

Location	Earthquake "A"		Earthquake "B"	
	Breaks in mains and services	Customers affected	Breaks in mains and services	Customers affected
SNOHOMISH--	0	0	0	0
KING-------	81	3,643	220	9,862
PIERCE-----	185	8,027	183	7,941
THURSTON---	40	1,815	6	270
MASON------	0	0	0	0
KITSAP-----	0	0	0	0
Totals--	306	13,485	409	18,073

to a water hammer, which significantly increased pressures, as noted by meters, broken service joints, and pipes.

In the 1965 Seattle earthquake, the Seattle Water Department reported disruption of several large mains: a 20-inch (0.5-m) main on Western Avenue, another at Lockheed Plant No. 2 on Harbor Island, and a 12-inch (0.3-m) main at 2801 S. W. Florida Street. Fire protection installations were disrupted at eight piers on the waterfront and at industrial plants which included Lockheed, Todd Shipyard, Fisher Flour Mills, Elliott Bay Mills, Sears Roebuck, Boeing, Black Manufacturing, Tubbs Cordage, and Seattle Cedar Company.

In downtown Everett, in the 1965 earthquake, two of the three 48-inch (1.2-m) main water supply lines for the city failed at locations where they cross an area of poor soil on trestles. The heavy consumption of water by the pulp mills was restricted, forcing the mills to use river pumps or to close. A few cases of minor damage were also reported.

The estimated damage to water distribution systems is summarized in table 76. The areas that count on wells and springs as a main source of water will experience some problems due to electrical power outages, damage to equipment, and contamination from adjacent ruptured sewer lines. Experience in past earthquakes indicates that damage to the wells and to the treatment and distribution systems in the heavily shaken and poor-soil areas will prevent distribution of potable water in these locations. In heavily damaged areas, supplies of drinking water via tank truck will be necessary until the treatment and distribution systems can be repaired.

Damage to the main water supply lines for King and Snohomish Counties is expected to be light from effects of earthquake "A". Much of the damage to Seattle's distribution system will be in the port and industrial areas situated in areas of poor soil subjected to MMI IX.

Damage to the distribution systems will be heaviest in Pierce County, owing primarily to the large area of poor soils extending southeast from the port area and also subject to MMI IX. The main supply line

TABLE 76.--DAMAGE TO WATER DISTRIBUTION SYSTEMS IN URBAN AREAS SUBJECTED TO MMI IX

Location	Earthquake "A"		Earthquake "B"	
	Breaks in mains	Service leaks	Breaks in mains	Service leaks
SNOHOMISH---	0	0	0	0
KING--------	78	110	209	296
PIERCE------	176	250	175	247
THURSTON----	39	54	6	8
MASON-------	0	0	0	0
KITSAP------	0	0	0	0
Totals----	293	414	390	551

TABLE 77.--DAMAGE TO SEWAGE SYSTEMS IN URBAN AREAS SUBJECTED TO MMI IX

Location	Damage to sewer lines			
	Earthquake "A"		Earthquake "B"	
	Miles affected	Breaks	Miles affected	Breaks
SNOHOMISH--	0	0	0	0
KING-------	9	248	24	673
PIERCE-----	21	564	20	558
THURSTON---	4	123	0	19
MASON------	0	0	0	0
KITSAP-----	0	0	0	0
Totals--	34	935	44	1,250

for the City of Tacoma from the Puyallup reservoir crosses an MMI IX zone about 13 miles (20.9 km) southeast of Tacoma, and significant damage should be expected at that location.

In the event of earthquake "B", the main supply lines for Everett, in Snohomish County, are expected to suffer damage where they cross Ebey Slough, based on the experience of the 1965 earthquake. Considerably more damage is expected to occur to the main supply lines for the Seattle area due to this shock than in earthquake "A", because the main lines, from the Cedar River and South Fork Reservoir on the Tolt River, both cross MMI IX areas. As shown in table 76, the damage expected to the water distribution systems in urban areas of King County is considerably greater than in the event of postulated earthquake "B" because of increased ground shaking. Pierce County damage, primarily due to large areas of structurally poor soils in high intensity areas, will experience essentially the same potential damage as in earthquake "A".

Sewage

Disruption of sanitary waste systems and the accompanying pollution of drinking water systems may produce a health hazard. For analysis purposes, sewage systems may be considered to consist of collection systems, pumping plants, and outfalls.

The magnitude of the damage to collections systems depends upon the size of the urban area affected by strong ground motion; damage is greatest where permanent ground movements occur due to fault rupture, landslide, or poor soil conditions. Older sewer lines are frequently clay products that are relatively brittle, tolerate little movement without fracturing, and consequently are susceptible to earthquake damage. Table 77 was developed using experience from the San Fernando earthquake as described earlier in this section, based upon the assumption that 10 percent of the damage to collection systems was due to ground shaking and the rest was caused by permanent ground movements. The time necessary to determine the overall damage and make repairs to a collection system depends upon the area involved and the available manpower, equipment, and materials. For example, in the relatively small area affected by the San Fernando earthquake, 90 miles (145 km) of sewer lines were surveyed for damage by pulling television cameras through them. From a practical standpoint, the sewer collection lines will not require significant use until adjacent water distribution systems are restored to their normal use.

Pumping plants are susceptible to damage to buildings, piping, machinery, and equipment, and to loss of electrical power in the event of either postulated earthquake. Some, but not all, pumping plants in the study area have standby emergency power. Raw sewage must either bypass damaged pumping plants by gravity flow or be dumped into the flood control systems. Damage to any of the sewage treatment plants shown in figure 51 will affect a large portion of the population in the study area.

As indicated in table 77, heavy damage to sewage collection systems is expected in Pierce County only as a result of earthquake "A". The most heavily damaged collection system in Tacoma, *extending southeast* from the port area, will be without sewage services for at least 1 month. For planning purposes it should be assumed that 50 percent of the treatment plants in Seattle will be inoperable for 2 weeks.

Damage to collection systems in Tacoma is expected to be essentially the same as for earthquake "A". However, damage in Seattle will be much more extensive for this postulated earthquake. For planning purposes, in areas of poor soil subjected to MMI IX, there will be no sewage service for at least 1 month. In both Seattle and Tacoma, it should be assumed that 50 percent of the sewage treatment facilities will be inoperable for at least 1 month.

Natural gas

An analysis of damage to natural gas systems must consider the bulk supply system entering the study area via steel transmission pipelines, the reduction stations, and the distribution systems. In the event of ruptures either in the bulk-supply line or in the reduction stations, the natural gas suppliers are prepared to quickly bypass the damaged area while repairs are made.

Experience in past earthquakes in California indicates that disruption of the underground distribution system can result in lengthy periods of outage. Areas must be isolated, leaks located, and repairs completed before service can be restored. Damage to underground lines is usually intensified in areas of poor soils and in slide-prone areas. Damage to natural gas distribution systems was estimated by using the factors discussed in the introduction to this section, with results shown in table 75.

Additional damage to distribution systems can be caused by structural damage to buildings that affect the entering gas lines. The toppling of unanchored water heaters will cause ruptures of connecting gas lines. Fortunately, extensive structural fires attributable to natural gas leaks have not occurred in past earthquakes, but this does not mean that such a problem does not exist.

Table 75 summarizes the expected damage to the natural gas distribution systems caused by the postulated earthquakes. As in the case of other utilities, King County will sustain much more damage in earthquake "B", due primarily to ground shaking. The damage in Pierce County will occur almost entirely in areas of structurally poor soils in high intensity zones where extensive permanent ground movements can be expected.

The El Paso Natural Gas bulk pipeline entering from Canada and passing through the area as shown in figure 52 is subject to damage from both postulated earthquakes. Damage caused by earthquake "A" is expected to occur where the line passes through an MMI IX zone east of Tacoma. This could affect natural gas supplies in Tacoma and along the pipeline south from Tacoma. Earthquake "B" is expected to cause damage further north in the line, in Snohomish and King Counties as well as in Pierce County. Until this damage is repaired, the bulk supply for almost the entire study area would be cut off.

Petroleum pipelines

Figure 53 shows the location of the major pipelines distributing petroleum products in the six-county study area. In postulated earthquake "A", the pipeline passes through an MMI IX zone near Tacoma only.

In earthquake "B" it passes through a considerable number of MMI IX areas of poor soil in southern King County and a smaller portion in southern Snohomish County. Because the petroleum products generally flow southward, a greater number of people will be affected by damage occurring in the northern part of the study area.

Experience regarding the behavior of petroleum pipelines in past earthquakes is not well documented. Most of the lateral lines to delivery and the terminal locations are located, at least partially, in MMI IX areas of poor soil for both postulated earthquakes. Extensive breakage of pipelines is expected in those areas, due to permanent ground movement aggravated by subsidence and associated problems.

In the 1949 Puget Sound earthquake, 12,000 gallons (45.3 m^3) of gasoline and 5,000 gallons (18.9 m^3) of fuel oil escaped from damaged pipelines in Olympia, causing a serious fire hazard. At the same time water service in the area was interrupted by a break in a water main. Fortunately, no fire occurred.

Petroleum can burn on water and very quickly spread fire as it did in the 1964 Alaska earthquake. It can be swept into sewer systems, spreading flames on surfaces of rivers and harbors and threatening other structures.

Schools

School buildings in the Puget Sound Basin are distributed throughout the populated areas in direct proportion to the density of the resident population. Schools that remain in a safe condition after a disaster may be used for emergency shelter and feeding. This section of the report deals, therefore, both with potential deaths and injuries to the student population and with the availability of public school buildings for mass housing and feeding after a natural disaster.

Since the Puget Sound earthquake of April 1949, consideration has been given to earthquake-resistive systems in the design of virtually all buildings. The State of Washington requires that a registered structural engineer be responsible for the design of all public buildings, including schools. Other building structures may be designed by architects or civil engineers. Other than this requirement, no legislation exists in the State of Washington that prescribes treatment in the design of a school that differs from that of other structures. Throughout the six-county study area, there has been much new school construction since 1950 that conforms in most areas to the requirements of the Uniform Building Code, with the exception of Seattle and Tacoma schools which conform to independent codes.

Data collection

For investigative purposes, schools in the Puget Sound Basin were classified as pre-1950 and post-1950 construction, because much new school construction has been completed later than the 1949 earthquake which gave impetus to the greater concern for earthquake problems. Data were collected from school districts in four urban communities: Everett, Seattle, Tacoma, and Olympia. The Seattle School District provided a listing of all buildings including construction dates, types of construction, and the estimated costs of structural and nonstructural damage caused by the Seattle earthquake of April 1965. It also provided a descriptive list of damage to schools in the earlier earthquake in 1949. Tacoma, Everett, and Olympia districts were not able to furnish such complete records for the schools under their respective jurisdictions.

Time and budget did not permit detailed data collection for all newer schools. Many of these are wood-frame structures, but also, depending upon size and arrangement, some are constructed of steel with metal deck on steel joists, of pre-cast concrete, and some have reinforced-masonry-bearing walls. Most are single story. The consultants are familiar with the construction types and dates of construction as influenced by the patterns of community development throughout the study area. This enabled them to rationally apply results of the detailed analysis from the Seattle school data to areas for which less information was available.

Specific construction data were not collected for schools in rural areas and small outlying communities. Much of the older construction in these areas consists of two-story wood-frame structures with wood siding. Historically, these have been earthquake resistive.

Table 78 is an inventory of public schools in the six-county study area, compiled from information supplied by the School Apportionment and Statistics Division of the Office of the Superintendent of Public Instruction, Olympia, Wash. Statistics from the same source were used to prepare a similar inventory, table 79, for private schools in the six counties.

Additional information on damage to schools in earlier earthquakes was found in "United States Earthquakes, 1965," (von Hake and Cloud, 1967); "The Puget Sound, Washington, Earthquake of April 29, 1965," (Algermissen and Harding, 1965); and "Report on Damage Resulting from Earthquake of 13 April 1949," (U.S. Army Corps of Engineers, 1949).

Analysis

Investigations of the behavior of public schools in the Puget Sound Basin indicate that the performance of the schools built since 1950 has been considerably better than the performance of pre-1950 schools. The 1949 earthquake and the 1965 earthquake both caused substantial structural and nonstructural damage to many of the pre-1950 schools in Seattle. Buildings constructed after 1949 suffered essentially no structural damage in the 1965 earthquake. The average of total damage costs to post-1950 buildings was about one-third the average damage cost to buildings built before 1950.

TABLE 78.--INVENTORY OF PUBLIC SCHOOLS IN THE SIX-COUNTY AREA
(Information supplied by the Office of Superintendent of Public Instruction, Olympia, Wash., written commun., 1975)

County	FACILITIES							ENROLLMENT				
	Elementary	Middle school	Jun. high	Sen. high	Special	Community college	Total	Pre-school/ kindergarten	Grades 1-6	Grades 7-12	Community college	Total
SNOHOMISH--	69	7	13	18	5	2	114	4,586	28,069	31,547	5,340	69,542
KING-------	277	3	65	46	[1]42	7	440	17,085	103,285	119,235	30,615	270,220
PIERCE-----	117	6	23	19	11	2	178	6,752	40,389	44,768	5,796	97,705
THURSTON---	26	5	5	8	2	0	46	1,720	9,859	10,810	0	22,389
MASON------	10	1	2	3	0	0	16	394	2,416	2,499	0	5,309
KITSAP-----	28	2	5	6	3	1	45	1,870	11,345	12,084	3,085	28,384
Totals---	527	24	113	100	63	12	839	32,407	195,363	220,943	44,836	493,549

[1] Includes one K-12 school.

TABLE 79.--INVENTORY OF PRIVATE SCHOOLS IN THE SIX-COUNTY AREA
(Information supplied by the Office of Superintendent of Public Instruction, Olympia, Wash., written commun., 1975)

County	FACILITIES: Elementary grades K-8	FACILITIES: Middle grades 5-8	FACILITIES: High grades 9-12	FACILITIES: Complete grades K-12	FACILITIES: Total	ENROLLMENT: Pre-school/ kinder-garten	ENROLLMENT: Grades 1-8	ENROLLMENT: Grades 9-12	ENROLLMENT: Total
SNOHOMISH---	15	0	1	0	16	267	2,353	84	2,704
KING -------	57	1	12	4	74	358	13,741	5,621	19,720
PIERCE------	16	1	2	4	23	124	3,763	1,332	5,219
THURSTON----	2	0	2	0	4	0	307	206	513
MASON-------	1	0	0	0	1	0	18	0	18
KITSAP------	3	0	0	0	3	0	304	0	304
	94	2	17	8	121	749	20,486	7,243	28,478

The geographic distribution of the pre-1950 schools is not uniform in urban areas; older areas tend to have a higher proportion of old schools. A few of the oldest (generally pre-1900) have been replaced or demolished, but many unreinforced-masonry schools built before 1930 remain in use. Suburban areas have very few pre-1950 schools in present use. Some rural areas may have older schools, but these are predominantly smaller, wood-frame structures.

A detailed analysis of older Seattle schools was carried out. Damage-susceptibility factors were developed with specific relation to construction dates and types, and to extent of past earthquake damage. Because geographic distribution of schools is essentially uniform, the percentage of schools located in the various intensity zones was applied proportionately to both the pre- and post-1950 schools.

The proportion of buildings with the various damage susceptibilities for locations outside the large urban areas was developed from the actual figures for the urban areas, limited information available on pre-1950 schools, and the consultants' knowledge. The proportion of school buildings within each intensity zone was then derived from the proportion of the total area under consideration, within each seismic zone, and weighted on the basis of population density.

Deaths and injuries will be related to the number of pupils exposed, the intensity level experienced, and the ability of the structure to withstand seismic forces. Total enrollment in the study area and the total number of schools is given for public and private schools in tables 78 and 79, respectively. A compilation of schools in the several intensity zones, separated into those constructed before 1950 and those constructed since that time, is contained in table 80.

Schools constructed prior to 1950 were generally lacking in seismic resistance and included many unreinforced masonry structures, a number of which are still in use. In the period following 1950, greater recognition of earthquake problems has resulted in improved design procedures. Lacking the type of legislation that has been enacted in California, schools in this area are designed with no restrictions other than those

TABLE 80.--THE PROBABILITY OF FATALITIES BASED UPON SITING OF SCHOOLS IN AREAS OF HIGH INTENSITY

Earthquake "A"

MMI	Total schools Pre-1950	Total schools 1950-1974	Pupil distribution Pre-1950	Pupil distribution 1950-1974	Rate per 10^5	Fatalities Pre-1950 [1/]	Fatalities 1950-1974	Fatalities Total
IX-----	22	33	13,900	20,800	12	4	3	7
VIII-----	141	159	88,800	100,200	9	20	9	29
VII-----	150	145	94,500	91,400	6	14	6	20
VI-----	73	105	46,000	66,200	3	5	2	7
						Total deaths--		63

Earthquake "B"

MMI	Total schools Pre-1950	Total schools 1950-1974	Pupil distribution Pre-1950	Pupil distribution 1950-1974	Rate per 10^5	Fatalities Pre-1950 [1/]	Fatalities 1950-1974	Fatalities Total
IX-----	46	46	29,000	29,000	12	8	4	12
VIII-----	196	219	123,700	138,200	9	28	12	40
VII-----	109	187	68,800	118,000	6	10	7	17
VI-----	9	15	5,700	9,500	3	0	0	0
						Total deaths--		69

[1/] Fatalities in pre-1950 structures are increased by a factor of 2.5 to recognize the increased hazard for older buildings.

placed on any structure by the limitations of the building code currently in use. Casualties for schools are therefore based on the same casualty ratio as that used in other death and injury determinations, except that the determination of casualties in pre-1950 structures has been increased by a factor of two and one-half, to recognize the increased hazard in these older buildings, some of which date back to early in the century and continue in use.

The statistical analysis of casualties is given in table 80. It must be recognized that this type of numerical analysis is indicative only of general potentials, as a single collapse of an occupied auditorium may cause more deaths than the prediction for the entire study area. At the same time, the significance must also be modified by the recognition that these structures are actually only occupied for a limited time each day, lessening the overall risk.

Expected damage patterns

Referring to table 81, it can be seen that substantial classroom outages are expected in earthquake "A" particularly in Pierce, Thurston, and Kitsap Counties. On the other hand, a large proportion of the school buildings are expected to sustain minor, if any, damage and will, therefore, be available for mass housing and feeding in the event of a disaster.

Of more concern is the potential for loss of life and injuries to occupants of schools in the six-county area. If an earthquake of a Richter magnitude 7.5 occurred during a school day, it is not unreasonable to anticipate that there could be a significant number of deaths.

Table 81 indicates that overall damage to buildings would not differ much in postulated earthquake "B" but damage to structures would be higher in Snohomish, King, and Kitsap Counties. Deaths and injuries will be statistically somewhat greater, because the epicenter is closer to the major population centers, resulting in greater MMI experienced by a larger number of schools.

TABLE 81.--PERCENTAGE OF CLASSROOM OUTAGES IN THE PUBLIC SCHOOLS IN THE SIX-COUNTY STUDY AREA OWING TO POSTULATED EARTHQUAKES.

County	Earthquake "A" Classroom outage (percent)	Earthquake "B" Classroom outage (percent)
SNOHOMISH--	5	15
KING-------	15	25
PIERCE-----	20	20
THURSTON---	25	15
MASON------	20	15
KITSAP-----	20	25

Foodstuffs

Emergency feeding of homeless and displaced persons, including those affected by loss of power or fuel as well as those displaced by structural damage, is an early problem for the responding agencies. Available supplies of food in local supermarkets are normally adequate to satisfy customer needs of the market area for a number of days, depending somewhat upon resupply schedules. Wholesale warehousing capacities, before earthquake losses are assessed, may be adequate to carry the market area normally served for about seven days. The disruption of transportation routes, coupled with loss to vehicles, will require that local stocks of food be husbanded, while losses in stocks from direct earthquake damage will magnify the problem. There are no backup facilities within easy reach of the Puget Sound Basin. Alternate sources are located in Spokane, Wash., and in Portland, Oreg., or in food-processing centers in Yakima and Walla Walla, in eastern Washington.

Schools have long been considered as staging areas for people needing food and shelter at a time of disaster. Nearly every local resident is aware of the location of the nearest school, and most publicly owned school facilities will be available and can support the emergency needs of displaced persons. Large shopping centers located out of vulnerable congested areas should also be considered in the programs for development of care facilities. Because they are keyed to the population growth patterns and transportation networks, shopping centers are regional in concept, and they offer a facility that will remain at least partially functional in terms of access to food and drug services. The shopping centers, under private ownership, do not necessarily have assembly areas to shelter large groups and require great coordination and advance planning to establish emergency procedures.

Data collection

Major warehouses containing foodstuffs, and wholesale food suppliers were identified by the field office of the Food and Nutrition Service of the U.S. Department of Agriculture. The location of these food resource facilities is shown in figure 54. Note that these resources are found only in Everett, Tacoma, and metropolitan Seattle. The "Directory of Shopping Centers in the United States and Canada, 1973", supplied the location of the major shopping centers in the six-county study area.

Analysis

Wholesale warehousing structures are so varied in construction types, earthquake-resistive properties, year built, and geographic location with respect to the foregoing that it is impractical to list them and discuss damage patterns except in general terms.

Food warehousing, including cold storage and cannery storage, is frequently located in one-story structures having wood roofs and reinforced concrete walls. These reinforced concrete walls are often of a type known as "tilt-up", in which the wall is constructed as a panel in a horizontal position, raised to vertical position, and tied to its adjoining tilt-up wall panel by weld attachments or by cast-in-place reinforced concrete columns (pilasters) located between the panels. In the 1971 San Fernando earthquake, this type of construction in the heaviest hit areas experienced building damage that averaged almost 20 percent of the cash value of the building. Similar buildings with reinforced hollow concrete block or reinforced brick experienced similar damage. Contents within the structures, which commonly lost part of their roofs, were damaged, but no experience figures are known with respect to the foodstuffs.

Partial roof failure is expected to be a frequent problem in the hardest shaken areas. Stocks of nonrefrigerated foods will last for days, but the most serious problems from a food-loss standpoint stem from damage to refrigerated warehouses, as damage to the building can also rupture insulation. This kind of building damage, compounded by an extended loss of electric power and the resulting loss of refrigeration, is expected to cause serious foodstuff losses at some locations.

It is probable, considering the Puget Sound climate, that more than 15 percent of the foodstuff in wholesale warehouses located in Snohomish, King, and Pierce Counties will be so greatly damaged as to be unusable.

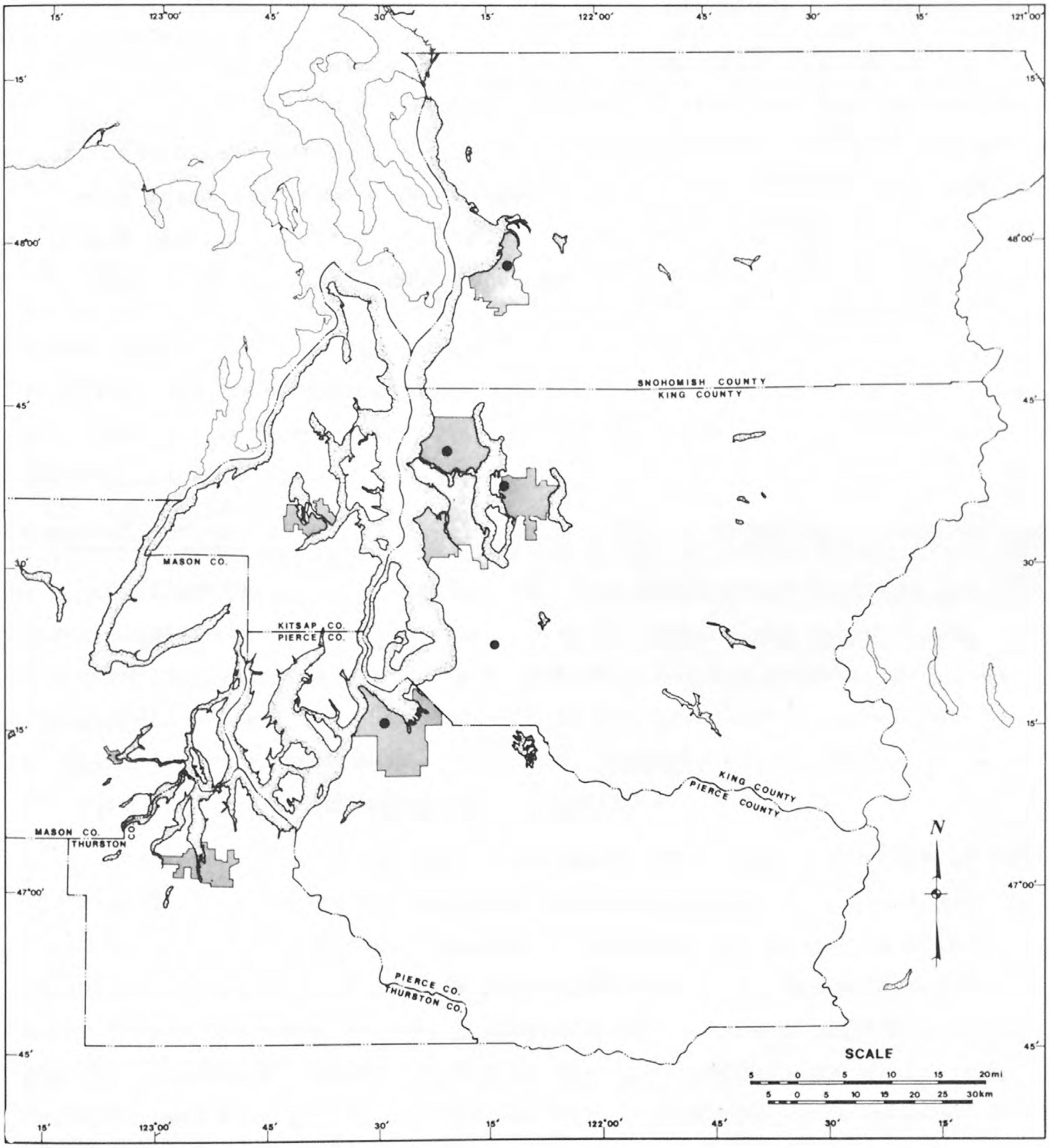


Figure 54.--Location of major wholesale food suppliers in the six-county study area. One dot may represent more than one facility.

This damage will be due to falling stock, building damage, or water damage. Rainwater or water from fire-protection sprinkler systems can destroy paper cartons containing foodstuffs, or loosen labels, making content identification difficult or impossible.

Post-disaster distribution of food to areas outside Seattle, Everett, and Tacoma will be seriously hampered if ground-transportation facilities are disrupted for an extended length of time. Waterborne freight handling has almost vanished from Puget Sound, and inland communities might have impaired rail or highway access. Small communities in the Cascade foothills are generally accessible only from the Puget Sound Basin, particularly during the winter months.

Fire following earthquake

In the event of an earthquake, demands may be levied on fire services that may temporarily channel manpower and equipment toward community service to disaster victims. Regardless of the definition of the primary role of the fire services the public is aware of them as an organized group frequently responding to non-fire-related problems. The strategic location of fire stations and equipment throughout the populated areas give them the capability to respond to requests for nonfire assistance immediately following an earthquake. Such requests, combined with damage to fire stations, firefighting equipment, and communications, disruption of access routes to reach fires, and earthquake-related problems with water supply, compound the problem of firefighting by the diversion of available personnel to emergency medical aid or other functions. These are some of the factors that disaster-response agencies must consider in their planning.

Data collection

The location of fire stations and fire departments in urban and rural areas is shown on figure 55. Data collection and analysis for fire stations are given earlier in this section under the heading of Public structures. Strengths of departments in the urban areas were obtained directly from the departments concerned, together with information on deployment of personnel under alarm conditions.

Water-supply lines are shown on figure 50, in the discussion of public utilities. Information was also obtained through maps previously prepared by the Puget Sound Governmental Conference and augmented with information from the Washington State Department of Social and Health Services, Water Supply and Waste Section. Congested areas were established on the basis of studies of Sanborn maps made available through the Washington Surveying and Rating Bureau, together with a study of aerial photographs of the principal urban areas. These in turn can be related to population through census-tract information.

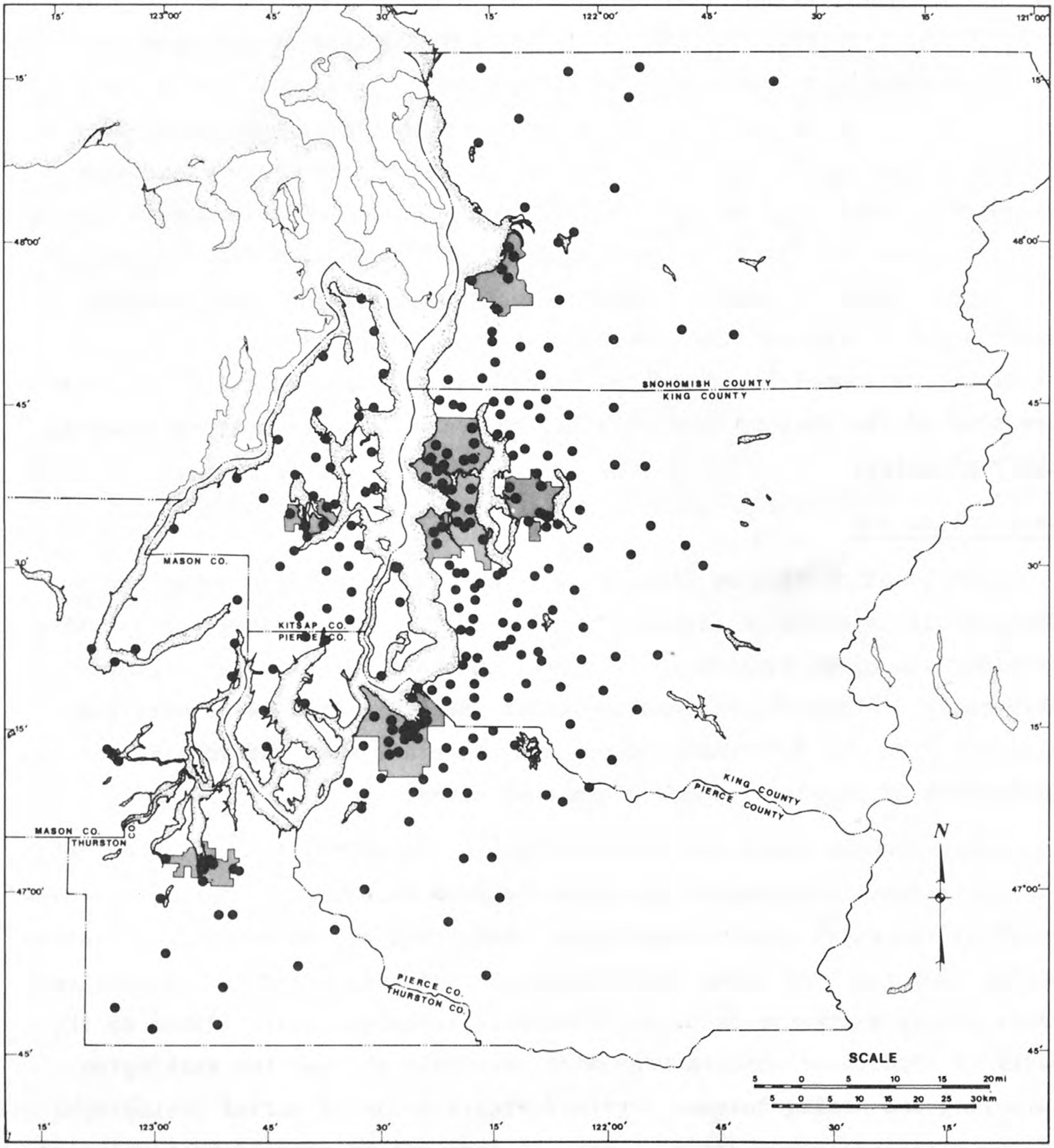


Figure 55.--Location of fire stations throughout the six-county study area. In municipalities, one dot may represent more than one station.

Background information

Records of earthquakes in the United States indicate that fires almost always occur after severe earthquakes, but most of these fires are not classed as true conflagrations. Table 82 shows a history of fire occurrence after earthquakes in the United States. A conflagration is defined, within the limits of this study, as a large fire which spreads in an uncontrolled manner for a long length of time.

There are three principal conditions which, occurring in combination, make conflagration seem a probability following severe earthquakes. These conditions include (1) high density of combustible construction; (2) unfavorable weather conditions--high winds, low humidity; and (3) impaired firefighting capabilities caused by blocked access, water-supply shortage, trapped or damaged fire apparatus, and injured or diverted personnel. Fires in oil and fuel-storage facilities may be initiated without the foregoing special conditions. These in turn create a special type of conflagration, which is both expensive and debilitating to the community undertaking reconstruction, but does not affect life hazard to the degree of congested-area fires. The Puget Sound Basin has not been subjected to conflagration or even to major earthquake-related fires, although severe impairment of water supply has been experienced as well as rupturing of fuel storage containers in the proximity of congested areas.

Congested areas having the potential for large-scale fires, and areas of high-rise structures are shown on figure 34. Older construction in the congested areas is frequently of a type which would no longer be permitted as new construction in such areas. Over the years, much of this construction has been gradually eliminated and replaced. There is a current trend toward retention of old masonry buildings with timber framing, which, in some areas, tends to preserve the condition of hazard. At the same time, elimination of older buildings has been accomplished in order to construct new high-rise, multistory buildings which in themselves create a new firefighting problem. Where buildings of recent design have been constructed within an older community, the improved code restrictions assist such buildings to act as fire separations where rapid spread of

TABLE 82.--FIRES FOLLOWING EARTHQUAKES, SELECTED UNITED STATES EARTHQUAKES

(Abbreviations: N.B.F.U., National Board of Fire Underwriters;)
B.F.U.P., Board of Fire Underwriters of the Pacific;)
P.F.R.B., Pacific Fire Rating Bureau;)
B.S.S.A., Bull. Seismol. Soc. America)

Earthquake	Date	Magnitude	Number of reported fires	References
San Francisco, Calif.	Apr. 18, 1906	8.3	50 fires, 3 hours after	N.B.F.U. 1906.
Santa Barbara, Calif.	June 29, 1925	6.3	1 (dwelling fire)	B.F.U.P., 1925.
Long Beach, Calif.	Mar. 10, 1933	6.3	2 fires in Los Angeles, 11-15 in Long Beach	N.B.F.U., 1933.
Imperial Valley, Calif.	May 18, 1940	7.1	4 (possibly more in Mexico	Insurance Journal, May, 1940.
Kern County, Calif.	July 21, 1952	7.7	1 Refinery fire	B.S.S.A., v. 44, p. 270.
Bakersfield Calif.	Aug. 22, 1952	5.8	1 (dwelling fire)	B.F.U.P., written commun., 1952.
San Francisco, Calif.	Mar. 22, 1957	5.3	1 (2-story apartment)	Calif. Div. Mines, Special Report 57.
Anchorage, Alaska 1/	Mar. 27, 1964	8.4	4 "minor" 1/	N.B.F.U. and P.F.R.B., 1964.
San Fernando, Calif.	Feb. 9, 1971	6.4	109	Steinbrugge and others, "San Fernando E.Q.", P.F.R.B., 1971

1/ Oil fires elsewhere in Alaska not included.

fire might result between buildings of older construction.

Water supply plays an important role in fire department operations, and the integrity of the supply source and system must be maintained. Few major interruptions have been experienced as a result of an earthquake. In cases where major interruptions have occurred, very hazardous conditions were experienced until full service could be restored. Lack of earthquake-induced fires under the circumstances in no way reduces the condition of hazard. Large, widely separated water-supply grids in Seattle allow for ready cutoff and rerouting in the event of main breaks. Most other cities in the Puget Sound area have reasonably high capacities designed into their primary supply systems; duplicate facilities are not as effective. All, however, have tank or reservoir facilities capable of maintaining water flow for several hours.

Water-main systems serving schools in residential areas may not be designed to respond to the heavy water demand made upon them in the event of a major fire or other disaster. In the discussion of Foodstuffs, schools are mentioned as potential service centers for persons needing food and shelter. Schools require adequate fire protection so that they will remain available for shelter purposes and community service following disaster, as well as for protection against hazards occurring at a school.

Firefighting problems are different and greater in high-rise buildings than in low structures. Water pressure required for fire streams at higher elevations in the buildings may be inadequate in the event that broken water mains cause reduced residual pressures. By the same token, damage to standpipe installations in high-rise buildings may well have a serious effect on firefighting efforts. Within the context of present building codes, Seattle has elevator and standpipe requirements, and several other cities in the Puget Sound Basin are working in this direction. Smaller communities with limited building departments do not always have a detailed understanding of code provisions and purposes. From this lack of understanding, nonconforming buildings may exist.

<u>Fire departments</u>

Firefighting forces in the Puget Sound Basin vary with the community size. Their approximate strengths, on the basis of department reports, are given in table 83. Suburban and rural areas are generally serviced by volunteer personnel, operating equipment under control of the nucleus of regular, paid firefighters.

Seattle maintains a department strength of approximately 1,000 men, with about one-third on duty at any given time. Other communities have proportionately smaller duty forces. Callback facilities for increasing manpower strengths during an emergency range from individual telephone calls to automatic radio facilities. The effectiveness of tactics and fire ground operations is determined by the number of men on duty and those assigned as active firefighting personnel, rather than the total fire department roster, which includes administrative and inspection personnel.

Distribution of fire stations and assigned strength at the station location are intended to match the probable logistic requirements for normal fire-response expectations in the station area, combined with a complex system of reassigning responsibilities and moving up equipment to cover areas in which personnel and apparatus are currently actively engaged. Apparatus and fittings are standardized to facilitate prompt emergency operations between neighboring communities.

Disposition of equipment and personnel is intended to utilize the best normally travelled routes in the area. Damage to arterials could affect response time and cause serious delays in the response of fire apparatus. Fire departments in the greater Puget Sound area have reciprocal mutual aid agreements. Such agreements are usually of more benefit to the smaller communities, by providing assurance of backup following an earthquake. However, it is conceivable that blocked access routes might mean that some areas on the perimeter of the larger community would be more readily accessible by equipment from an adjacent small department.

Fire-department functions have been expanded to normally include aid car services in response to injury, accident, or acute illness. This work is performed by regular firefighting personnel with special or additional

TABLE 83.--CATEGORIES OF MANPOWER EMPLOYED IN FIREFIGHTING IN REPRESENTATIVE COMMUNITIES IN THE SIX-COUNTY AREA OF THE PUGET SOUND BASIN

(Source: Information supplied by the Washington Local Personnel Institute of the Association of Washington Cities, and by the Washington State Association of Firefighters, 1974)

County	Over 25,000 population	10,000-24,000 population	Number of professional firefighters 1/	Augmented by volunteers
SNOHOMISH	Everett---	-------------------	176	No.
		Edmonds------------	23	Yes.
		Lynnwood-----------	26	Do.
		Mountlake Terrace--	7	Do.
KING		Auburn-------------	39	Do.
		Bothell------------	16	Do.
	Bellevue--	-------------------	61	Do.
		Kent---------------	38	Do.
		Kirkland-----------	13	Do.
		Mercer Island------	18	Do.
		Redmond------------	14	Do.
		Renton ------------	63	No.
		Sea-Tac Airport-- --(Port of Seattle)	34	Do.
	Seattle---	-------------------	995	Do.
		Tukwila -----------	25	Yes.
PIERCE		Puyallup-----------	26	Do.
	Tacoma----	-------------------	298	No.
THURSTON		Olympia------------	47	Unreported.
MASON		Shelton------------	13	Yes.
KITSAP	Bremerton-	-------------------	72	No.

1/ A total of 30 local fire districts in Snohomish, King, Pierce, and Thurston Counties report the employment of professional firefighters. Nine of these districts employ 12 or more men.

training. As a result, occupation of part of the force in a paramedic capacity following a major earthquake might significantly reduce the direct firefighting capabilities. A major fire in a congested area, concurrent with a high injury rate due to structural collapse in the same area, will create difficult response decisions.

Telephone alarms in Seattle are handled through the "911" emergency reporting system, whereby all types of emergency are processed through one center and relayed to the appropriate agency for response. Other communities in the Puget Sound Basin also have police and fire dispatching centers, some of which are combined. Manpower demands in response to alarms vary with the location and nature of the fire. In a three-alarm fire in the congested area of downtown Seattle, the department reports that as many as 100 men may be activated, and off-shift personnel could be alerted for return to duty. Outside of the congested areas, response will be substantially less and may vary from a specialty crew of 4 men to a battalion with a strength of 30 men. From this it can be seen that serious fires, short of conflagration, can rapidly utilize a large portion of the equipment and manpower available to the community. Fires are to be expected as an outgrowth of earthquake damage and may well occur in residential, commercial, and industrial types of structures, where earthquake-induced short-circuits, fuel leaks, and other combustion-inducing occurrences are experienced. The ultimate size of these fires will be dependent on their detection and the ability of the fire department to respond.

Conflagration

Where access has been limited, or water supply reduced, the possibility of the development of major fires can be understood. The necessary conditions for conflagration have been spelled out previously and a review of the conditions throughout the Puget Sound Basin leads to the conclusion that conflagration as defined appears to be limited in potential. This limitation results from smaller sizes of communities and generally limited areas of high-density combustible construction, and the lack of normal weather conditions favorable to fire expansion and travel. Studies of Sanborn maps and aerial photographs, together with direct observation of buildings and information secured from building departments, establishes the general boundaries of areas where serious fires might become conflagrations. Actual areas which might be susceptible to the development of conflagration are generally limited, or have inherent fire breaks.

While conflagration does not appear to be probable, the possibility for extremely severe fires extending beyond a single building or beyond a single block requires consideration. To the extent that major fires can be experienced, disaster planning must set the priorities for use of fire-fighting personnel in other activities requiring emergency response, where the request might be directed to the fire department.

Congested area conditions

Comments are made on each of the principal communities in the Puget Sound Basin, to outline the extent of the problem and delineate critical areas that may exist or special conditions which are of concern.

Everett

In the city of Everett, the principal business district covers approximately 23 blocks and an area of 35 acres (14 ha), approximately 5 blocks in each direction with the southerly boundary at the Snohomish County Courthouse. Thirty-eight percent of this area is dedicated to streets 24-100 feet (7-30 m) in width, with 74 percent of the remaining available block area covered with construction. Of the construction in the area, 2 percent is protected by automatic sprinklers, 21 percent is fire-resistive, and 7 percent is unprotected noncombustible over wood-frame construction. Buildings range up to seven stories in height, eliminating the problem of extreme high-rise fire response.

Industrial districts are separated from the business district; they are located along Port Gardiner Bay and the Snohomish River. Occupancies include both small businesses and large mills and woodworking plants. However, most of the buildings are well separated and low, while a few are protected by automatic sprinkler systems.

The fire department is quite large for a city of this size; it has experienced several major fires and prevented them from extending beyond immediate exposure. The water-supply system is well laid out and modern. However, its weakness is in the incoming mains serving the city across Ebey Slough, where previous breaks in the water mains have occurred.

Seattle

In Seattle, the principal business district comprises 107 blocks or part blocks. Fifty-one percent of the district, or 248 acres (100 ha), consists of open space and dedicated streets varying from 36 to 100 feet (11-30 m) in width. Nineteen percent of the construction in the area is protected by automatic sprinklers and only one percent is of wood-frame construction. Since 1965, a number of additional high-rise buildings have been constructed in the central business district, generally replacing older, more fire-susceptible structures with construction having a better fire-resistive classification. Countering this, of course, is the additional difficulty of combatting fires which might be started in major high-rise buildings at upper levels. All of the large, major shopping centers are of recent construction, generally fire-resistant and well separated by open areas from surrounding parts of the community. Older small business districts provide limited areas of congestion together with impaired access and increased fire risk; however, they are not generally conducive to very broad spread of fire.

Commercial and industrial facilities cover an extensive portion of waterfront, not only on Elliott Bay but also on the Lake Washington Ship Canal and around the shores of Lake Union. A number of the older piers have been retained in the area north of Yesler Way, along the waterfront to Broad Street, and the construction around the Lake Union waterfront varies in its fire-resistant capabilities. In the industrial area that lies south of Elliott Bay, waterfront sections are changing in character and consist largely of open wharfs handling containerized cargo. The largest part of the industrial district lies south of Jackson Street in the Duwamish Valley, between Interstate Highway I-5 and West Marginal Way, and consists of low-rise structures, largely of unprotected metal or masonry construction and tilt-up concrete construction. Beyond this concentration of industrial structures is that of the Boeing Company. These buildings, while involving an area covering many acres, are well separated and equipped with automatic sprinklers and have the extra protection of a private fire department.

Harbor Island and the areas to the east and west of it are involved with all types of waterfront activity, from cargo handling to ship repair, and also provide areas for a large amount of bulk flammable liquid storage. Automatic sprinklers are provided in most facilities in this area, and the waterfront structures are served in addition by two fireboats, one capable of delivering 22,800 gallons per minute (86,298 lpm) and the other, 16,000 gallons per minute (60,560 lpm). This capability can be augmented on request by pump-equipped tugboats. Under emergency circumstances, the fireboats could be used to supply water to firefighting units at some distance from the waterfront. Severe fires in the industrial area may occur. However, industrial structures are well separated from surrounding commercial and residential facilities.

Tacoma

The principal business district of the city of Tacoma covers an area of approximately 87 acres (35 ha) and includes some 39 blocks of commercial construction. It is located along the west bank of the Puyallup River as it enters Commencement Bay, and consists of an elongated area generally centered in Pacific Avenue. Laterally in an east-west direction, the zone is relatively narrow and built on steep sidehill conditions. Fifty percent of the area is dedicated to streets in widths varying from 40 to 100 feet (12-30 m). Of the available area for construction, 75 percent is built up, with a wide range of individual block coverage. Only nine percent of the construction is protected by automatic sprinklers. However, wood-frame and noncombustible construction is limited to one percent of the area. Building heights range from 1 to 23 stories. However, most buildings are two and three stories in height. Some old masonry construction remains, but original upper stories and parapets were removed from older business district buildings following the 1949 earthquake, to reduce the structural-failure hazard.

The industrial area extends across the tideflats at the head of Commencement Bay and also into the area south of the business district to

Interstate Highway I-5. Large manufacturing plants and maritime service structures along the waterfront through the tideflat area are generally well separated, although some individual plants could experience large fires. Separation between them could prevent uncontrolled spread. The waterfront is active and well developed, served by one fireboat having 10,000 gallons per minute (37,850 lpm) pumping capacity and augmented by 15 private pump-equipped boats on call. Earthquake-related problems affecting bridges on the roadway that pass across several waterways serving the industrial area might prevent access by fireboat to some of the area otherwise served. While the layout of the community is such that development of conflagration appears unlikely, the possibility that more than one major fire might occur simultaneously could pose demands for equipment and manpower sufficient to eliminate reserve strength. Moreover, past experience records that numerous breaks have occurred in waterlines and some reductions in pressure have been experienced, adversely affecting firefighting capabilities.

Olympia

In the city of Olympia, which has a population of approximately 20,000, the business district occupies about 20 blocks and lies adjacent to the industrial area, which is on filled land extending out into the southern extremity of Puget Sound. Ordinary masonry construction is common and blocks are well covered. Streets are 60-80 feet (18-24 m) in width and would constitute a reasonable barrier to the travel of fire. However, the possibility of fire within any given block exists, and the type of construction lacks protection against lateral fire extension.

Those buildings composing the campus of the Washington State Capitol are separated from the commercial and industrial areas of the city by several blocks. In turn, buildings of the capitol are well separated from each other and of relatively high fire-resistant standards.

Other industrial operations exist outside the major communities. These are generally separated from other community areas and do not become an immediate emergency problem in the event of an earthquake.

In the assessment of fire following earthquake and the response of personnel to that situation, reference should be made to the section on

Losses from causes other than dam failure, which indicates total injured in various parts of the Puget Sound Basin. All of these injuries would occur at the same time and, as a consequence, calls for emergency assistance would be concentrated into a short time period. The capability of a fire department to respond to emergency medical calls would be limited by the number of personnel available.

Analysis

Earthquake "A"--Olympia-Tacoma epicenter

High intensities in the southerly portion of the study area can bring structural damage to the business district and the industrial area of Olympia. It should be assumed for planning purposes that uncontrolled fire in industrial and commercial areas may be experienced over an area of 2-3 city blocks. Because Olympia is the capital city of the State, there are a great number of legislators, lobbyists and visitors, in the area for extended periods of time. Their presence adds substantially to the potential for personal injuries in the event of a major earthquake, and reduces the firefighting capability of the community.

High intensity will also be experienced in Tacoma, accompanied by the potential for fires in the industrial area. Conflagration is unlikely on the Puyallup River estuary, because of the broad separation between the individual industrial installations. Planning should anticipate the development of serious fires in older industrial structures and in the tank farms immediately across the waterway from the central business district. Uncontrolled fires could occur in a 1-3 block area of older construction along Pacific Avenue and immediately above it. Small outlying communities in Pierce County will be severely shaken and can anticipate fires as an accompaniment to structural damage.

Attenuation will result in lower impact on northerly portions of the study area, so that MMI IX will be limited in Seattle to the Duwamish River estuary, Harbor Island, and tide lands along the central waterfront. This includes much of the old masonry construction in that area but only a limited amount of high-rise. Serious fires in tank farms on Harbor Island, shipyards, and industry along the Duwamish River should be assumed for planning, together with extensive damage in the International district and historical area, possibly extending uncontrolled over a 4-5 block area in at least one instance.

North and east of Seattle and in Snohomish County the intensity drops sharply and the fire potential is nominal. Mason County and the Kitsap peninsula will experience damaging levels of intensity. Less congested conditions make conflagrations unlikely; however, fires are to be assumed in commercial and industrial areas of Shelton, Port Orchard, and Bremerton.

Earthquake "B"--Seattle epicenter

Intensities in the southerly portion of the study area will be less than in earthquake "A". Conditions in the port and industrial areas of Tacoma will be approximately the same for both postulated earthquakes. The location of the epicenter is such that more high-rise construction will be affected in the event of this earthquake. The damage to older high-rise structures in Tacoma's business district may create firefighting problems at an elevation above the capabilities of the fire equipment.

Uncontrolled fires at the tank farms in the industrial area of Seattle may occur, accompanied by the occurrence of severe shipyard and waterfront fires along the Duwamish River. For planning purposes, it should be assumed that serious structural damage in older masonry buildings at the south limits of the business district will occur, as well as uncontrolled fires covering 4-5 city blocks in both the international and historical areas.

At the same time, serious structural damage to older high-rise buildings will be accompanied by fire at an elevation above the reach of fire equipment. For planning purposes, it should be assumed that two uncontrolled fires will occur in the congested areas of the older commercial district accompanied by one fire in a high-rise structure in the business district, above the reach of fire equipment, and one fire in a high-rise residential structure in the same general area of high intensity. Planning for these contingencies should be combined with the need for immediate patient evacuation from one major hospital in the First Hill area.

In earthquake "B", the highest intensity areas would encompass most of the commercial area in Metropolitan Seattle and be extended through the industrial area to include the city of Renton and all of the Kent

Valley, bringing major fires to Renton, Kent, and Auburn. In large areas of residential communities, damaging intensity levels will aggravate the problem of response to major fire calls. Under the same conditions, it should be postulated that major water lines serving the city of Everett are cut and that one uncontrolled fire throughout one city block is encountered. Conditions on the Kitsap peninsula are generally the same as for earthquake "A".

Structural collapse of fire stations, or access problems resulting from either postulated earthquake will reduce the amount of equipment immediately available by 20 percent. An additional 20 percent of normal strength will be dissipated in meeting immediate secondary needs in residential areas.

Debris removal

For the purposes of this six-county study, debris removal may be placed into two categories: (1) that which requires immediate removal or moving, and (2) that which can be moved later. The first category includes debris in public ways in sufficient quantities to prevent the passage of emergency vehicular traffic and also debris covering injured persons. In the case of blocked streets, it may be sufficient to move the debris aside with bulldozers in order to clear a single traffic lane. Later removal (in the second category) can be by skiploaders and trucks. Streets and freeways blocked by collapsed overpasses will pose a much more serious removal problem, as the concrete or steel members will have to be cut into smaller pieces to facilitate removal, and heavy equipment will be required.

The careful removal of debris that covers trapped and injured persons is a time-consuming and meticulous job requiring cranes, skiploaders, cutting equipment, and considerable manual labor. For example, the collapsed buildings at the Veteran's Hospital, caused by the 1971 San Fernando earthquake, resulted in the deaths of 47 persons, while 60 people were trapped in the two buildings. The rescue operations were not completed until some 58 hours after the collapse, according to the Los Angeles City Police Department.

In heavily damaged areas, it will be difficult, if not impossible, to determine where bodies remain in the rubble. Following the Managua, Nicaragua, earthquake of December 23, 1972, large areas of rubble were sprinkled with gasoline and set afire to destroy buried bodies as a precautionary measure against the outbreak of epidemics.

Debris in the second category may be removed at a later time, using heavy equipment, and trucked to disposal sites. This category includes debris from collapsed structures that fall into public thoroughfares, parking lots, and vacant lots, and within the building site.

Earthquake-initiated landslides may block streets or highways and require emergency action to secure passage. This problem, which is allied to that of building debris, has been discussed under Transportation.

The location of search-and-rescue problems will vary with the time of day and population pattern. Time will also affect the seriousness of problems encountered, with abrupt short-period fluctuations when large numbers of people are temporarily in hazardous situations, as during the noonhour, when streets are filled with pedestrians adjacent to old buildings or around high-rise buildings immediately abutting the street.

Height of construction is not necessarily a measure of hazard. Many single-story or two-story stores in old neighborhood shopping areas have masonry parapets sufficient to cause numerous casualties if the time of earthquake occurrence coincides with that of heavy pedestrian use. Smaller old communities have hazards of a similar nature, which may not have been as well recognized as those in the urban centers.

While large volumes of debris, partially blocking streets and requiring development of access lanes, might be found in such locations as the Pioneer Square area in Seattle, or even in portions of the central business district, small community and older neighborhood areas of commercial development could also experience collapse problems. This debris probably would not block street access, but could create a debris-removal problem in areas where injured persons might be trapped. This generalization can be applied to the entire six-county area, in communities such as Monroe, Renton, Puyallup, Bremerton, or Shelton, as well as in Seattle, Tacoma, Everett, or Olympia.

<u>Data collection</u>

The principal sources of debris may be classified as follows:

1. Unreinforced brick-masonry parapets and bearing walls with wood roofs and floors;
2. Inadequately anchored cornices, masonry walls, marquees, signs, precast-concrete wall panels, and veneer;
3. Glass windows;
4. Fallen wires, pole and platform-mounted transformers, and poles;
5. Collapsed and partially collapsed multistory buildings; and
6. Collapsed and partially collapsed highway, freeway, and railway bridges.

The principal sources of building debris are the pre-1950 unreinforced brick-masonry-bearing-wall buildings and the old as well as new high-rise buildings. These data for congested areas are given in tables 43 and 44; these selected areas are geographically located in figure 34, for Seattle and Tacoma. There are few other areas of modern high-rise buildings in the other parts of the Puget Sound Basin, and, where located, the buildings are so separated that no true congestion occurs.

Data on freeway collapses are given in the section on Transportation and need not be repeated here.

Analysis

Unreinforced brick buildings predating 1950 are found in limited pockets, or as individual structures scattered through the commercial areas. They remain the most likely candidates for collapse, and thus a major factor in debris development. Starting with intensities as low as VII, unreinforced brick-masonry parapets begin to topple. As the ground motions increase, entire bearing walls fall, and roofs and floors sometimes collapse. Alternately, roofs and floors can remain supported by numerous interior bearing partitions, such as those found in apartment buildings, even though the brick exterior walls may be gone. Parapet-correction programs have resulted in the removal of many unreinforced brick-masonry parapets and nominal anchorage of the walls below to the roof systems.

However, experience in the San Fernando earthquake indicates that, in areas having MMI VII, some walls that had received such corrections failed below the roof line and large areas of the walls were thrown down. Therefore, the parapet-correction program will not result in greatly improved conditions in MMI VIII and IX areas in the postulated earthquakes. Although unreinforced brick-masonry walls will still be thrown down when subjected to these high intensities, the quantity of resulting debris will be reduced as a result of the previous removal of many parapets.

Insufficient data were available to make a debris analysis for all pre-1950 unreinforced brick-masonry buildings, and the analysis was restricted to the selected congested areas covered by tables 43 and 44. For purposes of analysis, table 84 was used in conjunction with the following reasonable building street-front and wall characteristics:

Average height of parapet wall:	3 feet	(91.4 cm)
Average thickness of parapet wall:	12 inches	(30.5 cm)
Average number of stories	3	
Average total height of building, floor to roof:	40 feet	(12.2 m)
Average thickness of wall below parapet:	14 inches	(35.6 cm)
Average percentage of openings:	40 percent	

TABLE 84.--ESTIMATED DAMAGE TO NON-EARTHQUAKE-RESISTIVE BRICK-MASONRY BUILDINGS IN CONGESTED AREAS IN PUGET SOUND BASIN
(All measures of collapse are shown in percent)

Modified Mercalli Intensity	Pre-1950 conditions			Improved conditions (parapet corrections)	
	Collapsed parapets[1/]	Collapsed walls	Collapsed buildings	Collapsed walls	Collapsed buildings
VII	20	10	5	5	0
VIII	40	20	10	15	10
IX	55	40	20	30	20

[1/] "Collapse" is defined to include major partial collapse.

Table 85 is the result of the analysis. A review of this table indicates that the magnitude 7.5 earthquake postulated on the Seattle epicenter produces about 50 percent more debris than will the postulated shock on the Olympia epicenter.

No effort has been made to estimate or tabulate debris from buildings faced with precast elements, or stone veneer and column encasement. This type of facing is used extensively, often for surface cladding of multistory buildings. Experience in the Good Friday earthquake of 1964 in Anchorage, Alaska, where precast panels on the J. C. Penney building were torn loose, is indicative of the potential for high-hazard debris, which

TABLE 85.--NON-EARTHQUAKE-RESISTIVE BRICK-MASONRY BUILDINGS IN SELECTED CONGESTED SECTIONS OF SEATTLE AND TACOMA
(Nonreinforced brick buildings constructed prior to 1950)

		Earthquake "A"		Earthquake "B"	
Location	Sanborn Map vol.	Brick in street (tons) 1/	Number of buildings collapsed 2/	Brick in street (tons) 1/	Number of buildings collapsed 2/
Seattle:					
North---	5	230	0	1,400	7
	6	300	1	910	6
	14	70	0	210	1
	15	40	0	180	1
Central--	1	600	3	1,280	8
	2	1,700	6	3,700	19
	4	1,100	4	2,300	11
	16	90	1	190	2
South---	3	620	4	620	4
Tacoma---	1	1,800	7	580	1
	2	900	5	300	1
	3	540	2	380	1
Totals		7,990	33	12,050	66

1/ From street front walls only.

2/ "Collapse" is defined to include major partial collapse.

might develop in quantity.

Current practice to use exposed concrete framework removes the problem of loose veneer, but may result in lethal falling pieces of concrete as spalling occurs under building distortion. This does not create a removal problem because debris would probably be limited in quantity.

Similarly, marquees, signs, and inadequately anchored cornices may create a hazard, but not a quantitative debris problem.

Glass windows are frequently broken due to the distortions of the building frames. In the case of the collapsed Psychiatric Unit at the Olive View Hospital in the San Fernando earthquake of 1971, broken glass was found as far as 100 feet (30.5 m) from this two-story structure. In the April 1965 Puget Sound earthquake, glass breakage occurred on all floors of a ten-story building in the Tacoma business district.

Earthquake "A"--Olympia-Tacoma epicenter

Severe problems can be expected in South Puget Sound communities, including Olympia and Shelton, and in the Puyallup River alluvial plain, including the Tacoma industrial areas, Puyallup, Sumner, Auburn, and Kent. The Duwamish River industrial area of Seattle and the south and west portions of the business district, where much old masonry construction remains, will suffer substantial damage to brick structures.

Earthquake "B"--Seattle epicenter

Damage from this earthquake will be greater in the north portion of the study area. Because this includes the greater Seattle metropolitan area, a very marked increase in debris development can be expected with much more widespread damaging effects in both the business district and in the residential areas. Damage potential will be severe in the Kent valley, and heavy shaking will be experienced in Bellevue and north to Everett, with high intensity in the Snohomish, Snoqualmie and Skykomish River valleys.

MODIFIED MERCALLI INTENSITY SCALE OF 1931

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

See (Wood and Neumann, 1931) for complete details of this Intensity Scale.

SELECTED REFERENCES

American Society of Civil Engineers, 1907, Effects of the San Francisco earthquake of April 18, 1906 on engineering constructions: Am. Soc. Civil Engineers Trans., v. 59, p.208-329.

Algermissen, S. T., and Harding, S. T., 1965, The Puget Sound, Washington earthquake of April 29, 1965: U.S. Dept. Commerce, Coast and Geodetic Survey, 51 p.

Algermissen, S. T., (principal investigator), Rinehart, W. A., Dewey, James, Steinbrugge, K. V. (principal consultant), Lagorio, H. J., Degenkolb, H. J., Cluff, L. S., McClure, F. E., Scott, Stanley, and Gordon, R. F., 1972, A study of earthquake losses in the San Francisco Bay Area--A report prepared for the Office of Emergency Preparedness: U. S. Dept. Commerce, NOAA, Environmental Research Laboratories, 220 p.

Algermissen, S. T. (principal investigator), Steinbrugge, K. V. (principal consultant), Hopper, Margaret, Campbell, Kenneth, Rinehart, W. A., Perkins, David, Lagorio, H. J., Moran, D. F., Cluff, L. S., Degenkolb, H. J., Duke, C. M., Gates, G. O., Jacobson, D. W., and Olson, R. A., 1973, A study of earthquake losses in the Los Angeles, California area--A report prepared for the Federal Disaster Assistance Administration, Department of Housing and Urban Development: U.S. Dept. Commerce, NOAA, Environmental Research Laboratories, 331 p.

Algermissen, S. T., Stepp, J. C., Rinehart, W. A. and Arnold, E. P., 1969, Studies in seismicity and earthquake damage statistics: ESSA, U.S. Dept. Commerce, Appendix B, 68 p.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. America Bull., v. 81, p. 3513-3536.

Atwater, T., and Menard, H. W., 1970, Magnetic lineations in the northeast Pacific: Earth and Planetary Sci. Letters, v. 7, p. 445-450.

Barksdale, J. D., and Coombs, H. A., 1946, The Puget Sound earthquake of February 14, 1946: Seismol. Soc. America Bull., v. 36, no. 4, p. 349-354.

Battson, G. E., survey coordinator, 1965, Earthquake survey, beginning April 30, 1965: Seattle, Wash., Building Dept., 262 p.

Bechtel, Inc., 1975, Investigation of the December 14, 1872 earthquake in the Pacific Northwest: Puget Sound Power and Light Company Skagit Nuclear Power Project, Preliminary Safety Analysis Report, Appendix 2J, 128 p.

Berg, G. V. and Stratta, J. L., 1964, Anchorage and the Alaska earthquake of March 27, 1964: New York, American Iron & Steel Inst., 63 p.

Binder, R. W., 1952, Engineering aspects of the 1933 Long Beach earthquake, in Symposium on earthquake and blast effects on structures: Earthquake Engineering Research Inst. and California Univ., Los Angeles, Proc., p. 186-211.

Bodle, R. H., 1941, United States earthquakes, 1939: U.S. Dept. Commerce Coast and Geodetic Survey, Serial No. 637, 71 p.

__________ 1946, United States earthquakes, 1944: U.S. Dept. Commerce Coast and Geodetic Survey, Serial No. 682, 43 p.

Bodle, R. H., and Murphy, L. M., 1947, United States earthquakes, 1945: U.S. Dept. Commerce Coast and Geodetic Survey, Serial No. 699, 38 p.

__________ 1948, United States earthquakes, 1946: U.S. Dept. Commerce Coast and Geodetic Survey, Serial No. 714, 48 p.

Bolt, B. A., Lomnitz, C., and McEvilly, T. V., 1968, Seismological evidence on the tectonics of central and northern California and the Mendocino escarpment: Seismol. Soc. America Bull., v. 58, p. 1725-1767.

Bradford, D. C., 1935, Seismic history of the Puget Sound Basin: Seismol. Soc. America Bull., v. 25, p. 138-153.

Bradford, D. C., and Waters, A. C., 1934, The Tolt River earthquake and its bearing on the structure of the Cascade range: Seismol. Soc. America Bull., v. 24, p. 51-62.

Brazee, Rutlage and Cloud, W. K., 1959, United States earthquakes, 1957: U.S. Dept. Commerce Coast and Geodetic Survey, 108 p.

__________ 1960, United States earthquakes, 1958: U.S. Dept. Commerce Coast and Geodetic Survey, 76 p.

Bulletin of the International Seismological Centre, 1965, 1969: Available from 6 South Oswald Road, Edinburgh, EH9 2HX, Scotland, U.K.

Cady, W. M., Sorensen, M. L., and Macleod, N. S., 1972, Geologic map of the Brothers quadrangle, Jefferson, Mason, and Kitsap Counties, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-969.

California, State of, 1971, Earthquake risk: Joint Committee on Seismic Safety Conf., Carmel, Sept. 22-24, Proc., 152 p.

Campbell, K. W., and Duke, C. M., 1974, Bedrock intensity attenuation and site factors from San Fernando earthquake records: Seismol. Soc. America Bull., v. 64, no. 1, p. 173-185.

Carder, D. S., ed., 1965, Earthquake investigations in the western United States, 1931-1954: U.S. Dept. Commerce Coast and Geodetic Survey Pub. 41-2, 264 p.

Cater, F. W., and Crowder, D. F., 1967, Geologic map of the Holden quadrangle, Snohomish and Chelan Counties, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-646.

Coffman, J. L., and von Hake, C. A., 1972, United States earthquakes, 1970: Washington, D. C., U.S. Govt. Printing Office, 81 p.

____________ 1973, Earthquake history of the United States: U.S. Dept. Commerce Pub. 41-1, Rev. Ed. (through 1970), 208 p.

____________ in press, United States earthquakes, 1973: Washington D.C., U.S. Govt. Printing Office.

Coombs, H. A., 1953, A summary of Washington earthquakes: Seismol. Soc. America Bull., v. 43, no. 1, p. 1-6.

Coombs, H. A., and Barksdale, J. D., 1942, The Olympic earthquake of November 13, 1939: Seismol. Soc. America Bull., v. 32, no. 1, p. 1-6.

Coulomb, J., 1952, Love waves of the Queen Charlotte Islands earthquake of August 22, 1949: Seismol. Soc. America Bull., v. 42, p. 29-36.

Crandell, D. R., and Gard, L. M., Jr., 1959, Geology of the Buckley quadrangle, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-125.

Crosson, R. C., 1972, Small earthquakes, structure and tectonics of the Puget Sound region: Seismol. Soc. America Bull., v. 62, no. 5, p. 1133-1171.

Crowder, D. F., Tabor, R. W., and Ford, A. B., 1966, Geologic map of the Glacier Peak quadrangle, Snohomish and Chelan Counties, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-473.

Degenkolb, H. J., 1969, An engineer's perspective on geologic hazards, in Geologic hazards and public problems: Office of Emergency Preparedness Conf., Santa Rosa, Calif., Proc., p. 183-195.

Disaster Mitigation Planning Committee, 1974, Disaster mitigation plan for Snohomish County: Snohomish County, Everett, Wash., 172 p.

Disaster Planning Committee, 1973, City of Seattle disaster readiness and response plan: Seattle, Wash., 121 p.

Donovan, N. C., 1972, Earthquake hazards for buildings, in Building practices for disaster mitigation: U.S. Dept. Commerce Natl. Bur. Standards Building sc. ser. 46, p. 82-111. (1973)

Duke, C. H., Moran, D. F., and Benjamin, J. R., 1975, Learning from earthquakes: Earthquake Engineering Research Inst., working draft in 5 v., v.p.

Duke, C. M., and Leeds, D. J., 1959, Soil conditions and damage in the Mexico earthquake of July 28, 1957: Seismol. Soc. America Bull., v. 49, no. 2, p. 179-191.

Dutton, C. E., 1889, The Charleston earthquake of August 31, 1886, in 9th Annual Report of the Director, 1887-1888: U.S. Geol. Survey, p. 203-528.

Earthquake Engineering Research Institute, 1973, Managua, Nicaragua earthquake of December 23, 1972: San Francisco, Conf. Proc., v. 1, 528 p.; v. 2, 475 p.

Edwards, H. H., 1951, Lessons in structural safety learned from the 1949 Northwest earthquake: Western Construction, v. 26, no. 2, p. 70-74; no. 3, p. 85-88; no. 4, p. 90-92.

Engle, H. M., 1936, The Montana earthquakes of October, 1935; structural lessons: Seismol. Soc. America Bull., v. 26, no. 2, p. 99-109.

Eppley, R. A. and Cloud, W. K., 1961, United States earthquakes, 1961: Washington, U.S. Govt. Printing Office, 115 p.

Ergin, Kazim, 1969, Observed intensity-epicentral distance relations in earthquakes: Seismol. Soc. America Bull., v. 59, p. 1227-1238.

Gonen, B., and Hawkins, N. M., 1974, Building standards and the earthquake hazard for the Puget Sound basin: Seattle, Washington Univ., 136 p.

Gower, H. D., and Wanek, A. A., 1963, Preliminary geologic map of the Cumberland quadrangle, King County, Washington: Washington Div. Mines and Geology Geol. Map GM-2.

Gringorten, I. J., 1963, A plotting rule for extreme probability paper: Jour. Geophys. Research, v. 68, p. 813-814.

Gutenberg, B., and Richter, C. F., 1942, Earthquake magnitude, intensity, energy, and acceleration: Seismol. Soc. America Bull., v. 32, no. 2, p. 163-191.

____________ 1954, Seismicity of the earth aassociated phenomena: Princeton, N.J., Princeton Univ. Press, 309 p.

Hanson, R. D., and Degenkolb, H. J., 1969, The Venezuela earthquake, July 29, 1967: New York, American Iron & Steel Inst., 176 p.

Hershberger, J., 1956, A comparison of earthquake accelerations with intensity ratings: Seismol. Soc. America Bull., v. 46, no. 4, p. 317-320.

Hodgson, E. A., 1946, British Columbia earthquake, June 23, 1946: Royal Astronomical Soc. Canada Jour., v. 40, no. 8, p. 184-319.

Hodgson, J. H., and Storey, R. S., 1954, Direction of faulting in some larger earthquakes of 1949: Seismol. Soc. America Bull., v. 44, p. 57-83.

Holden, E. S., 1898, A catalogue of earthquakes of the Pacific Coast, 1769 to 1897: Smithsonian Misc. Collections No. 1087, 253 p.

Hollis, E. P., 1971, Bibliography of earthquake engineering [3d ed.]: Oakland, Earthquake Engineering Research Inst., 144 p.

Hudson, D. E., ed., 1971, Strong motion instrumental data on the San Fernando earthquake of February 9, 1971: Pasadena, California Inst. Technology, 258 p.

Huntting, M. T., Bennett, W. A. G., Livingston, V. E., Jr., and Moen, W. S., 1961, Geologic map of Washington: Washington Div. Mines and Geology.

Jennings, P. C., ed., 1971, Engineering features of the San Fernando earthquake, February 9, 1971: Pasadena, California Inst. Technology Pub. EERI 73-04, 153 p.

King County Office of Emergency Services, 1974, King County man-made and natural disaster plan (other than war caused): King County, Wash., Annex "G" of V. 1, 146 p.

Lawson, A. C., ed.; 1908, California earthquake of April 18, 1906, report of the State earthquake investigation commission: Washington, D.C., Carnegie Inst. Pub. 87.

Leipold, L. E., ed., 1969, The Prince William Sound, Alaska, earthquake of 1964 and aftershocks: Washington, U.S. Dept. Commerce Coast and and Geodetic Survey Pub. 10-3, v. 2, Parts B and C, 350 p.

Liesch, B. A., Price, C. E. and Walters, K. L., 1963, Geology and ground-water resources of northwestern King County, Washington: Washington Div. Water Resources Water Supply Bull. 20, 214 p., plate 1.

Lipman, P., Prostka, H. J., and Christiansen, R. L., 1971, Evolving subduction zones in the western United States, as interpreted from igneous rocks: Science, v. 174, p. 821-825.

Livingston, V. E., Jr., 1971, Geology and mineral resources of King County, Washington: Washington Div. Mines and Geology Bulletin No. 63, 200 p., plate 1.

Luzier, J. E., 1969, Geology and ground-water resources of southwestern King County, Washington: Washington Div. Water Resources Water Supply Bull. 28, 260 p., plate 1.

McAdie, A. G., 1907, Catalogue of earthquakes on the Pacific coast 1897 to 1906: Smithsonian Misc. Collections No. 1721, 64 p.

McClure, F. E., 1967, Studies in gathering earthquake damage statistics: U.S. Dept. Commerce, ESSA.

McCulloch, D. S., and Bonilla, M. G., 1970, Effects of the earthquake of March 27, 1964, on the Alaska railroad: U.S. Geol. Survey Prof. Paper 545-D, p. D1-D161.

McKenzie, D. P., and Parker, R. L., 1967, The north Pacific--An example of tectonics on a sphere: Nature, v. 216, p. 1276-1280.

McKenzie, D., and Julian, B., 1971, Puget Sound, Washington earthquake and the mantle structure beneath the northwestern United States: Geol. Soc. America Bull., v. 82, p. 3519-3524.

McManus, D. A., 1967, Physiography of Cobb and Gorda rises, northeast Pacific Ocean: Geol. Soc. America Bull., v. 78, p. 527-546.

McWilliams, R. G., 1970, Evidence for thrust faulting in northern Olympic peninsula, Washington: Am. Assoc. Petroleum Geologists Bull., v. 54, p. 344-349.

Miller, A. L., 1952, Earthquake lessons from the Pacific Northwest, in Symposium on earthquake and blast effects on structures: EERI and California Univ., Los Angeles, Proc., p. 212-223.

____________ (n.d.), Working files made available through archives department, Washington Univ., Seattle.

Milne, W. G., 1956, Seismic activity in Canada west of the 113th meridian, 1841-1951: Ottawa, Canada, Publications of the Dominion Observatory, Ottawa, p. 119-146.

____________ 1963, Seismicity of western CAnada: Bol. Bibliogr. Geofis. Oceanografia Am., v. 3, p. 17-40.

Mogi, K., 1963, Some discussions on aftershocks, foreshocks, and earthquake swarms--The fracture of a semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena: Earthquake Research Inst. Tokyo Univ. Bull., v. 41, p. 615-658.

Molenaar, Dee and Noble, J. B., 1970, Geology and ground-water occurrence, southeastern Mason County, Washington: Washington Dept. Water Resources Water Supply Bull. 29, 145 p., plate 1.

Mullineaux, D. R., 1965a, Geologic map of the Renton quadrangle, King County, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-405.

____________ 1965b, Geologic map of the Auburn quadrangle, King and Pierce Counties, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-406.

____________ 1965c, Geologic map of the Black Diamond quadrangle, King County, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-407.

Mullineaux, D. R., Bonilla, M. G., and Scholocker, J., 1967, Relation of building damage to geology in Seattle, Washington, during the April, 1965, earthquake: U.S. Geol. Survey Prof. Paper 575-D, p. D183-D191.

Mullineaux, D. R., Waldron, H. H., and Meyer, R., 1965, Stratigraphy and chronology of late interglacial and early Vashon glacial time in the Seattle area, Washington: U.S. Geol. Survey Bull. 1194-O, 10 p.

Murphy, L. M., 1950, United States earthquakes, 1947: U.S. Dept. Commerce Coast and Geodetic Survey Serial No. 730, 62 p.

Murphy, L. M., and Ulrich, F. P., 1951a, United States earthquakes, 1948: U.S. Dept. Commerce Coast and Geodetic Survey, Serial No. 746, 50 p.

____________ 1951b, United States earthquakes, 1949: U.S. Dept. Commerce Coast and Geodetic Survey Serial No. 748, 64 p.

____________ 1952, United States earthquakes, 1950: U.S. Dept. Commerce Coast and Geodetic Survey Serial No. 755, 47 p.

National Board of Fire Underwriters, 1964, The Alaska earthquake of March 27, 1964, report by the National Board of Fire Underwriters and the Pacific Fire Rating Bureau: San Francisco, Pacific Fire Rating Bur., 35 p.

National Research Council, 1973, The great Alaska earthquake of 1964, Engineering: Washington, D. C., Natl. Acad. Sci. Pub. 1603, 1190 p.

Neumann, F., 1954, Earthquake intensity and related ground motion: Seattle, Washington Univ. Press, 77 p.

__________, 1959, Crustal structure in the Puget Sound area: Travaux Scientifiques, Ser. A, p. 153-167.

Newcomb, R. C., 1952, Ground-water resources of Snohomish County, Washington: U.S. Geol. Survey Water-Supply Paper 1135, 133 p., plate 1.

Noble, J. B. and Wallace, E. F., 1966, Geology and ground-water resources of Thurston County, Washington: Washington Div. Water Resources Water Supply Bull. 10, v. 2, 141 p., plates 1, 2, and 4.

Nuttli, O. W., 1952, The western Washington earthquake of April 13, 1949: Seismol. Soc. America Bull., v. 42, p. 21-28.

Office of Civil Defense Training, 1967, Emergency plans, assumptions and local resources data for Mason County, Washington: Seattle, Washington Univ., 43 p.

__________ 1970a, Emergency plans, assumptions and local resources data for Kitsap County, Washington: Seattle, Washington Univ., 91 p.

__________ 1970b, Emergency plans, assumptions and local resources data for Thurston County, Washington: Seattle, Washington Univ., 47 p.

__________ 1972, Emergency plans, assumptions and local resources data for Pierce County, Washington: Seattle, Washington Univ., 61 p.

Office of Emergency Management Training, 1972, Emergency plans, assumptions and local resources data for Snohomish County, Washington: Seattle, Washington Univ., 101 p.

Page, R., 1968, Focal depths of aftershocks: Jour. Geophys. Research, v. 73, p. 3897-3903.

Pinkham, C. W., 1972, Procedures and criteria for earthquake resistant design, in Building practices for disaster mitigation, Building science series 46: U.S. Dept. Commerce Natl. Bur. Standards Building sci. ser. 46, p. 188-208.

Rasmussen, N. H., 1967, Washington state earthquakes, 1840 through 1965: Seismol. Soc. America Bull., v. 57, no. 3, p. 463-476.

Rasmussen, N. H., Millard, R. C., and Smith, S. W., 1974, Earthquake hazard evaluation of the Puget Sound region, Washington state: Seattle, Washington Univ. Press., 99 p.

Richter, C. F., 1958, Elementary seismology: San Francisco, Calif., W. H. Freeman & Co., 768 p.

Rinne, John E., and others, 1951, Lateral forces of earthquake and wind: Am. Soc. Civil Engineers Trans., v. 117, p. 716-780.

Rockwood, C. G., 1873, Notices of recent earthquakes: Am. Jour. Sci. and Arts, 3d Ser., v. 5, p. 263.

____________ 1878, Notices of recent American earthquakes, No. 7: Am. Jour. Sci. and Arts, 3d Ser., v. 15, p. 25.

Rogers, W. P., 1970, A geological and geophysical study of the central Puget Sound lowland: Univ. Washington Ph. D. thesis, 123 p.

Saint-Amand, Pierre, Lombardi, O. W., and Shuler, H., 1963, Earthquakes of the western United States: Bol. Bib. de Geof. y Ocean. Amer., v. 3, p. 40-105.

Sbar, M. L. Barazangi, M., Dorman, J., Scholz, C. H., and Smith, R. B., 1972, Tectonics of the intermountain seismic belt, western United States--Microearthquake seismicity and composite fault plane solutions: Geol. Soc. America Bull., v. 83, p. 13-28.

Sceva, J. E., 1957, Geology and ground-water resources of Kitsap County, Washington: Washington Water Resources Div. Water-Supply Paper 1413, 178 p., plate 1.

Schiff, A. J., Yao, J. T. P., 1972, Response of power systems to the San Fernando Valley earthquake of 9 February 1971: Center for Large Scale Systems, Purdue Univ. rept. 72-1, 76 p.

Scholz, C. H., Barazangi, M., and Sbar, M. L., 1971, Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin: Geol. Soc. America Bull., v. 82, p. 2979-2990.

Schussler, H., 1906, The water supply of San Francisco, California, before, during, and after the earthquake of April 18, 1906 and the subsequent conflagration: Spring Valley Water Co., California, 103 p.

Seeber, L., Barazangi, H., and Nowroozi, A., 1970, Microearthquake seismicity and tectonics of coastal northern California: Seismol. Soc. America Bull., v. 60, p. 1669-1699.

Seismological Society of America, 1974, Special papers on the Managua, Nicaragua earthquake of December 23, 1972: Seismol. Soc. America Bull., v. 64, no. 4, p. 993-1158.

Shannon & Wilson, Inc., 1964, Report on Anchorage, Alaska area soil studies to U.S. Army Engineers district: Seattle, Office of Emergency Planning, 109 p.

Silver, E. A., 1971a, Transitional tectonics and late Cenozoic structure of the continental margin off northernmost California: Geol Soc. America Bull., v. 82, p. 1-22

____________ 1971b, Small plate tectonics in the northeastern Pacific: Geol. Soc. America Bull., v. 82, p. 3491-3496.

Sims, J. D., 1975, Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments: Tectonophysics (in press).

Steinbrugge, K. V., 1970, Engineering aspects of the Santa Rosa, California, earthquakes, October 1, 1969, in Santa Rosa, California, earthquakes of October 1, 1969: U.S. Dept. Commerce ESSA, 99 p.

Steinbrugge, K. V., chmn., 1970, Report of the task force on earthquake hazard reduction: Executive Office of the President, Office of Science and Technology, 53 p.

Steinbrugge, K. V., and Bush, V. R., 1965, Review of earthquake damage in western U.S., 1933-1964, in Earthquake investigations in the western United States, 1931-1964: U.S. Dept. Commerce Coast and Geodetic Survey, p. 223-256.

Steinbrugge, K. V., and Cloud, W. K., 1962, Epicentral intensities and damage in the Hebgen Lake, Montana, earthquake of August 17, 1959: Seismol. Soc. America Bull., v. 52, no. 2, p. 181-234.

Steinbrugge, K. V., and Moran, D. F., 1954, An engineering study of the southern California earthquake of July 21, 1952, and its aftershocks: Seismol. Soc. America Bull., v. 44, no. 2b, p. 199-462.

Steinbrugge, K. V. and Schader, E. E., 1973, Earthquake damage and related statistics, in San Fernando, California, earthquake of February 9, 1971: U.S. Dept. Commerce National Oceanic and Atmospheric Administration, v. 1, part B, p. 691-724.

Steinbrugge, K. V., Schader, E. E., Bigglestone, H. C. and Weers, C. A., 1971, San Fernando earthquake, February 9, 1971: San Francisco, Pacific Fire Rating Bureau, 93 p.

Steinbrugge, K. V., Schader, E. E., and Moran, D. F., 1975, Building damage in the San Fernando Valley, in California Div. Mines and Geology Bull. 196, p. 323-353.

Stepp, C. J., 1971, An investigation of earthquake risk in the Puget Sound area by use of the Type I distribution of largest extremes: Pennsylvania State Univ. Ph. D. thesis, 131 p.

____________ 1973, Analysis of completeness of the earthquake sample in the Puget Sound area, in Harding, S. T., ed., Contributions to seismic zoning: N.O.A.A. Technical Rept. ERL 267-ESL 30, p. 16-28.

Stewart, J. H., 1971, Basin and range structure--A system of hoists and grabens produced by deep-seated extension: Geol. Soc. America Bull., v. 82, p. 1019-1044.

Stewart, R. J., 1969, Petrology and structure of the Hob River area, western Olympic peninsula, Washington: Stanford Univ. Ph. D. thesis.

Structural Engineers Association of California, 1973, Recommended lateral force requirements and commentary: San Francisco, Seismology Committee, 146 p.

Talley, H. C., Jr., and Cloud, W. K., 1962, United States earthquakes, 1960: U.S. Dept. Commerce Coast and Geodetic Survey, 90 p.

Tobin, D. G., and Sykes, L. R., 1968, Seismicity and tectonics of the northeast Pacific: Jour. Geophys. Research, v. 73, p. 3821-3845.

Townley, S. D., and Allen, M. W., 1939, Descriptive catalog of earthquakes of the Pacific coast of the United States, 1769 to 1928: Seismol. Soc. America Bull., v. 29, p. 1-297.

Tubbs, D. W., 1974, Landslides in Seattle: Washington State Div. Geology and Earth Resources Inf. Circ. 52, 15 p.

Ulrich, F. P., 1941a, The Imperial Valley earthquakes of 1940: Seismol. Soc. America Bull., v. 31, no. 1, p. 13-31.

__________ 1941b, The Santa Barbara earthquake: Building Standards Monthly, v. 10, no. 10, p. 22-25.

Ulrich, F. P., 1949, Reporting the northwest earthquake: Building Standards Monthly, June 1949, p. 8-11, 16.

U.S. Army Corps of Engineers, 1949, Report on damage resulting from earthquake of 13 April 1949: Seattle, U.S. Army, Corps of Engineers, 60 p.

U.S. Bureau of Census, 1970a, Census of housing, block statistics, Seattle-Everett, Wash., urbanized area: U.S. Dept. Commerce, final rept. HC(3)-260, 174 p.

__________ 1970b, Census of housing, block statistics, Tacoma, Wash., urbanized area, U.S. Dept. Commerce, final rept. HC(3)-262, 59 p.

__________ 1970c, Census of housing, block statistics, selected areas in Wash., urbanized area: U.S. Dept. Commerce, final rept. HC(3)-263, 161 p.

U.S. Coast and Geodetic Survey, 1950, Abstracts of earthquake reports for the Pacific coast and the western mountain region, April, May, June, 1949: MSA-62, p. 15-73, 76.

____________ 1967, Abstracts of earthquake reports for the Pacific coast and the western mountain region, April-June, 1965: MSA-126, p. 14-123, 127, 128.

U.S. Department of Commerce. Preliminary determination of epicenters, monthly cards, October 1964-April 1965: Coast and Geodetic Survey.

Vine, J. D., 1962, Preliminary geologic map of the Hobart and Maple Valley quadrangles, King County, Washington: Washington Div. Mines and Geology Geol. Map GM-1.

von Hake, C. A., and Cloud, W. K., 1961, United States earthquakes, 1959: Washington, D. C., U.S. Govt. Printing Office, 115 p.

____________ 1966, United States earthquakes, 1964: Washington, D. C., U.S. Govt. Printing Office, 91 p.

____________ 1967, United States earthquakes, 1965: Washington, D. C., U.S. Govt. Printing Office, 91 p.

____________ 1969, United States earthquakes 1967: Washington, D.C., U.S. Govt. Printing Office, 90 p.

Waldron, H. H., 1961, Geology of the Poverty Bay quadrangle, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-158.

____________ 1962, Geology of the Des Moines quadrangle, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-159.

____________ 1967, Geologic map of the Duwamish Head quadrangle, King and Kitsap Counties, Washington: U.S. Geol. Survey Geol. Quad. Map GQ-706.

Waldron. H. H., Liesch, B. A., Mullineaux, D. R., and Crandell, D. R., 1962, Preliminary geologic map of Seattle and vicinity, Washington: U.S. Geol. Survey Misc. Geol. Inv. Map I-354.

Walters, K. L., and Kimmel, G. E., 1968, Ground water occurrence and stratigraphy of unconsolidated deposits, Central Pierce County, Washington: Washington Dept. Water Resources Water Supply Bull. 22, 428 p., plates 1 and 2.

Washington, State of, 1973, Pocket data book: Olympia, Wash., Office of Program Planning and Fiscal Management, 300 p.

____________ 1974, Bridge list: Olympia, Wash., Washington State Dept. Highways Pub. M23-09 (HB), 241 p.

Wiegel, R. L., ed., 1970, Earthquake engineering: Englewood Cliffs, N.J., Prentice Hall, 505 p.

Wood, F. J., ed., 1966, The Prince William Sound, ALaska, earthquake of 1964 and aftershocks: U.S. Dept. Commerce U.S. Coast and Geod. Survey Pub. 10-3, v. 1, 263 p.; v. 2, pt. A., 392 p.

Wood, H. O., and Neumann, Frank, 1931, Modified Mercalli intensity scale of 1931: Seismol. Soc. America Bull., v. 21, no. 4, p. 277-283.

Wooley, J. K., 1950, Earthquake of April 13, 1949, affecting principally western portion of the State of Washington: Seattle, Washington Surveying and Rating Bureau, 13 p.

Wyss, M., and Molnar, P., 1972, Source parameters of intermediate and deep focus earthquakes in the Tonga arc: Phys. Earth Plane. Int., v. 6, p. 279-292.

☆ U. S. GOVERNMENT PRINTING OFFICE 1975 - 681-256/29 Reg. 8