

EARTHQUAKE-INDUCED GROUND FAILURE IN WESTERN WASHINGTON

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INTRODUCTION

Ground failure is generally regarded as a permanent disruption of geologic materials at the ground surface. For this paper, we will consider earthquake-induced ground failure to include: (1) slope failures (landslides) on moderate to steep slopes, (2) surface disruption or settlement due to soil liquefaction, and (3) minor surface cracking. These types of earthquake-induced ground failure destroy or damage residential and industrial structures and transportation facilities; in addition, earthquake-induced landslides have caused great numbers of casualties and severe negative impacts on agricultural and forest lands and on the quality of water in rivers and streams.

Several catastrophic examples of earthquake-induced ground failure can be cited. In 1920, as many as 100,000 people were killed by earthquake-triggered loess landslides in Gansu Province, China (Close and McCormick, 1922; Varnes, 1978). In 1949, a M 7.5 earthquake in the Tien Shan Mountains of Soviet Tadzhikistan triggered a series of massive slides and debris flows that buried some 33 population centers, killing from 12,000 (Jaroff, 1977) to 20,000 (Wesson and Wesson, 1975) residents. Youd (1978) estimated that ground failure caused 60 percent of the \$300 million total damage from the 1964 Alaska earthquake. Ground-failure (primarily due to liquefaction) damage from the 1964 Niigata, Japan, earthquake was estimated at \$800 million (Lee and others, 1977). In 1970, a M 7.75 quake off the coast of Peru triggered a debris avalanche on the slopes of Mount Huascaran in the Cordillera Blanca, burying the towns of Yungay and Ranrahirca and killing more than 18,000 people (Plafker and others, 1971). In March 1987, landslides (and associated floods) triggered by a M 6.9 earthquake in eastern Ecuador killed an estimated 1,000-2,000 people; destruction of 16 miles of the TransEcuadorian oil pipeline by these landslides and floods resulted in economic losses totaling about \$1 billion (Crespo and others, 1987).

Ground failures due to historic earthquakes in western Washington have resulted in only a few deaths, but have caused significant damage over large areas (Hopper, 1981; Keefer, 1983; Grant, 1986). The 1949 Olympia earthquake scattered ground failures over an area of approximately 11,000 mi² (fig. 1), and the 1965 Seattle-Tacoma earthquake triggered ground failures within an area of about 8,000 mi² (fig. 2).

This paper discusses the types and distribution of ground failure that have occurred due to historic earthquakes in western Washington, with emphasis on landslides and on ground failures resulting from liquefaction, which are the types that have caused the greatest amounts of damage. In addition, it briefly reviews studies planned by U.S. Geological Survey scientists and engineers relating to earthquake-induced ground failure in the area.

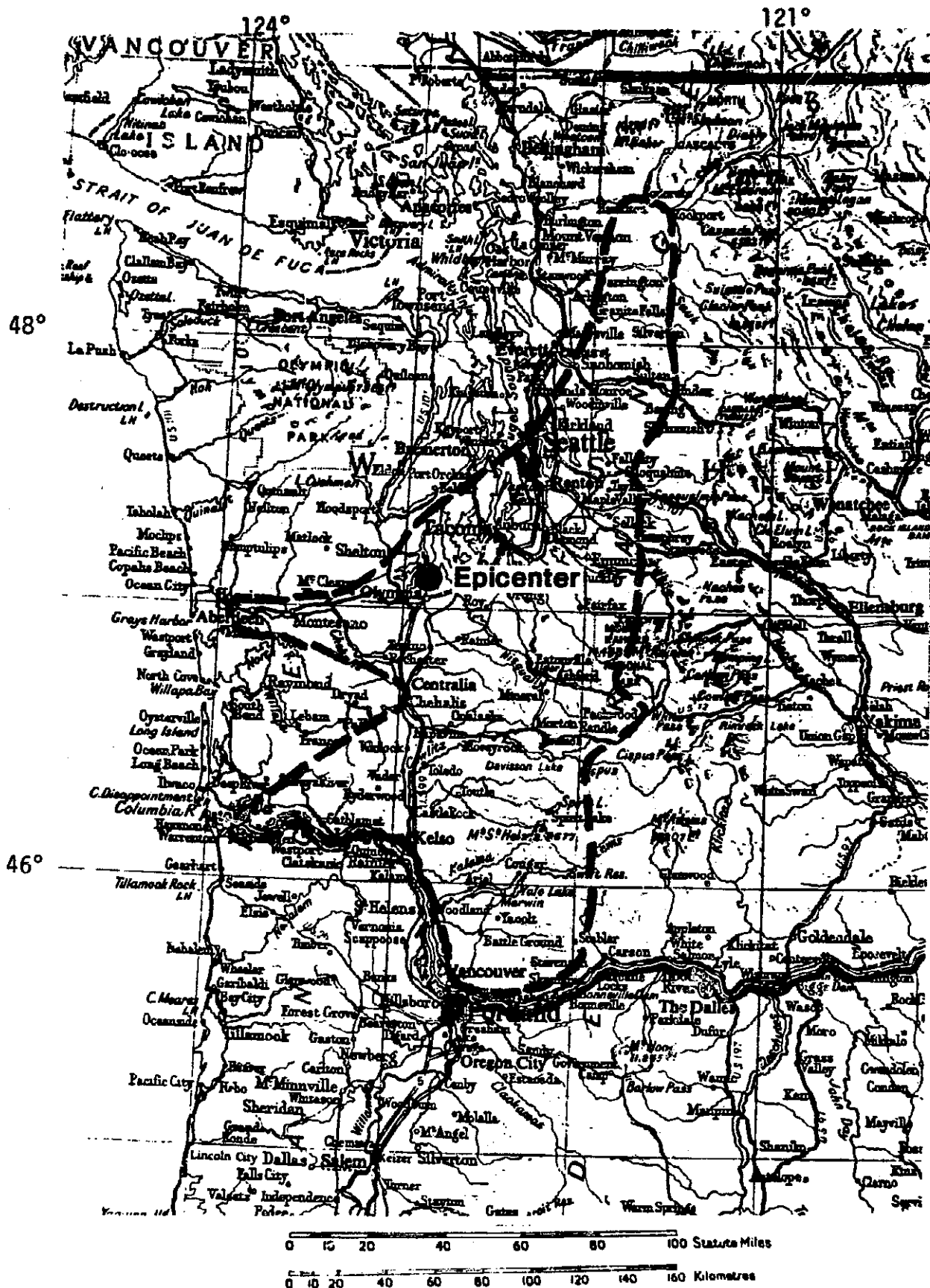


Figure 1. Area within which ground failures were reported for the April 13, 1949, Olympia earthquake (modified from Keefer, 1983).

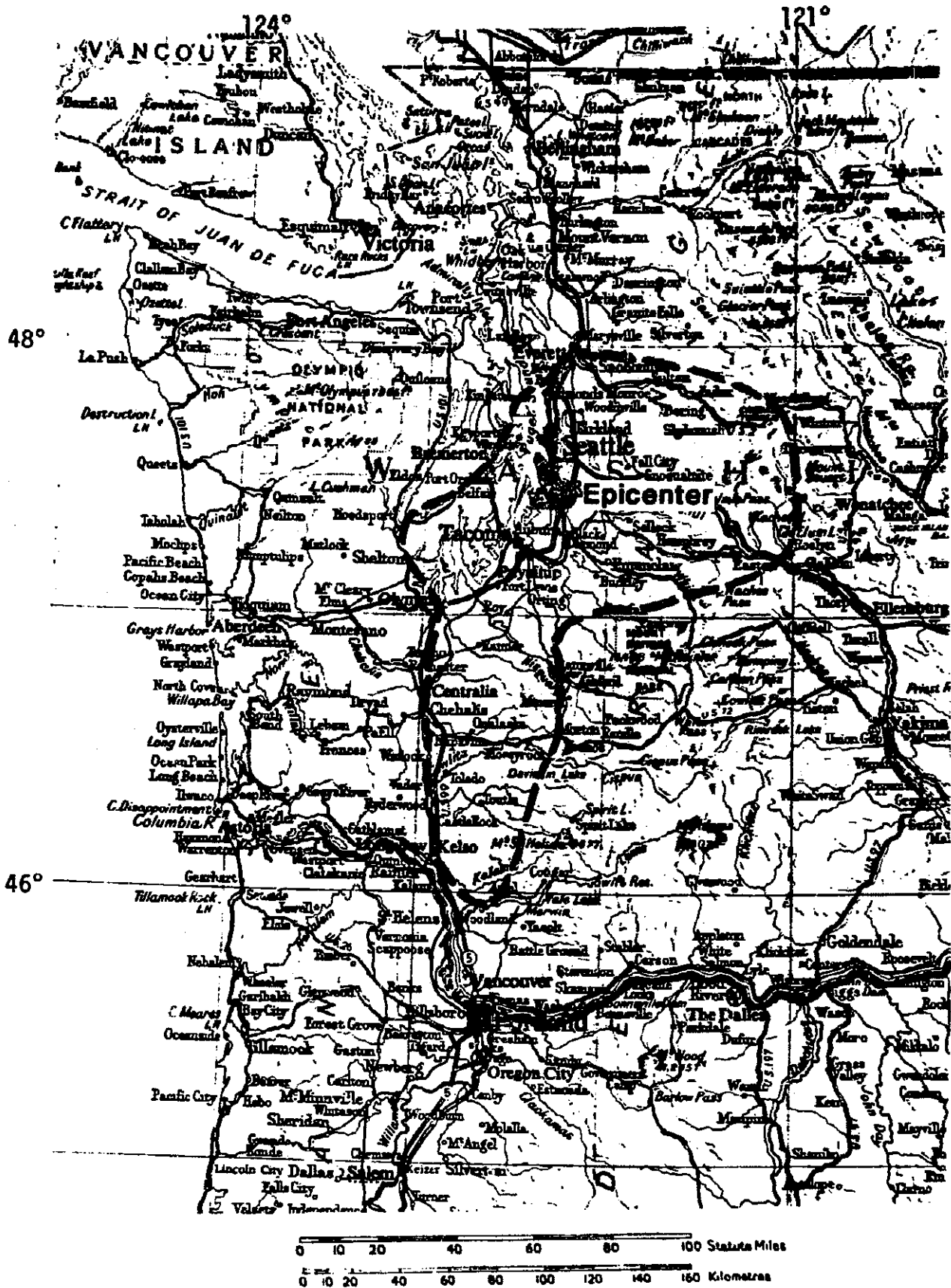


Figure 2. Area within which ground failures were reported for the April 29, 1965, Seattle-Tacoma earthquake (modified from Keefer, 1983).

SLOPE FAILURES (LANDSLIDES)

Keefer (1984) has documented data on slope failures caused by 40 major earthquakes in many parts of the world. His studies have shown that the most abundant types of earthquake-induced landslides have been rock falls and soil and rock slides. The greatest losses of life have been due to rock avalanches, rapid soil flows, and rock falls. According to Keefer's study the smallest earthquakes that cause specific types of landslides are as follows: (1) M 4.0: rock falls, rock slides, soil falls, and disrupted soil slides; (2) M 4.5: soil slumps and soil block slides; (3) M 5.0: rock slumps, rock block slides, slow earthflows, soil lateral spreads, rapid soil flows, and subaqueous landslides; (4) M 6.0: rock avalanches; and (5) M 6.5: soil avalanches.

As noted by Noson and others (in press), 14 earthquakes triggered landslides in the State of Washington between 1872 and 1980. The greatest landslide activity was recorded as a result of the M 7.1 Olympia earthquake of April, 13, 1949, which had a focal depth of 40 miles (Nuttli, 1952). Landslides occurred as far as 110 miles from the epicenter (Keefer, 1983). The largest landslide (volume: about 650,000 yd³) occurred in a section of sand and gravel that overlies clay in a bluff forming the eastern shore of the Tacoma Narrows (fig. 3). Many smaller landslides occurred from Seattle south to Portland. Although Keefer's (1983) review of published accounts noted a total of only 23 landslides triggered by the 1949 earthquake, current studies by the authors indicate that the number of landslides was considerably under-reported at the time of the quake. In the Cascade Range, these slope failures consisted primarily of rock falls and rock slides. In the Puget Trough (lowlands from Puget Sound to the Willamette Valley of northern Oregon), numerous minor soil and rock slides and slumps occurred. Many of these occurred in fills and cuts situated in highway and railroad corridors. These failures were particularly common where the corridors were located along the shores of rivers or lakes. Sidehill embankments often failed at the contacts with their foundation slopes. Downslope movement in such failures ranged from only a few inches to tens of feet. Most of the failed embankments were brought back to grade by maintenance crews soon after the earthquake.

The 1965 M 6.5 Seattle-Tacoma earthquake caused significant landslide activity in the Puget Sound area. Utilizing published accounts, Keefer (1983) noted 24 individual landslides located as far as 60 miles from the epicenter. As was the case for the 1949 earthquake, recent study by the authors indicates that landslide occurrences were significantly under-reported at the time of the quake. There were no large landslides, such as the 1949 Tacoma Narrows slide, but there were many small slips and slumps. As was the case for the 1949 earthquake, slope failures in fills and cuts of transportation corridors were common (figs. 4 and 5).

Much of the damage related to the 1980 eruption of Mount St. Helens was caused by a rockslide/debris avalanche (fig. 6) triggered by a M 5 earthquake associated with the eruption. This 0.62 mi³ landslide (the world's largest historic landslide) swept some 14 mi down the valley of the North Fork Toutle River, destroying public and private buildings, State Highway 504, U.S. Forest Service and logging company roads, and several bridges (Schuster, 1983).

Most of the landslides triggered by the 1949 and 1965 earthquakes occurred in areas of low population density. Because of increased residential development of hillside slopes in western Washington since 1965, significant losses due to earthquake-induced slope failures can be expected from future earthquakes in the area (Grant, 1986). This will be particularly true for earthquakes of greater magnitude, shallower focus, or longer duration than those that occurred in 1949 and 1965. In addition, greater earthquake-induced slope-failure activity is to be expected when the quakes occur at times of the year when heavy, prolonged precipitation or melting snow results in exceptionally high ground-water levels and saturated soils.

GROUND FAILURE ASSOCIATED WITH LIQUEFACTION

As related to earthquakes, liquefaction is the process by which saturated cohesionless soils change from a solid state to a liquefied state as a consequence of dynamic loading that increases pore pressures and reduces effective stress (Youd, 1978). Liquefaction by itself is not ground failure; however, the liquefaction process results in almost total reduction of shear strength. This reduction can result in ground failure of several types; the most common are: (1) lateral spreads, (2) flow failures, (3) ground settlement, and (4) loss of bearing capacity. As noted above, the first two are, in effect, varieties of landslides, in that they occur on slopes due to reduction of shear strength.

Lateral spreads due to earthquakes involve lateral displacement of large surficial blocks of soil as a result of liquefaction in subsurface layers (Committee on Earthquake Engineering, 1985). They generally develop on very gentle slopes (most commonly between 0.3° and 3°) and move toward a free face, such as an incised stream channel. Lateral displacements range up to several feet, and, in particularly susceptible conditions, to several tens of feet, accompanied by ground cracking and differential vertical displacement (Youd, 1978). Lateral spreads often disrupt the foundations of buildings or other structures, rupture pipelines and other utilities in the failure mass, and compress engineering structures crossing the toes of the failures.

Flow failures are liquefaction-caused landslides that develop in loose saturated sands or silts on natural or man-made slopes greater than 3° (Committee on Earthquake Engineering, 1985). Flows may consist of completely liquefied soils, or of blocks of intact material riding on layers of liquefied soil. They often displace large masses of material for many tens of feet at velocities ranging up to tens of miles per hour.

Densification and ground settlement of saturated sediments are commonly associated with and enhanced by liquefaction. Several classic examples of ground settlement caused by seismic shaking occurred in saturated sediments along the coast of Alaska due to the 1964 earthquake; at Portage, Alaska, settlement lowered the ground surface sufficiently so that houses and highway and railroad grades were inundated at high tide (Committee on Earthquake Engineering, 1985). The 1949 Olympia earthquake caused structural damage to buildings on the Duwamish Flat in south Seattle due to settlement of saturated sediments (U.S. Army Corps of Engineers, 1949).

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Sand boils often form at the surface during ground settlement. Although sand boils are not strictly a form of ground failure because alone they do not cause ground deformation, they provide diagnostic evidence of elevated pore-water pressure at depth and indication that liquefaction has occurred (Committee on Earthquake Engineering, 1985). Sand boils occurred at several locations in western Washington during the 1949 and 1965 earthquakes. Of particular interest were 1949 sand boils on the flood plain of the Chehalis River about 1 mi southwest of Centralia; spouts of sand and water reached heights of several feet immediately after the earthquake (T. Dorn, Centralia, Washington, personal commun., 1988).

Loss of bearing capacity occurs when the soil supporting a building or other structure liquefies and loses strength. This process results in large soil deformations under load, allowing the structures to settle and tip. An outstanding example of loss of bearing capacity due to seismic activity resulted from the the 1964 earthquake at Niigata, Japan, where spectacular bearing failures occurred at the Kwangishicho apartment complex; several four-story buildings tipped as much as 60 degrees (Committee on Earthquake Engineering, 1985). Minor destabilization of structures founded on saturated sediments occurred in the Seattle area in the 1949 and 1965 earthquakes.

MINOR CRACKING

Minor cracking of the ground surface independent of the above types of ground failure is noted after nearly all major earthquakes. Such cracks seldom cause significant damage. They were noted in many places in western Washington following the 1949 and 1965 earthquakes.

PLANNED U.S. GEOLOGICAL SURVEY RESEARCH ON EARTHQUAKE-INDUCED GROUND FAILURE IN WESTERN WASHINGTON

Ground-failure studies planned for western Washington by U.S. Geological Survey scientists and engineers deal with records and effects of seismicity for three different time frames: (1) prehistoric time, (2) historic time, and (3) the future. The object of each of these categories of study is to aid in prediction of future seismic activity and/or to provide additional insight into the characteristics and effects of ground failure from future earthquakes. The specific objectives of these three research components are as follows:

- (1) To identify major paleoseismic events in western Washington by means of the stratigraphic record of earthquake-induced liquefaction and landslides, and to determine the dates of prehistoric ground failure using applicable Quaternary-dating techniques. The search for liquefaction-disturbed strata will focus on the Holocene stratigraphic record, which is mainly concentrated on the valley floors of large rivers. The estuaries of these rivers are the areas that have been most susceptible to liquefaction-caused ground failure during Holocene time. Study of earthquake-induced landslides will be less constrained geographically than the study of features due to paleoliquefaction. The principal requisites for selecting landslides for study are that they be: (a) earthquake-induced, (b) amenable to dating by ^{14}C , lichonometry, or other suitable Quaternary-dating techniques, and (c) relatively accessible.

- (2) To define the distribution and characteristics of historic (1872 and later) earthquake-induced ground failure (with emphasis on landslides and liquefaction-associated ground failure) in western Washington as a step in better understanding what types of ground failure have occurred due to prehistoric earthquakes and what types can be expected in the future. Information obtained on historic ground failure will also be of value in further defining the characteristics of historic earthquakes in the area.
- (3) To produce susceptibility maps for landslides and liquefaction-associated ground failure for selected metropolitan areas of western Washington. Geographic Information Systems (GIS) techniques will be utilized in this effort. The need for such mapping is clearly indicated by the occurrence in the Puget Sound region of numerous earthquake-induced ground failures related to the 1949 and 1965 earthquakes. Initially, data will be collected on the distribution and character of earthquake-induced ground failures as indicated in the above study plans. Subsequently, this information will be combined with other data on geology, hydrology, and topography, and will be manipulated using GIS technology to produce high-quality earthquake-induced ground-failure susceptibility maps.

REFERENCES

- Close, Upton, and McCormick, Elsie, 1922, Where the mountains walked: National Geographic Magazine, v. 41, no. 5, p. 445-464.
- Committee on Earthquake Engineering, 1985, Liquefaction of soils during earthquakes: Commission on Engineering and Technical Systems, National Research Council, National Academy Press, Washington, D.C., 240 p.
- Crespo, E, Nyman, K. J., and O'Rourke, T. D., 1987, 1987 Ecuador earthquakes of March 5, 1987: Earthquake Engineering Research Institute Special Earthquake Report, 4 p.
- Grant, P. W., 1986, The potential for ground failures in the Puget Sound area, in Kitzmiller, Karla, Proceedings of Conference XXXIII, A Workshop on Earthquake Hazards in the Puget Sound Washington Area, October 29-31, 1985, Seattle, Washington: U.S. Geological Survey Open-File Report 86-253, p. 134-138.
- Hopper, M. G., 1981, A study of liquefaction and other types of earthquake-induced ground failures in the Puget Sound, Washington, region: M.S. thesis, Virginia Polytechnic and State University, Blacksburg, 131 p.
- Jaroff, Leon, 1977, Forecasting the earth's convulsions, in Nature/science annual, 1977 edition: Time/Life Books, New York, p. 21-33.
- Keefer, D. K., 1983, Landslides, soil liquefaction, and related ground failures in Puget Sound Earthquakes, in Jacobson, Muriel, compiler, Proceedings of Workshop XIV, Earthquake Hazards of the Puget Sound Region, Washington, 13-15 October 1980, Lake Wilderness, Washington: U.S. Geological Survey Open-File Report 83-19, p. 280-299.
- Keefer, D. K., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406-412.
- Lee, K. L., Marcuson, W. F., III, Stokoe, K. H., II, and Yokel, F. Y., 1977, Research needs and priorities for geotechnical earthquake engineering applications: Report of workshop at the University of Texas, Austin, NSF Grant No. AEN77-09861, 134 p.
- Noson, L. L., Qamar, Anthony, and Thorsen, G. W., in press, Washington State earthquake hazards: Washington Department of Natural Resources, Division of Geology and Earth Resources.

- Nuttli, O. W., 1952, The western Washington earthquake of April 13, 1949: Seismological Society of America Bulletin, v. 42, no. 1, p. 21-28.
- Plafker, George, Ericksen, G. E., and Fernandez Concha, Jaime, 1971, Geological aspects of the May 31, 1970, Peru earthquake: Seismological Society of America Bulletin, v. 61, no. 3, p. 543-578.
- Schuster, R. L., 1983, Engineering aspects of the 1980 Mount St. Helens eruptions: Bulletin of the Association of Engineering Geologists, v. 20, p. 125-143.
- U.S. Army Corps of Engineers, 1949, Report on damage resulting from earthquake of 13 April 1949: Seattle District, Washington, 28 p.
- Varnes, D. J., 1978, Slope movement types and processes, in Schuster, R. L., and Krizek, R. J., eds., Landslides -- analysis and control: Transportation Research Board Special Report 176, National Academy of Sciences, Washington, D.C., p. 12-33.
- Vogel, Elmer, 1949, Cliff topples into Sound: Tacoma News Tribune, April 18, p. 1, 2.
- Wesson, C. V. K., and Wesson, R. L., 1975, Odyssey to Tadzhik -- an American family joins a Soviet seismological expedition: U.S. Geological Survey Earthquake Information Bulletin, v. 7., no. 1, January-February, p. 8-16.
- Youd, T. L., 1978, Major cause of earthquake damage is ground failure: Civil Engineering, American Society of Civil Engineers, v. 48, no. 4, p. 47-51.