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Relative Earthquake Hazard Maps of the Salem East and Salem West Quadrangles, Marion and Polk Counties, Oregon

By
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NOTICE

The results and conclusions of this report are necessarily based on limited data and resources available for this project. Information provided in this publication should **NOT** be used in place of site-specific studies. For example, the relative hazard zones are not intended to replace site-specific evaluations, such as for engineering analysis and design. Site-specific earthquake hazards should be assessed through geotechnical or engineering geology investigation by qualified practitioners.

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ABSTRACT

The *Relative Earthquake Hazard Maps* were developed to identify and characterize earthquake hazards in the Salem East and Salem West quadrangles, Marion and Polk Counties, Oregon. The publication includes this text and the following maps: (1) *Liquefaction Susceptibility Map*, (2) *Amplification Susceptibility Map*, (3) *Landslide Susceptibility Map*, and (4) *Relative Earthquake Hazard Map*. These maps show categories of relative susceptibility to earthquake-induced liquefaction, amplification of peak ground acceleration, landslides, and general earthquake hazard zones, respectively. Areas within the highest susceptibility zone have the greatest hazard and are likely to suffer the most intense damage related to ground response; those in the lowest hazard zone are likely to suffer the least.

Three earthquake hazards related to site geology (liquefaction, amplification, and landsliding) were individually evaluated. They were combined to develop the *Relative Earthquake Hazard Map*, which allows both technical and nontechnical users to gain an understanding of earthquake hazards and take steps to reduce the risk to life and property through planning policy and other mitigation measures. The map set was developed to serve as a regional planning tool and does not have site-specific accuracy. All areas shown on the map are susceptible to strong earthquake shaking due to the regional earthquake setting.

FOREWORD

The techniques used to prepare portions of these maps were initially developed for the earthquake hazard maps of the Portland, Oregon, metropolitan area. The two initial publications, *Relative Earthquake Hazard Map of the Portland, Oregon, 7½-Minute Quadrangle* (Mabey and Madin, 1993; Mabey and others, 1993a), and *Earthquake Hazard Maps of the Portland Quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington* (Mabey and others, 1993b), are suggested as supplemental references.

In addition to the list of cited references, a selected bibliography is provided at the end of this report. The selected bibliography is divided into four sections: general information and liquefaction, amplification, and landsliding, which refer to the corresponding sections of the text.

INTRODUCTION

This report was developed to identify and characterize earthquake hazards in the Salem East and Salem West quadrangles of Marion and Polk Counties, Oregon (Figure 1). The study area is located in the Willamette Valley and is about 80 km (50 mi) east of the Cascadia deformation front, where several large-magnitude subduction zone earthquakes are thought to have occurred in the past few thousand years. This study does not predict the size, location, or frequency of damaging earthquakes. Instead, it evaluates the ground response, influenced by site geology, that results from estimated ground motions associated with a strong earthquake. A strong local crustal earthquake or a great subduction zone earthquake would likely produce significant ground shaking for all the areas shown on the maps.

This report includes the following maps: (1) *Liquefaction Susceptibility Map*, (2) *Amplification Susceptibility Map*, (3) *Landslide Susceptibility Map*, and (4) *Relative Earthquake Hazard Map* (Plates 1 to 4). The hazards are defined in relative terms: Areas with the highest susceptibility have the greatest hazard in a strong earthquake and are likely to suffer the most intense damage related to ground response. Those with the lowest susceptibility are likely to suffer the least.

Three earthquake hazards (liquefaction, amplification of peak ground acceleration, and landsliding) were individually evaluated and are shown separately on the companion maps (Plates 1 to 3). The *Relative Earthquake Hazard Map* (Plate 4) was developed by combining the individual hazard maps. The *Relative Earthquake Hazard Map* is designed to allow both technical and nontechnical users to gain an understanding of the regional earthquake hazard. User groups include, but are not limited to, local jurisdictions, building officials, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens.

The goal of this study is to encourage and facilitate cost-effective mitigation actions to reduce loss of life, injury, and property damage in future earthquakes. Individuals seeking to implement such actions can use these maps as aids in planning and setting priorities.

EARTHQUAKE SOURCES

Much of the Pacific Northwest's topographic relief, including the Willamette Valley and the Coast and Cascade Ranges, is attributed to the plate-tectonic setting of the region. Seismologists believe that all parts of Oregon, including the Salem area, can be shaken by earthquakes. These earthquakes can occur in the Juan de Fuca Plate (intraplate earthquakes), in the overriding North American Plate (crustal earthquakes), or along the interface between the two plates (subduction zone earthquakes). All three possible earthquake types (subduction, intraplate, and crustal) can severely impact the region, and each of them was considered as part of this study.

The threat of a Cascadia Subduction Zone earthquake in the Pacific Northwest became widely accepted in the late 1980s. The seismically active Cascadia Subduction Zone extends from northern California to British Columbia and lies just off the coastline. The Juan de Fuca Plate, which lies offshore, is being forced under the North American Plate. Subduction zone earthquakes occur along the boundary of the Juan de Fuca and North American Plates. Although no significant subduction zone earthquake has occurred in historic times, several large-magnitude subduction

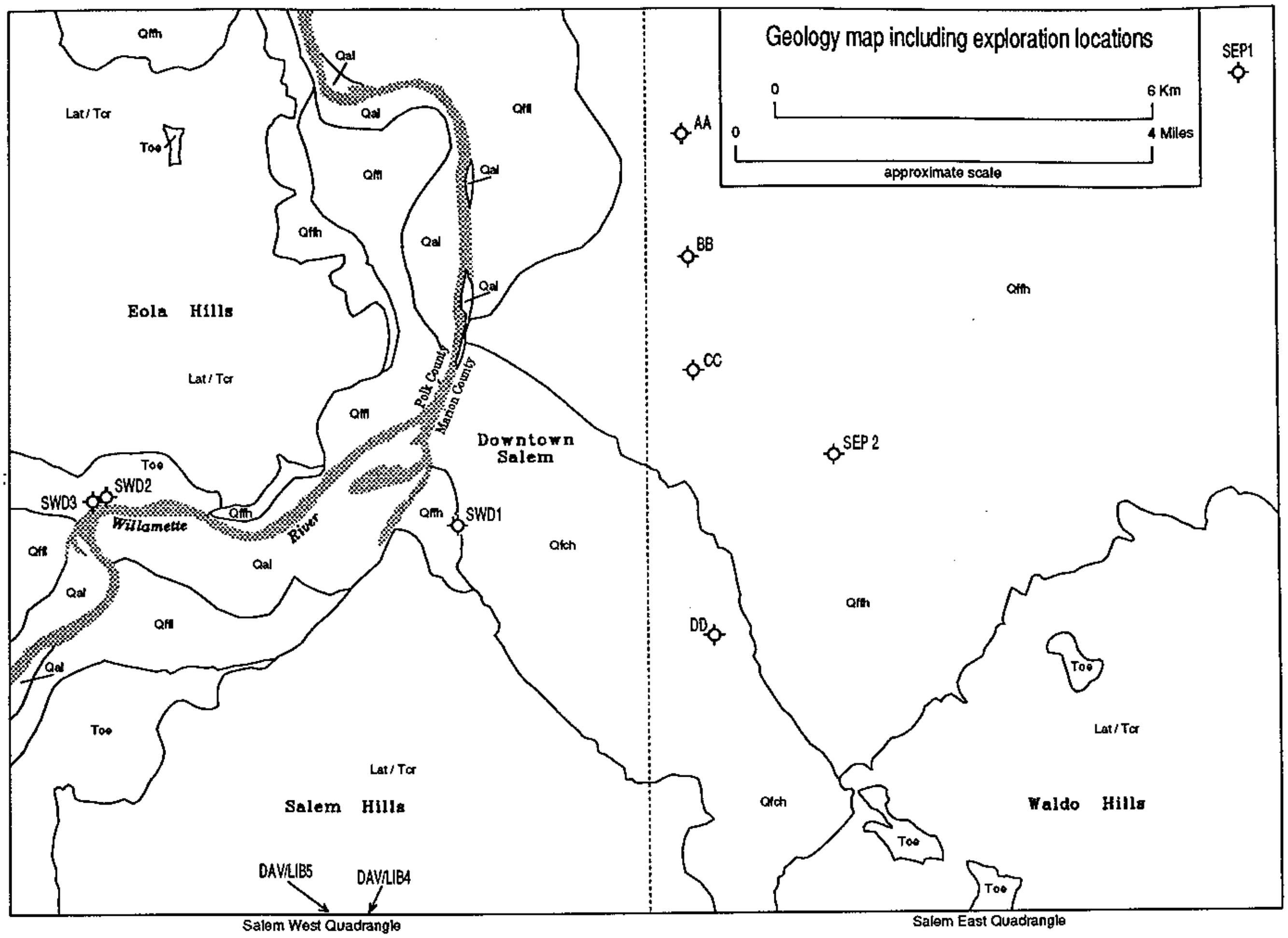

Figure 1. Sketch map of Salem East and Salem West quadrangles showing geologic units identified for this project (see Table 1) and locations of exploration drilling (see Table 2).

Table 1. *Geologic units shown in Figure 1*

Geologic unit description	Symbol	Shear wave velocity Vs (m/s)[1]	In situ density (pcf)[2]
Quaternary landslide deposits	Qls	360	135
Quaternary alluvium	Qal	250	115
Quaternary surficial 10-ft of lower and higher flood sediments	Qffl, Qffh	190	115
Quaternary lower terrace flood sediments	Qffl	250	115
Quaternary higher terrace flood sediments	Qffh	250	115
Quaternary fluvial gravels	Qfch	685	135
Quaternary flood gravels[3]	—	685	135
Quaternary fine-grained unit, blue clay[3]	—	330	120
Laterite- weathered Columbia River Basalt	Lat	450	125
Miocene Columbia River Basalt Group bedrock	Tcr	968	150
Eocene-Oligocene sedimentary bedrock	Toe	920	150

[1] Approximate weighted average shear wave velocity value from exploratory program outlined on Table 2; m/s = meters per second.
[2] Estimated values; pcf = pounds per cubic foot.
[3] Not shown on map in Figure 1. Units occur, in places, below terrace flood sediments (units Qffl, Qffh).

Table 2. *Summary of exploratory program. Locations shown in Figure 1; geologic units described in Table 1*

Cone penetrometer tests and boreholes	UTM easting (m)	UTM northing (m)	Depth (m)	Geologic units encountered*
SEP1	509547	4981767	13	Qffh
SEP2	503340	4975270	11	Qffh, flood gravels
SWD1	497018	4974724	22	Qffh, Qfch, Lat, Tcr
SWD2	491471	4975362	11	Qls
SWD3	491407	4975246	22	Qffh, Toe
AA	500617	4981150	74	Qffh, flood gravels
BB	500801	4979138	25	Qffh, flood gravels
CC	500943	4977401	90	Qffh, flood gravels, Lat, Tcr
DD	500907	4973238	65	Qfch, Lat, Tcr
DAV/LIB4[1]	495042	4968745	28	Colluvium, Lat, Toe
DAV/LIB5[1]	494962	4968825	31	Colluvium, Tcr, Toe

[1] Located just outside south border of Salem West quadrangle. See Figure 1.

zone earthquakes are thought to have occurred in the past few thousand years. The maximum estimated magnitude of a subduction zone earthquake ranges from M 8.5 to M 9.0.

Intraplate earthquakes occur within the Juan de Fuca Plate at depths of 40–60 km. The maximum estimated magnitude of an interplate earthquake is about M 7.5. The Pudget Sound region has experienced two intraplate events in modern times, magnitudes M 6.5 in 1965 and M 7.1 in 1949. Both events caused serious damage and were felt as far away as Montana.

Crustal earthquakes occur within the North American Plate typically at depths of 10–20 km. Several earthquakes larger than magnitude 5 have occurred in the Willamette Valley over the last 150 years (Bott and Wong, 1993). The recent Scotts Mills earthquake (1993, M 5.6) centered northeast of Salem was a crustal event. The estimated maximum magnitude of a crustal earthquake is about M 6.5.

EARTHQUAKE HAZARDS

The most severe damage from an earthquake is usually concentrated near the rupture zone due to large-amplitude ground motions and in areas where site geology enhances damage. Poor ground conditions that commonly contribute to damage are associated with the following phenomena:

Liquefaction, where saturated, loose, sandy soils become unstable like "quicksand."

Amplification, where ground shaking is intensified, especially in "soft" soils.

Landsliding, where "weak" slopes destabilize and move downhill.

These phenomena, which are discussed in the following subsections, have been evaluated in a relative sense based on simplified, yet credible, engineering parameters. That is, the maps do not depict the absolute degree of earthquake hazard at any site. For any given earthquake, it is possible to incur minimal damage even in the highest susceptibility zone or extensive damage even in the lowest susceptibility zone.

Other hazards that were not evaluated include fault rupture, seismically induced settlement, and seiches. Seiches, which are sudden oscillations of water, may cause detrimental fluctuations of water levels in waterfront areas of rivers and lakes.

Geologic Time Scale for the Cenozoic Era
(after Berggren and others, 1985)

Period	Epoch		Millions of years
Quaternary			
	Holocene		0.01
	Pleistocene		
		late	
		early	1.6
Tertiary			
	Pliocene		
		late	3.4
		early	5.3
	Miocene		
		late	10.4
		middle	16.5
		early	36.6
	Oligocene		
		late	23.7
		early	36.6
	Eocene		
		late	40.0
		middle	52.0
		early	57.8
	Paleocene		
		late	62.3
		early	66.4
(Mesozoic Era)			

MAPMAKING METHODOLOGY

The hazard maps are based on the local geology and topography, engineering properties of the geologic units, state-of-practice geotechnical engineering analysis, and professional judgment. The methodology includes developing a three-dimensional geologic model; measuring and estimating relevant geotechnical parameters for units in the geologic model; selecting earthquake scenarios and other input parameters for analyses of earthquake-induced liquefaction, ground motion amplification, and landsliding; performing the individual analyses and producing the individual hazard maps; and, lastly, producing the relative earthquake hazard map.

The three-dimensional geologic model for the study area was developed on the basis of previous work that defined soil units overlying bedrock, as described in "Mapping Geological Earthquake Hazards, Salem, Oregon" (Burns and others, 1992). The available model was refined by integrating (1) information on regional surface geology from published geologic maps, aerial-photograph interpretation, and limited field reconnaissance and (2) subsurface geologic and geotechnical data (such as from boreholes and water wells) from the exploratory program conducted for this study and from outside sources, including governmental agencies and private consultants. Exploratory locations associated with this study and surface geology are shown in Figure 1. Table 1 lists the geologic units modeled in this study and their corresponding material property values. Table 2 lists the results of the exploratory program conducted as part of this study, which consisted of soil and rock borings and cone penetrometer tests.

Engineering property values for geologic units were selected on the basis of in situ measurements and laboratory tests. These data were derived from technical literature and from new work performed for this study. In situ measurements conducted as part of this study involved downhole shear wave velocity tests, cone penetrometer tests including shear wave velocity measurements, and standard penetration tests.

The above data were integrated into a three-dimensional computer model of the geology on a 30-m grid in IDRISI, which is Geographical Information System (GIS) software (Eastman, 1993). Analytical methods used to develop the maps are described in the sections for the individual maps.

LOCAL GEOLOGIC SETTING

The study area is bounded approximately by Chemawa Road on the north, Howell Prairie Road on the east, Kuebler Road on the south, and the western slopes of the Eola Hills on the west and includes downtown Salem (Figure 1). The Willamette River flows north through the western portion of the study area. The local topography ranges from flat in the low-lying alluvial plains comprising the northeastern portion of the study area to gentle-to-moderate slopes in the Eola, Salem, and Waldo Hills.

Sedimentary and volcanic bedrock are locally overlain by younger deposits. Table 1 lists the geologic units modeled in this study; detailed descriptions can be found in Bela (1981), McDowell (1991), and Burns and others (1992). Figure 1, which is a simplified geologic sketch map, illustrates surficial geologic contacts.

Eocene-Oligocene sedimentary bedrock (unit Toe) is the oldest rock unit, and consists mostly of sandstone, siltstone, and mudstone, with lesser amounts of conglomerate and some interspersed localized volcanic rocks. Overlying the sedimentary bedrock is the Miocene Columbia River Basalt Group (unit Tcr), which typically consists of weathered and unweathered basaltic lava flows with interflow zones characterized by vesicular flow-top breccia, ash, and baked soils. Maximum thickness generally ranges from 400 to 600 ft, with thicknesses greatly modified by erosion and weathering. The basalt weathers to laterite, which is a red clay, to thicknesses of typically 30 ft. The laterite tends to develop thickest in the hills, sometimes up to 200 ft thick. A complete stratigraphic column in the hills is unit Toe, overlain by unit Tcr with an upper blanket of laterite; however, the upper laterite and unit Tcr may be denuded. Recent Holocene landslide masses, unit Qls, are present in areas.

Overlying the bedrock units in the valley are Quaternary sediments, including a fine-grained blue clay unit and flood gravels of early Pleistocene age; fluvial gravels (unit Qfch) of late Pleistocene age; Pleistocene and Holocene terrace deposits (units Qffh and Qffl); and Holocene river alluvium (unit Qal). The terraces, which are composed mostly of unconsolidated to semiconsolidated gravel, sand, silt, clay, and organic materials, blanket the lowlands of the entire alluvial valley. These terraces have been divided into higher flood sediments (unit Qffh), and lower flood sediments (unit Qffl). The higher flood sediments are older and occur at higher elevations than the lower flood sediments. Alluvium (unit Qal), which consists of unconsolidated cobbles, gravel, sand, and some silt and clay, occurs within the active channels of the Willamette River. The complete valley stratigraphy, where present, is older sedimentary rock (unit Toe) as the base rock overlain by Columbia River basalt (unit Tcr), laterite, fine-grained blue clay, flood gravels (not exposed in map area and not shown on map in Figure 1), fluvial gravels (unit Qfch), and the alluvial units Qffh, Qffl, and Qal.

Both bedrock and younger deposits can be hazardous during an earthquake. For example, the younger alluvial deposits tend to be more susceptible to liquefaction and ground motion amplification than the older geologic deposits. Deep, younger deposits also tend to contribute to a longer duration of shaking than the older units. In contrast, bedrock slopes are in many areas susceptible to landsliding. Identifying active faults is outside the scope of this study, and no faults are shown on the hazard maps.

LIQUEFACTION SUSCEPTIBILITY

General

Liquefaction is the process by which water-saturated, granular soils temporarily lose shear strength and behave as a viscous liquid rather than as a solid. When soils liquefy (often compared to "quicksand"), they suddenly take on "liquid" characteristics and may not provide adequate foundation support. Earthquake ground shaking can trigger liquefaction by destabilizing the soil grain structure and increasing pore water pressures. The soils most susceptible to liquefaction are young, loose, clean (low clay content) sands and silts that are below the groundwater table. Loose, saturated gravels, although less susceptible, may liquefy during strong ground shaking.

Liquefaction-induced ground failure is a major cause of earthquake damage. Hazards often involve structural and foundation failures due to (1) differential movement in the vertical direction between the structure and the ground and (2) lateral spreading, that is, horizontal movement of surface soil layers down gentle slopes or toward free faces (such as river banks). Ruptured pipelines, displaced bridge abutments, damaged buildings and other structures, and flotation of buoyant underground structures are potential hazards associated with liquefaction.

Method of analysis and discussion

The general procedures used to evaluate liquefaction susceptibility were to (1) analyze site-specific data in the upper 50 ft, assuming groundwater levels at the ground surface, with a selected earthquake scenario in order to assess geologic unit characteristics; (2) select and apply engineering parameters representative of geologic units based on site-specific analyses; (3) apply estimated regional groundwater levels to the available liquefiable sediments determined in the above-mentioned steps 1 and 2; and (4) categorize liquefaction susceptibility for map presentation.

The subsurface data were obtained through means described in the section "Mapmaking Methodology." Standard-of-practice liquefaction analyses were performed on a limited database of 27 sites with techniques set forth by Seed and others (1983). A magnitude 8.5 earthquake with a 0.3-*g* horizontal ground acceleration on soil was selected to represent critical, yet plausible, conditions. This acceleration value is about 50 percent higher than the peak rock acceleration value for a 500-year event, which accounts for possible amplification of ground motions from the bedrock through the overlying younger sediments (Geomatrix Consultants, Inc., 1995). Conservative groundwater level values were applied to the available thicknesses of liquefiable sediment, which maintains or reduces the available liquefiable materials used to develop the final susceptibility categories shown on the map. This conservative approach, which tends to overestimate the liquefaction susceptibility in nearly all instances and is commonly used for regional mapping, was adopted to avoid underestimating hazards and accounts for most uncertainties.

Six susceptibility categories (0 to 5) were developed on the basis of available thickness of liquefiable material as follows: Category 0—no susceptibility in bedrock areas; category 1—lowest susceptibility with less than 6 ft of liquefiable material; category 2—with 6 to 12 ft; category 3—with 12 to 18 ft; category 4—with 18 to 24 ft; and category 5—highest susceptibility with more than 24 ft.

The results from the analysis indicate that generally areas near river and stream channels and adjacent floodplains have the highest susceptibility for liquefaction and low-lying areas on the flood plains have intermediate and low susceptibility, depending on the groundwater conditions. Bedrock areas are not considered to be liquefiable, although local variations may present exceptions.

Settlement, lateral spreading, flow failures, and other ground failures associated with liquefaction were not specifically evaluated. Seismically induced settlement can occur in areas of saturated and unsaturated loose soils. For local areas, a site-specific study will provide more precise data and may reduce the conservative estimates associated with this map.

Map presentation

The *Liquefaction Susceptibility Map* (Plate 1) depicts the six categories of relative susceptibility to liquefaction associated with earthquake shaking as areas with different colors. The color for each susceptibility category is the same on Plates 1, 2, and 3, so that the different hazards for a given area can be easily compared. Areas within the highest susceptibility category (category 5) were analyzed to have the greatest liquefaction hazard and are anticipated to suffer the most intense liquefaction during a significant earthquake. The lowest susceptibility category (category 0) indicates the lowest liquefaction hazard—no anticipated liquefaction—with possible exceptions in small, localized areas.

AMPLIFICATION SUSCEPTIBILITY

General

Earthquake ground motions can be significantly modified by geologic deposits near the ground surface. This modification can intensify the ground shaking, which is termed "ground motion (or ground shaking) amplification." Modifications can also decrease the ground motions or otherwise change characteristics of shaking (such as frequency content or duration). Plate 2 shows amplification of peak ground acceleration (PGA), which can appropriately be applied to structures with higher frequency (or shorter period) response, such as typical short buildings. Plate 2 does not depict ground motion amplification at a range of frequencies or provide information on the duration of shaking. Thick deposits of soft soils (e.g. in the northeast portion of the study area) often experience significant amplification at an intermediate frequency range and prolonged shaking, which may lead to extensive damage.

Strong ground motions can produce severe damage to the built environment, such as buildings and lifeline systems. Amplification generally occurs in unconsolidated, younger soils as opposed to harder and older bedrock. It is largely influenced by soil thickness and engineering properties, such as soil stiffness, which is characterized by the shear wave velocity of the soil. Ground shaking hazards that are enhanced because of amplification involve both structural engineering failures and nonstructural damage (such as broken windows, fallen ducts, or overturned bookcases). Total building collapse is the most extreme structural engineering failure. The frequencies of ground shaking that lead to damage to buildings are a function of a building's height, shape, and construction type. Conducting a complete site-specific study requires a careful evaluation of the site geology and earthquake source properties, as well as of the structure under consideration in the appropriate period range.

Method of analysis and discussion

The two fundamental considerations for estimating ground shaking amplification are the input motion specification and the characterization of dynamic material properties. As described in the "Earthquake Hazards" section above, three earthquake sources (subduction, intraplate, and crustal) threaten the study area. The expected ground motions for a 500-year recurrence interval (about 10 percent probability in 50 years) that represent three types of earthquakes (subduction, intraplate, and crustal) and cover a range of duration and frequency characteristics of input motion were modeled (Geomatrix Consultants, Inc., 1995). Dynamic material properties, which are shear strain dependent, were selected on the basis of field and laboratory test results and literature (see Table 1).

The site effects of local geology on ground shaking were modeled on a 90-m grid using SHAKE91, which is a commercially available program for analyzing one-dimensional site response of vertically propagating (normally incident) shear waves at a level site (Schnabel and others, 1972; Idriss and Sun, 1992). An input peak rock acceleration value of 0.19 *g* was applied on a 90-m grid resolution for the entire mapped area. The calculated PGA amplification factor, which is applicable to the higher frequency (or shorter period) response domain, was assigned to one of six susceptibility categories (0 to 5) as follows: Category 0—no susceptibility in bedrock areas; category 1—lowest susceptibility with a PGA amplification factor of less than 1.2, category 2—with values between 1.2 and 1.4; category 3—with values between 1.4 and 1.6; category 4—highest susceptibility with a value greater than

1.6, and category 5—potentially high susceptibility in areas with abrupt changes in topography.

Amplification analysis was not performed on (1) exposed bedrock areas in the hills and (2) areas with abrupt changes in topography. Exposed bedrock areas, where base rock motion (with an amplification factor = 1) was assumed, were assigned to category 0. For areas of abrupt topography, local topographic amplification was assumed on the basis of recent research and professional judgment (Ashford and Sitar, 1994). Consequently, steep bedrock slopes and sharp ridges and swales, which were determined using Geographic Information System (GIS) tools, were categorized into category 5 with a potentially high susceptibility for amplification.

Numerous amplification studies by researchers have generally concurred in that the motion of the surface of soft sites is greater than that at stiff sites for the same level of relatively low excitation. These studies, in a general sense, have demonstrated that assuming plane wave propagation in modeling linear one-dimensional site response for engineering purposes, such as the one used in this study, is adequate for relatively flat sites. On this basis, detailed earthquake analyses that account for three-dimensional geology, such as basin effects and inclined and surface waves, were not performed. Local topographic effects (e.g., steep slopes) and lateral changes in the materials (e.g., every 90m interval) were not directly modeled but were generally accommodated by the methods described above.

Map presentation

The *Amplification Susceptibility Map* (Plate 2) depicts the six categories of relative susceptibility to amplification of earthquake shaking applicable to higher frequency (or shorter period) response as areas with different colors. The color for each susceptibility category is the same on Plates 1, 2, and 3, so that the different hazards for a given area can be easily compared. Areas within the highest susceptibility category have been analyzed to have the greatest peak ground acceleration (PGA) amplification hazard. It is to be noted that, while category 4 represents the highest quantified susceptibility, the special susceptibility of category 5 represents a potentially similar, if not higher, amplification hazard. The lowest susceptibility category (category 0) indicates the lowest amplification susceptibility hazard—no anticipated amplification—with possible exceptions in small, localized areas.

LANDSLIDE SUSCEPTIBILITY

General

Landslide is a term that encompasses many phenomena involving lateral and downslope movement of earth materials. Landslides, which generally occur on steep slopes composed of weak rock or soil, can be triggered by earthquake motions, as well as other processes such as high-intensity or prolonged rainfall or scour along stream banks. Factors controlling earthquake-induced landsliding include earthquake source and propagation path, topographic relief, groundwater conditions, local geology (such as material strength and bedding orientation), vegetation, construction activities, and others. Earthquakes can activate former landslide areas or generate new slide movements. Landslides can occur during earthquake shaking or long after shaking has stopped and can impact extensive areas, damage structures, and destroy or block roads.

Earthquake-induced landslides have caused tens of thousands of deaths and billions of dollars in economic losses during this century. Based on research from case histories, the rock types found in the hilly portions of the study area, including weakly cemented rocks (such as the sediments of unit Toe), as well as more indurated rocks with prominent or pervasive discontinuities (such as the basalt of unit Tcr) are susceptible to earthquake-induced landsliding (Keefer, 1984).

Apart from variability in the geologic conditions, the types and the distribution of landsliding are dependent on the character of the earthquake. For example, larger earthquakes with a longer duration of shaking tend to initiate coherent, generally deeper seated landslides and lateral spreads and flows. In contrast, short duration, high-frequency shaking characteristic of small earthquakes tend to generate shallow, highly disrupted landslides from steep slopes. Research indicates that earthquakes as small as M 4 can trigger landslides (Keefer, 1984).

Method of analysis and discussion

The mapmaking methodology takes into account slope angle and existing landslides. Slope angles are calculated with standard Geographic Information System (GIS) tools on a U.S. Geological Survey 7½-minute digital elevation model and are approximate. Existing landslides, which are considered to be highly susceptible to future sliding, were identified as part of this study through mapping and aerial photography analysis and were supplemented with published maps and data from geotechnical consultants. This conservative approach assumes that the slip surface of the slide mass has low material strength and is vulnerable to further movement.

The study area was divided into six susceptibility categories (0 to 5) as follows: Category 0—no susceptibility in nonbedrock areas; category 1—lowest susceptibility in bedrock slopes with less than 6 degrees of slope angle; category 2—slope angles 6 to 14 degrees; category 3—slopes 14 to 22 degrees; category 4—slopes greater than 22 degrees; and category 5—highest susceptibility in areas with existing landslides.

The map indicates that there is a greater susceptibility for earthquake-induced landslide activity where slopes are relatively steep and in existing landslide masses. The principal factors controlling existing landslides in the study area appear to be the slope angle and proximity to river valleys. This method of slope stability analysis produces landslide susceptibility categories (shown on Plate 3) that may be applied to landslide hazards not associated with earthquake shaking.

Landslide characteristics including rate of movement and type of slide (such as rock versus soil slides, falls, rotational slides, translational slides, debris flows, and earth flows) have not been differentiated. Technical analysis that incorporates basic data on material strength, groundwater, and horizontal acceleration is beyond the scope of this study and was not performed. In addition, three-dimensional slope geometry, bedding, foliation, jointing, and other discontinuities, slope aspect, influences of surface water, areas affected by human activities, such as road cuts and mine excavations, and potential lateral spread and flow areas were not specifically addressed. Site-specific investigations should be performed where more detailed information is warranted, such as in granular alluvium near free faces (such as river channels), to evaluate for lateral spreads and flows and other potentially hazardous areas.

Map presentation

The *Landslide Susceptibility Map* (Plate 3) depicts the six categories of relative susceptibility to landsliding associated with earthquake shaking as areas with different colors. The color for each susceptibility category is the same on Plates 1, 2, and 3, so that the different hazards for a given area can be easily compared. Areas within the highest susceptibility category have been analyzed to have the greatest landslide hazard and are anticipated to suffer the most intense landsliding during a significant earthquake. It is to be noted that, while category 4 represents the highest quantified susceptibility, the special susceptibility of category 5 represents a potentially similar, if not higher, landslide hazard. These susceptibility categories can also be used for purposes involving potential landsliding not associated with earthquake shaking.

RELATIVE EARTHQUAKE HAZARD MAP

General

The *Relative Earthquake Hazard Map* (Plate 4) is a composite map that integrates three separate earthquake hazards. The severity of the overall hazard is increased as the hazard category of individual hazards increases. Plate 4 accounts for (1) liquefaction, (2) amplification of peak ground acceleration (PGA), and (3) landsliding hazards and combines these hazards in a generalized hazard map.

The distinction between the separate hazards is important to technical specialists; thus, individual hazard assessments are shown on the companion maps (Plates 1 to 3). These hazards, discussed in previous sections of this text, are largely influenced by the local geologic conditions.

Method of analysis and discussion

For the purpose of developing the relative earthquake hazard map, the six categories shown on the three separate earthquake hazard maps were assigned numerical values of 0, 1, 2, or 3 as shown below:

	Plate 1 Liquefaction	Plate 2 Amplification	Plate 3 Landsliding
Category 0	0	1	0
Category 1	1	1	1
Category 2	1	2	1
Category 3	2	2	2
Category 4	3	3	3
Category 5	3	3	3

For each 30-m cell on the individual hazard maps, the following steps were taken: (1) the value for each hazard was squared, (2) the numbers for all hazards were then added together, (3) the square root of the sum from step (2) was taken, and (4) that number was truncated to the nearest whole number. Values of 4 and 5 were assigned to Zone A, which represents the highest susceptibility to earthquake hazards; a value of 3 was assigned to Zone B, which represents the range between high and intermediate susceptibility; a value of 2 was assigned to Zone C, which represents the range between intermediate and low susceptibility; and a value of 1 was assigned to Zone D, which represents the lowest susceptibility for earthquake hazards.

The procedure of combining individual hazard maps to produce the *Relative Earthquake Hazard Map* was adopted to provide a single, user-friendly map for both technical and nontechnical audiences. Limitations associated with this mapmaking procedure stem mostly from assigning equal ratings to hazard susceptibility categories for three independent hazards and from the actual combining of the independent hazards. For example, to produce this map, areas in the highest susceptibility category for landsliding are assigned the same rating as areas in the highest susceptibility category to liquefaction. Although, technically, these hazard susceptibilities are not directly comparable and thus cannot be equated, the premise behind adopting this mapmaking technique is that the susceptibility of the gross hazards remains well represented and the map provides a useful tool for preliminary screening. Another example is that ground shaking amplification of horizontal accelerations can occur below but not within the liquefied mass due to the loss of strength behavior. Thus, in zones where both amplification of ground motions at the ground surface and liquefaction are mapped hazards, combining the maps may be considered as conservative. However, the underlying assumption in this case is that risk from potential hazards is higher in areas where more than one potential hazard exists.

Map presentation

The *Relative Earthquake Hazard Map* depicts four zones of susceptibility to earthquake hazards associated with ground response as areas with different colors. Red represents Zone A, the highest susceptibility zone, analyzed to have the greatest earthquake hazard. Orange represents Zone B, indicating high to intermediate earthquake hazard. Bright yellow represents Zone C, indicating intermediate to low earthquake hazard. Pale yellow represents Zone C, indicating the lowest earthquake hazard.

COMMENTS ON HAZARD MAPS AND THEIR USES

The earthquake hazard susceptibility maps in this report provide basic information for anyone concerned with earthquake hazards. This map series, which was developed to serve as a regional planning tool, offers a basis for more substantive decision-making. The maps may be used to help reduce the risk to life, health, and property through planning policy and other mitigation measures. User groups include, but are not limited to, local jurisdictions, building officials, land use planners, emergency preparedness and response planners, engineering and geology consultants, lifeline managers, developers, realtors, insurers, and private citizens.

Earthquake hazard reduction in urban areas, such as Salem, is necessary and must involve short- and long-term directed efforts in order to provide a safer living environment. To address present-day conditions, mitigation must take into account existing facilities, as was forcefully demonstrated by the earthquakes of Northridge, California, in 1994 and of Great Hanshin, Japan, in 1995. To minimize tomorrow's earthquake risks, prudent land use plans and building designs need to be implemented. Scientists often view risk in urban areas as increasing as long as no corrective actions are being taken. The reason is that, as time passes without the occurrence of significant earthquakes in seismically active areas, the probability of a significant earthquake to occur increases.

It is possible that the information contained on the maps could be used inappropriately without careful consideration and a thorough understanding of the underlying assumptions and uncertainties. The maps show trends for hazard susceptibility from the estimated response of the ground when earthquake shaking occurs. They do not include or integrate information on the probability of earthquake-induced shaking or the probability of damage to occur. In addition, all areas shown on the maps are susceptible to earthquake hazards. For example, should a large earthquake occur nearby, it could affect even the "lowest" earthquake hazard zones.

Higher susceptibility zones do not in any way suggest that an area is unsafe or should be avoided. The actual risk in a given area depends not only on the susceptibility zone but also on factors including land use, seismic strength of structure(s), nonstructural hazards, and other site-specific influences. Secondary effects, such as presence of hazardous materials, flooding potential from upstream dam failures, and fire hazards, are additional risks. Areas identified to be in higher susceptibility zones can incorporate earthquake hazards as basic information into the first steps of planning or decision-making, which can involve emergency response, mitigation, geotechnical and structural engineering, and risk level considerations.

Information provided in this publication should NOT be used in place of site-specific studies. The relative hazard zones are not intended to replace site-specific evaluations, such as for engineering analysis and design. Site-specific earthquake hazards should be assessed through geotechnical or engineering geology investigation by qualified practitioners. Site-specific evaluations may, for example, conclude that a site mapped in the highest susceptibility zone actually has a moderate to low hazard.

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