STATE OF OREGON
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Interpretive Map Series

IMS-19

Relative Earthquake Hazard Map of the Klamath Falls Metropolitan Area, Klamath County, Oregon

By
Gerald L. Black, Zhenming Wang, Thomas J. Wiley, and George R. Priest,
Oregon Department of Geology and Mineral Industries

2000

Text

IMPORTANT NOTICE FOR INTERPRETIVE SERIES MAP IMS–19

This map depicts earthquake hazard zones that are based on limited geologic and geophysical data, as described in the text. **The map is not a substitute for site-specific investigations by qualified practitioners.** At any point in the map area, site-specific data may give results that differ from those shown on the map. Some appropriate uses for the map are discussed in the text. For a complete understanding of the earthquake hazard, consultation of the following Department publication is also recommended: Madin, I.P., and Mabey, M.A., 1996, *Earthquake hazard maps for Oregon*: Oregon Department of Geology and Mineral Industries Geological Map Series GMS–100.

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ABSTRACT

This *Relative Earthquake Hazard Map of the Klamath Falls Metropolitan Area* depicts the relative seismic hazard potential that results from local geologic conditions. For hazard assessment on a neighborhood-to-neighborhood scale, local geologic conditions contribute as much as, or more than, any other factor to the hazard portion of that assessment. The hazard contribution of three different earthquake-related hazards is shown in relative terms on a single composite map. This allows a nongeologic and nonengineering audience to work more effectively toward reducing the risk to life and property through planning, policy, and mitigation measures. The composite hazard map was produced by combining individual hazard maps for ground motion amplification, liquefaction, and slope instability. The single component maps were developed to show geographic patterns of stronger earthquake effects for the most likely earthquake source. Zones that are expected to have the most pronounced damage in any moderate or larger earthquake are shown on the map as having the greatest hazard.

INTRODUCTION

Since the late 1980s, there has been a significant increase in the understanding of earthquake hazards in the Pacific Northwest. It is now known that damaging earthquakes much larger than those that have occurred in the historical past are possible (Atwater, 1987; Heaton and Hartzell, 1987; Weaver and Shedlock, 1989; Yelin and others, 1994). Mitigation measures are a cost-effective means to minimize the damage that might occur in a strong earthquake. These measures should be based on the best possible assessment of the extent and distribution of earthquake hazards. Earthquake hazard maps are one way to prioritize mitigation efforts.

The amount of damage sustained by a building during an earthquake is difficult to predict and is a function of the size, type, duration, and location of the earthquake, the characteristics of the soils at the building site, and the characteristics of the structure. At present, scientists cannot accurately assess the location or size of future earthquakes. They can, however, predict the behavior of the soil column during an earthquake. Knowledge of the soil column enables them to understand how the site will behave during earthquake shaking, when it occurs.

The maps presented here are an attempt to identify those areas within the Klamath Falls Urban Growth Boundary that will suffer more damage, relative to other areas, during a damaging earthquake. The analysis is based on the behavior of the soils and does not depict the absolute earthquake hazard at any particular site. In order to understand how the soil behaves at one site relative to another, it is necessary to use a specific design earthquake for the analysis. For this study, the design earthquake was a magnitude (M) 6.5 crustal earthquake at a focal distance of 10 km (~6 mi). However, it is unlikely that any "real" earthquake will exactly match our design parameters. It is quite possible that, for any given earthquake, damage in even the highest relative hazard areas will be light. For instance, the earthquake might cause damage but be of lower magnitude or occur at a greater distance than our design earthquake. On the other hand, during an earthquake that is stronger or much closer than our design parameters, even the areas in the lowest relative hazard categories could experience severe damage. This serves to reemphasize that scientists do not know where future earthquakes will occur or how big they will be.

The assessment of soil behavior (and hence the relative earthquake hazard) is based on geologic mapping and specialized geophysical and geotechnical measurements. These measurements are combined with state-of-practice geotechnical analysis and Geographic Information System (GIS) methodology and tools to produce the final maps. The result is a map that assigns each map area to one of four relative hazard zones, ranked from the greatest hazard (Zone A) to the least hazard (Zone D).

Because the maps exist as "layers" of digital GIS data, they can easily be combined with earthquake source information to produce earthquake damage scenarios. The maps can also be combined with maps of earthquake probability to provide an assessment of the absolute level of hazard and an estimate of how often that level will occur. Finally, the maps can also easily be combined with GIS data on land use planning.

Levson and others (1995) described several applications of relative earthquake hazard maps to land use and emergency planning. They include (1) identification of areas with vulnerable lifeline systems; (2) planning of transportation and utility corridors; (3) setting priorities for seismic upgrades for structures such as schools, hospitals, and other public-safety and essential facilities; (4) initial screening for new sites for essential facilities; (5) identification of areas requiring special study before development; (6) identifying high-hazard areas with restricted development; (7) property insurance; (8) assessment of risk for financing new projects; (9) providing information on site effects for the design of new structures; and (10) establishing more stringent design requirements where needed.

EARTHQUAKE HAZARD

Earthquakes from three different sources threaten communities in Oregon (Figure 1). Accordingly, we distinguish crustal, intraplate, and subduction zone earthquakes. The most common are *crustal earthquakes*, which occur in the North American plate above the Juan de Fuca subduction zone at relatively shallow depths of 10–20 km (6–12 mi) below the surface. The 1993 earthquake at Scotts Mills (M 5.6) (Madin and others, 1993) and the 1993 Klamath Falls main shocks (M 5.9 and M 6.0) (Wiley and others, 1993) were crustal earthquakes.

Deeper *intraplate earthquakes* occur within the remains of the ocean floor (the Juan de Fuca plate) subducted beneath North America. Intraplate earthquakes caused damage in the Puget Sound region in 1949 and again in 1965.

Great *subduction zone earthquakes* occur around the world where the plates that make up the surface of the Earth collide. When the plates collide, one plate is shoved ("subducts") beneath the other, where it is reabsorbed into the mantle. This dipping interface between the two plates is the site of some of the most powerful earthquakes ever recorded, often having magnitudes of 8 to 9 on the moment magnitude scale. The 1960 Chilean (M 9.5) and the 1964 Great Alaska (M 9.2) earthquakes were subduction zone earthquakes (Kanamori, 1977).

The Cascadia subduction zone, which lies off the Oregon and Washington coasts, has been recognized for many years. There have been no earthquakes on the Cascadia subduction zone during our short 200-year historical record. However, in the last several years, various studies have found widespread evidence that very large earthquakes have occurred repeatedly in the past, most recently about 300 years ago, in January 1700 (e.g., Atwater, 1987). Best available evidence indicates that these earthquakes occur, on average, every 500–540 years; observed intervals between individual events range from about 100–300 years to about 1,000 years (Atwater and Hemphill-Haley, 1997). There is every reason to believe that they will continue to occur in the future at similar frequencies and magnitudes.

Because the strength of shaking decreases with increasing distance from the earthquake source, intraplate and subduction zone earthquakes do not threaten the Klamath Falls area. Shallow crustal earthquakes like the 1993 events, however, pose a significant threat to the region.

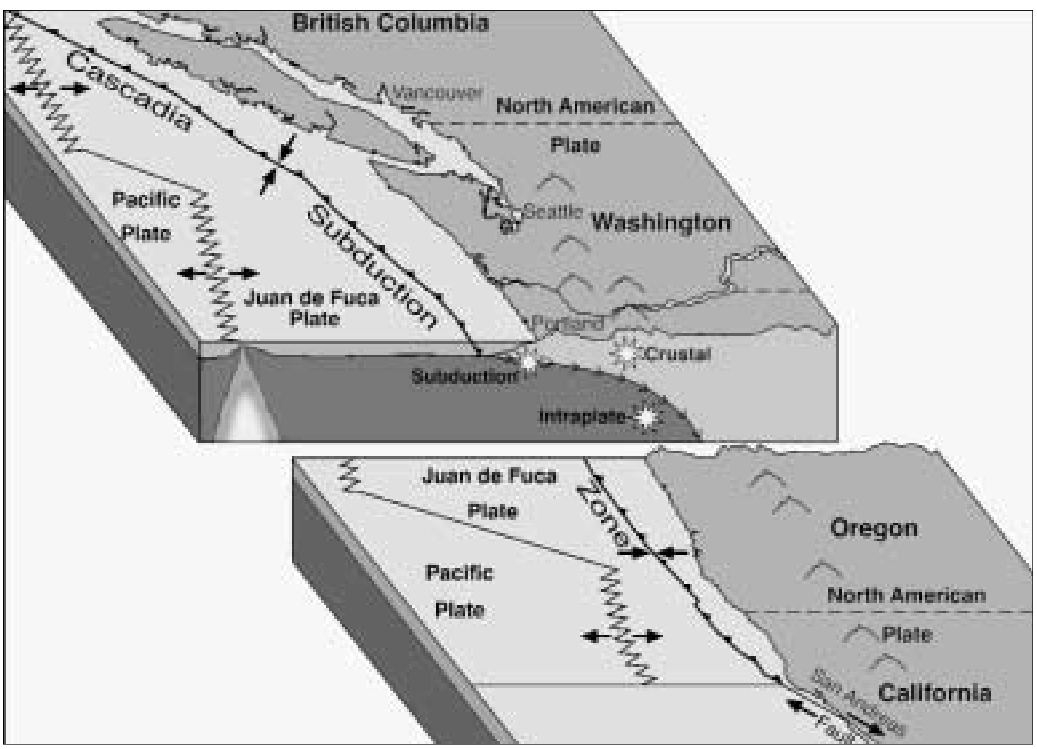

Figure 1. Schematic showing the regional plate tectonics setting and the three types of earthquake sources in the Pacific Northwest: subduction, intraplate, and crustal earthquakes.

EARTHQUAKE EFFECTS

Damaging earthquakes will occur in Klamath County. This fact was demonstrated by the 1993 Klamath Falls earthquakes (M 5.9 and M 6.0) (Wiley and others, 1993). Although it is not possible to predict when the next damaging earthquake will strike, where it will occur, or how large it will be, we can evaluate the influence of site geology on potential earthquake damage. This evaluation can occur while the exact sources of earthquake shaking are still being studied.

The most severe damage done by an earthquake commonly occurs in areas that experience one or more of the following phenomena: (1) amplification of ground shaking in a "soft" soil column; (2) liquefaction of water-saturated sand, silt, or gravel, creating areas of "quicksand"; and (3) landslides triggered by shaking. These effects can be evaluated before the earthquake occurs, if data are available on the thickness and nature of the geologic materials and soils at the site (Bolt, 1993). The exact nature and magnitude of the individual effects are useful to technical professionals, and the pertinent data for the Klamath Falls area are part of this publication (in digital form, on disk). For nonprofessionals, what is more important is that these effects increase the damage caused by an earthquake and localize the most severe damage. They will be more interested in the Relative Hazard Map, which combines data from the three individual hazards into a single map.

The *Relative Earthquake Hazard Map of the Klamath Falls Metropolitan Area* is a composite hazard map depicting the relative hazard due to the combination of the effects mentioned above. It delineates those areas that are likely to experience the most severe effects during a damaging earthquake. Areas of highest risk are those with high ground amplification, liquefaction potential, and existing landslides or steep slopes (>25° or >47%). Planners, lenders, insurers, and emergency responders can use such composite hazard maps for first-order hazard mitigation and response planning. It is very important to note that a relative hazard map predicts the tendency of an area to have greater or lesser damage than other areas in the region. These zones, however, should not be used as the sole basis for any type of restrictive or exclusionary development policy. To reemphasize: These maps indicate the relative hazard within the Klamath Falls urban growth boundary. They do not predict absolute levels of damage at any site.

HAZARD MAP METHODOLOGY

Geologic model

One of the most important element of any earthquake hazard evaluation is the development of a geologic model. For analysis of the amplification and liquefaction hazards, bedrock geology is not as important as the distribution and thickness of unconsolidated sediments. For analysis of the landslide hazard, bedrock geology of the steeper slopes (>25° or >47%) is important. For intermediate slopes (5°–25° or 9%–47%), the physical characteristics of the soil and colluvium covering the bedrock are of prime importance. The geologic model is developed from a combination of surface geologic mapping, surface shear-wave refraction, and subsurface borehole information. Author Priest completed the surface geologic mapping for the Klamath Falls study (Priest and others, in preparation). Information on soil and colluvium was obtained from the Klamath County soil survey (Cahoon, 1985). Authors Z. Wang and G.L. Black performed surface shear-wave refraction measurements.

Geologic history

(The following brief summary of the geology was prepared by George R. Priest:)

Between 4 and 6 million years ago, the area looked very different from today. The landscape was nearly flat, with wide-spread lakes where ridges now stand. Local volcanoes formed low mounds from which basaltic lava flows erupted. Between 2.4 and 4 million years ago, earthquake activity probably began to increase, as the area was slowly pulled apart (extended) in a northeast-southwest direction. This extension caused normal faulting and tilting of rocks and lake sediments toward the southwest and northeast away from Upper Klamath Lake and the Altamont-Lake Ewauna area. The cross

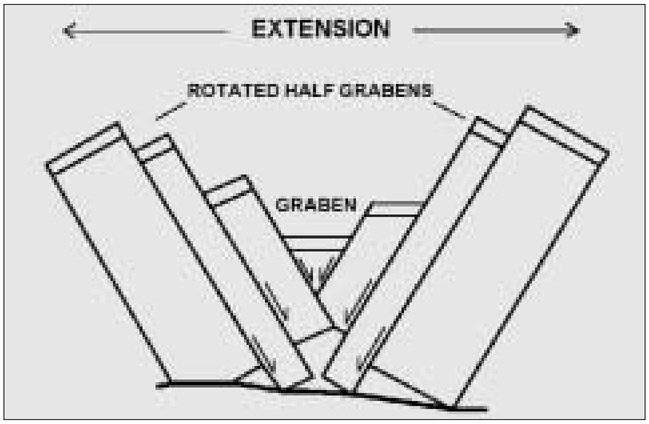

Figure 2. Schematic illustration of how development of half-grabens can rotate fault blocks. The diagram represents an idealized vertical cross section east-west across an area like Upper Klamath Lake, which is underlain by a graben and flanked by northwest-trending ridges.

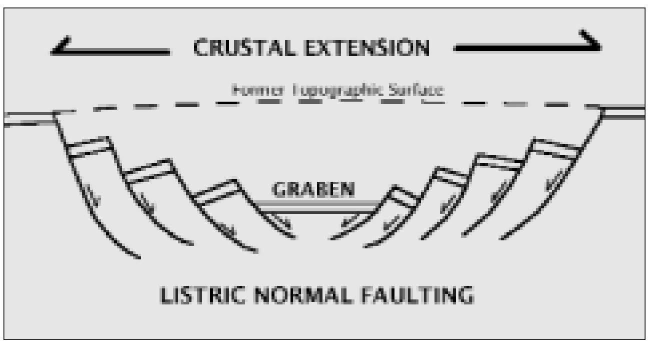

Figure 3. Schematic illustration of how listric (curved) normal faulting can rotate fault blocks.

sections in Figures 2 and 3 show ways in which this may have occurred. Keystonelike blocks (grabens) started to drop, forming depressions similar to the current basin at Upper Klamath Lake. Additional blocks formed on each side of these basins, rotating backward toward the northeast on the northeast side and southwest on the southwest side.

Between 1.8 and 2.4 million years ago, the faulted topography began to take on some of its current shape as volcanic activity decreased, forming, by 1.8 million years ago, a belt of vents located both immediately west of Klamath Falls and in the High Cascades. Between 1.1 and 1.8 million years ago, the current northwest-trending ridges and valleys became fully formed. Hard basaltic lava flows that are 2.4–4 million years old cap ridges on the east side of the area. Similar lava flows that are 1.8–4 million years old cap ridges on the west side. Mudstone and sandstone from former lakes and streams form the base of most of these ridges. Since the Klamath River did not exist at this time, sediment from lakes and streams accumulated in the valleys, eventually reaching elevations of about 1,420 m (4,700 ft).

Sometime after 1.1 million years ago, a radical change occurred. The Klamath River began to drain the area, and instead of filling the valleys with sediment, it flushed the sediment out, down the river. The river had probably eroded its headwall back through the High Cascades and into the Klamath Basin at this time, so sediment could for the first time escape to the sea. This erosion was so effective that in the Altamont area nearly all of the sediment was stripped away. Indeed, local canals in the Altamont basin are excavated in mudstone most of which is older than 2.4 million years.

Volcanic activity during the Pleistocene ice ages (10,000 years to 1.6 million years ago) and during the Holocene (the last 10,000 years) has been primarily restricted to the High Cascades, signaling a further shrinking of the belt of volcanic activity. The most impressive eruption was the explosion of Mount Mazama about 7,540 years ago (Bacon, 1983; Hallet and others, 1997).

Earthquake activity on the numerous fault zones continues, as illustrated by the recent M 6 earthquakes in 1993. Earthquakes as large as M 7.25 could occur in the future (Bacon and others, 1999).

Subsurface data

Information from surface geologic mapping and surface geophysical studies is integrated with subsurface data from boreholes to produce a three-dimensional geologic model. The boreholes used were originally drilled for water wells or foundation investigations. Water-well data were obtained from the Oregon Department of Water Resources (ODWR), which maintains a public database of all water wells drilled in the state. Information on boreholes drilled for foundation studies was obtained from consulting geotechnical engineers and used with permission. The resulting model defines the thickness of soil units beneath any location on the map so that their effect on earthquake damage can be assessed.

To assess the potential hazards associated with local geologic materials, data on more than just their thicknesses are needed. Additional geotechnical parameters include the Standard Penetration Test (SPT), which is a measure of the soil stiffness (relative density of a soil) and hence of its liquefaction potential. Many of the required measurements such as the SPT are acquired in the normal course of a foundation investigation. Thus, the needed information is available from many of the same sources as the thickness information.

In addition to the data acquired from borehole records, the assessment technique requires shear-wave velocities, which are used to determine the low-strain stiffness of the soils. Downhole measurements of shear-wave velocities were made at four sites in the Klamath Falls area. These four sites were drilled by the Oregon Department of Geology and Mineral Industries (DOGAMI), using conventional drilling techniques. In addition to shear-wave velocities measured in the boreholes, additional SPTs were performed, and samples were obtained for grain-size analysis. At 10 additional sites, shear-wave velocities were determined with surface seismic methods. These sites also produced useful information on the thickness of geologic units.

All of this information was used to produce a detailed computer-generated map of the subsurface throughout the study area. With the information from this map, the response to earthquake shaking at any specific location can be assessed.

HAZARD ANALYSIS

An earthquake causes damage through a variety of effects, including ground shaking, liquefaction, landslides, fault rupture, tsunamis, and seiches (Bolt, 1993). The severity of any one of these effects, or hazards, is influenced by a number of factors. We can assess many of these factors in relative terms, without knowing the exact details of the earthquake itself.

The *Relative Earthquake Hazard Map* integrates three separate earthquake hazard components. They are (1) ground shaking amplification, (2) liquefaction, and (3) earthquake-induced landsliding. Tsunamis are not a threat in the Klamath Falls area. Fault rupture and seiches are potential problems in Klamath Falls, but they are not addressed in this study, which focuses specifically on ground response.

Each of these phenomena is a distinct and separate hazard and, in concert with others, can increase the severity of the total hazard at a given locality. Differentiating between these map components is important to technical specialists but less critical to a nontechnical audience. It therefore makes sense to generate a map of each of the individual hazard components that will be available to those able to use them and to then combine the individual maps into a simple, unified hazard map that generalizes the issues in a way useful to nonspecialists. A variety of raster- and vector-based GIS programs, including IDRISI (Eastman, 1997), MapInfo™, and Vertical Mapper™, were used to perform the map analysis.

Ground shaking amplification

The soils and soft sedimentary rocks near the surface can modify bedrock ground shaking caused by an earthquake. This modification can increase the strength of shaking (or alternatively decrease it) or change the frequency of the shaking. The nature of the modifications is determined by the thickness of the geologic materials and their physical properties, such as stiffness. Topography can also amplify shaking. Near the crests of bluffs, within a distance approximately equal to the height of the bluff, amplifications on the order of 1.5 times the bedrock shaking can occur (Ashford and Sitar, 1997). Because topographic effects are directional and not fully understood, they were not considered in this study.

Past DOGAMI earthquake hazard studies (Mabey and others, 1993, 1995a–d, 1996, 1997; Wang and Priest, 1995; and Wang and Leonard, 1996) used the sophisticated computer program SHAKE91 (Schnabel and others, 1972; Idriss and Sun, 1992) to estimate the effect of local geology on ground shaking. The SHAKE methodology has proven to be quite accurate in predicting the location and degree of ground shaking amplification in locations such as Mexico City and the San Francisco Bay area. However, most present-day amplification studies use a method first described by the Federal Emergency Management Agency (FEMA) (Building Seismic Safety Council, 1994) and adopted in the 1997 version of the Uniform Building Code (International Conference of Building Officials, 1997). This methodology will henceforth be referred to as the UBC–97 methodology. The SHAKE91 methodology is reserved for certain critical facilities (e.g., hospitals and fire and police stations) and sites underlain by very soft soils.

The UBC–97 methodology defines six soil categories based on average shear-wave velocity in the upper 30 m (100 ft) of the soil column. It then assigns amplification factors to each soil type. The six soil categories are hard rock (A), rock (B), very dense soil and soft rock (C), stiff soil profile (D), soft soil profile (E), and special soils (F). Category F soils are very soft soils requiring site-specific evaluation.

DOGAMI first used the UBC-97 methodology in a ground response study of the Eugene-Springfield metropolitan area (Black and others, 2000). For that study, the amplification hazard was analyzed using both the SHAKE91 and UBC–97 methodologies. The distribution of the amplification hazard from the SHAKE91 analysis was very similar to the result from the UBC–97 methodology. There were minor differences in the absolute value of the amplification hazard due to the fact that the UBC–97 method assigns a single amplification factor to soils that actually have a range of physical properties. The SHAKE91 methodology takes those subtle differences into account and also depends on input ground motions. In the Eugene-Springfield and subsequent studies, the change from the SHAKE91 method to the UBC–97 method was made because it is (1) faster, (2) a more appropriate methodology for regional-scale maps, (3) compatible with current engineering design practice, and (4) independent of input ground motions. To generate the amplification hazard map for the present publication, only the UBC–97 method was used.

Geologic units in the Klamath Falls study area fall into one of three UBC-97 soil classes. Accordingly, using the UBC-97 methodology, three amplification hazard categories were defined for the study area: (1) areas with amplification less than or equal to 1.0 (Soil S_B), (2) areas with amplification of 1.5 (Soil S_C), and (3) areas with amplification of 1.8 (Soil S_D).

The *Amplification Hazard Map* shown on the map sheet accompanying this report is the resulting three-category map. The amplification hazard in the Klamath Falls area is significant. A little over one-third (36.4%) of the area does not amplify shaking. However, almost one-half (47.9%) amplifies by a factor of 1.8. The remainder amplifies by a factor of 1.5. Thus nearly two-thirds of the Klamath Falls urban area significantly amplifies ground shaking. What this means is that, if an earthquake produces bedrock accelerations of 0.2 *g* (where *g* is the acceleration due to gravity), a building that sits on a soil column that amplifies shaking by a factor of 1.5 will experience accelerations of 0.3 *g*. If it sits on a soil column that amplifies shaking by a factor of 1.8, it will experience accelerations of 0.36 *g*. The most recent study of the overall earthquake hazard in Oregon (Geomatrix Consultants, 1995) indicates that earthquakes with a 1,000-year return period can cause peak horizontal bedrock accelerations of about 0.25 g in the Klamath Falls area. Thus the amplified accelerations in the urban area could be as much as 0.45 g over large portions of the city. Acceleration of 0.45 g can cause considerable damage in specially designed structures, great damage with partial collapse in substantial buildings, and total collapse in poorly designed structures (Bolt, 1993).

Liquefaction

Liquefaction is a phenomenon in which shaking of a saturated soil causes its material properties to change, so that it behaves like a liquid. In qualitative terms, the cause of liquefaction was described very well by Noson and others (1988): “Liquefaction occurs when saturated sand or silt is shaken violently enough to rearrange its individual grains. Such rearrangement has a tendency to compact the deposit. If the intergranular water cannot escape fast enough to permit compaction, the load of overlying material and structure may be temporarily transferred from the grains of sand or silt to the water, and the saturated deposit becomes 'quicksand'."

Soils that liquefy tend to be young, loose, granular soils that are saturated with water (National Research Council, 1985). Unsaturated soils will not liquefy, but they may settle. If an earthquake induces liquefaction, several things can happen: The liquefied layer and everything lying on top of it may move downslope; alternatively, it may oscillate with displacements large enough to rupture pipelines, move bridge abutments, or rupture building foundations. Light objects, such as underground storage tanks, can float toward the surface, and heavy objects, such as buildings, can sink. Typical displacements can range from centimeters to meters. Thus, if the soil at a site liquefies, the damage resulting from an earthquake can be significantly increased over what shaking alone might have caused.

Lateral spreading is a liquefaction-induced hazard that involves the displacement of essentially intact blocks of soil either downslope or toward a free face, such as a river channel. Movement occurs on a liquefied layer within the soil column. Lateral spreads generally develop on gentle slopes of <3° (5%) and can involve displacements of several meters (National Research Council, 1985).

Soils that are subject to liquefaction and/or lateral spreading can be identified. Soils that liquefy tend to be young, unconsolidated, water-saturated silts and sands with low clay content. Gravel will liquefy only under exceptional circumstances.

In the Klamath Falls area, Standard Penetration Test (SPT) information was limited to boreholes in geologic units Qs and Qac. Unit Qac consists of Holocene undifferentiated alluvium and colluvium that mantles gentle bedrock slopes. Texturally it consists of poorly to moderately sorted cohesionless sands and gravels (Priest and others, in preparation). Unit Qs consists of Holocene lacustrine (lake-deposited), peaty, silty sands. It is unconsolidated, forms on flat slopes, and texturally varies from fine-grained sandy or silty units to highly plastic organic clays (Priest and others, in preparation). We had data from two boreholes in unit Qac and four boreholes in unit Qs. This limited information indicated that unit Qac had marginal potential for liquefaction and that the upper 2 m (6.5 ft) of unit Qs would liquefy.

Even though unit Qs has low SPT values, is texturally capable of liquefying, and consists of Holocene lake sediments which are generally considered to have moderate liquefaction potential (Youd and Perkins, 1978), it was assigned a low liquefaction potential. This is because the liquefiable layer is thin (less than 2 m) and unconfined, which reduces the chance for the pore pressure increase that is necessary for liquefaction to occur. Unit Qac was also assigned low potential for liquefaction.

Certain soil units were also assigned low liquefaction potential. These typically occur on relatively flat slopes, are water saturated during the winter months, and consist of silts and sands with clay contents of less than 15% and low liquid limits (Cahoon, 1985)

The remaining geologic and soil units in the Klamath Falls area will not liquefy.

Thus the accompanying liquefaction hazard map is a simple two-component map. Approximately two-thirds of the urban area will not liquefy. The remainder has low liquefaction potential. Still, the possibility of liquefaction should be considered for any critical facility built in areas of even low liquefaction potential.

Within about 50 m (165 ft) of Upper Klamath Lake, Lake Ewauna, and the Klamath River, there is some potential for lateral spread. The unconfined portion of unit Qs is up to 6 m thick (20 ft) in these areas (Priest and others, in preparation), making liquefaction and resulting lateral spread more likely. The displacement was calculated using the following empirical relationship from Bartlett and Youd (1995):

$$\log(D_H) = -15.787 + 1.178\,M - 0.927\log R - 0.013R + 0.429\log S + 0.348\log T_{15} + 4.527\log(100 - F_{15}) - 0.922D50_{15}$$

where D_H is the lateral-spread displacement in meters; M is the moment magnitude of the earthquake; R is the horizontal distance (in km) to the seismic energy source; S is the ground slope in percent; T_{15} is the cumulative thickness (in m) of saturated cohesionless soils with $(N_1)_{60}$ values of ≤15; F_{15} is the average fines content in percent; and $D50_{15}$ is the mean grain size in millimeters.

The calculation was performed within 50 m (165 ft) of the above-named bodies of water, using the design earthquake of M 6.5 at 10 km (6 mi). Other parameters used were slopes between 0º and 3.5º (0%-6%), cumulative thickness of 3 m (0-10 ft), an average fines content of 45%, and a mean grain size of 0.075 mm (the dividing line between silt and sand). Calculated displacements ranged from 0 to 13 cm (0-5 in). We then assigned calculated displacements to a hazard category in such a way that displacements of 0–1 cm (0–0.4 in) were considered to represent no hazard, 1–10 cm (0.4–4 in) a low hazard, 10–100 cm (4–39 in) a moderate hazard, and displacements of >100 cm (39 in) a high hazard. Thus the lateral-spread hazard in the Klamath Falls area ranges from none to moderate.

The result of the lateral-spread analysis is included as part of the slope instability map.

Slope instability (landslides)

In the Klamath Falls area, slope instability resulting from strong shaking will be a threat. Its analysis for this study is based on state-of-practice dynamic analysis for slope stability and lateral spreading; empirical correlation of slope stability with engineering properties of materials; and manipulation of data on local topography, engineering geology, and hydrology (Wang and others, 1998).

The particular method used to evaluate seismically induced ground deformation is a function of slope steepness. Different analytical techniques are used for different slope categories, because failure mechanisms vary depending on steepness. Slopes between 0° and 5° (0%–9%) fail by liquefaction and/or lateral spreading and are analyzed using the techniques discussed in the previous section. Steep slopes (>25° or >47%) most commonly fail by rock falls, rock slides, and debris slides (Keefer, 1984) and are analyzed using empirical data that relate slope stability to degree of weathering, strength of cementation, spacing and openness of rock fractures, and hydrologic conditions. Moderate slopes produce larger numbers of rotational slumps and translational block slides in soil (Keefer, 1984). Therefore, slopes between 5° and 25° (9%–47%) are analyzed using a dynamic slope stability analysis that uses slope inclination, engineering-geologic characteristics of geologic units, and shaking parameters from design earthquakes as inputs.

These analyses are performed on computers using a variety of GIS programs. For the slope stability analyses a digital elevation model (DEM) is required. A DEM is nothing more than a set of land elevations at regularly spaced intervals (like a grid) that blanket the study area—in this case, the area enclosed by the Klamath Falls Urban Growth Boundary. DEMs are produced by the U.S. Geological Survey (USGS) and have a grid spacing of 30 m (98 ft). For slope stability analysis, it is preferable to have 10-m DEMs. We produced our own 10-m DEMs from USGS hypsographic (contour) data, using MapInfo and Vertical Mapper GIS software. This is the same data set that is used to produce the USGS 30-m DEMs. Therefore, where slopes are shallow, our DEMs will be no more accurate that the 30-m DEMs. This does not impact the model integrity, however, because the slope stability hazards are negligible in these areas. Where slopes are steep, our DEMs will contain significantly more information. The GIS programs use the DEMs to calculate the slope angle at each point in the grid. This slope angle is one of the inputs into the stability analyses.

The grid spacing of the DEM is important because it determines the size of the smallest landslide that can be predicted. The 10-m (33-ft) grids used in this study are significantly better than the 30-m (98-ft) USGS grids. However, small landslides and debris flows with dimensions of a few meters that occur in gullies and small hollows and may pose a relatively high risk will not show up on even a 10-m (33-ft) grid.

Slope analyses

Existing landslides

The movement characteristics of existing landslides are highly variable, ranging from active movement to stable. Although most earthquake-induced landslides occur in materials not previously involved in sliding (Keefer, 1984), it requires site-specific studies to understand the nature of any existing landslide. Therefore, it was assumed that the slip planes of mapped landslides are at reduced shear strength of unknown value, and that the slide masses are inherently unstable under earthquake loading. Existing landslides are conservatively assigned to the highest hazard category. No analytical techniques were applied. In the Klamath Falls area only one small landslide is mapped within the urban growth boundary (Priest and others, in preparation).

Steep slopes (>25° or >47%)

The analysis of the landslide potential on steep slopes was a three-step procedure. First, bedrock outcrops in the study area were examined and evaluated for their failure potential. Then, based on the analysis of individual outcrops, the concentration of landslides in each geologic formation was calculated. Finally, each geologic formation was placed into one of five slope instability hazard categories (None, Low, Moderate, High, Very High), on the basis of landslide concentration.

Not every geologic unit was examined for its failure potential. Some (e.g., units Qal, Qs, Qac, Mf) do not crop out in readily observable exposures. These units were assigned to a hazard category based on experience. For instance, alluvial units commonly fail where they occur on steep slopes such as river banks and artificial cuts. Therefore, they were assigned to the "High" hazard category when they occurred on slopes >25°.

Slopes >25° (>47%) are particularly vulnerable to bedrock failures. Keefer (1984, 1993) noted that more than 90% of earthquake-induced slope failures on rock slopes were rock falls and rock slides—typically thin, highly disrupted landslides that move at high velocities. The physical characteristics of the rock masses underlying steep slopes are of fundamental importance in evaluating their susceptibility to earthquake-induced slope failure. Accordingly, author Black examined outcrops in order to evaluate their physical characteristics. This data set includes most bedrock outcrops available for examination in the Klamath Falls study area. At each outcrop, the geologic unit, slope angle, degree of weathering, degree of induration, nature and spacing of fractures, and hydrologic conditions were noted. With this information each outcrop was evaluated for failure potential, according to a decision tree (Figure 4) originally presented by Keefer (1993). Use of the decision tree results in the assignment of each outcrop to one of five failure susceptibility categories (Extremely High, Very High, High, Moderate, or Low).

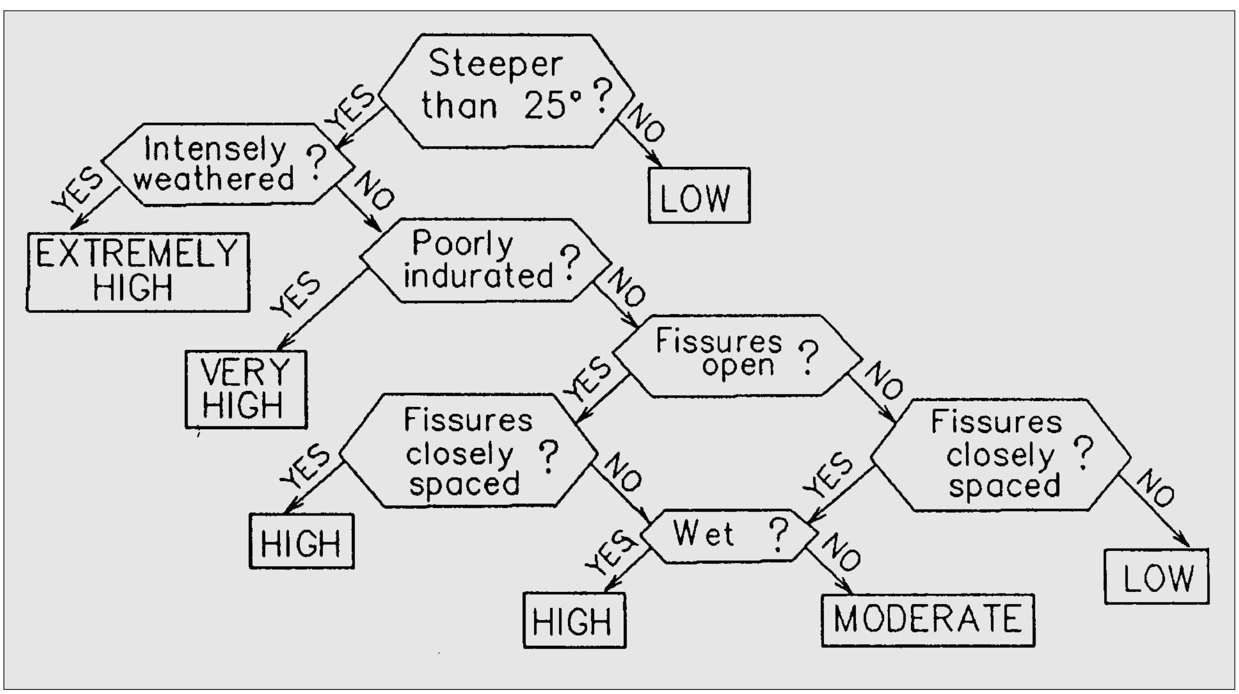

Figure 4. Decision tree for susceptibility of rock slopes to earthquake-induced landslides (from Keefer, 1993). For the Eugene-Springfield study, all slopes were assumed to be wet.

Based on the outcrop evaluations, the landslide concentration (number of landslides occurring per square kilometer, or LS/km^2) was calculated for each geologic unit, using the following empirical relationship:

$$LS/\text{km}^2 = (32\ LS/\text{km}^2)(\%\ \text{extremely high}) + (8\ LS/\text{km}^2)(\%\ \text{very high}) + (2\ LS/\text{km}^2)(\%\ \text{high}) + (0.50\ LS/\text{km}^2)(\%\ \text{moderate}) + (0.125\ LS/\text{km}^2)(\%\ \text{low})$$

where "% extremely high" represents the percentage of outcrops of a given geologic unit rated (by the decision tree) as having extremely high failure potential. The coefficient represents the average number of landslides per km^2 in control study areas examined by Keefer (1993) that (1) have experienced earthquake-induced landsliding and (2) have outcrop characteristics that indicate an extremely high failure potential. The other terms in the equation represent the other failure categories. The above equation is slightly modified from that presented in Keefer and Wang (1997) and Wang and others (1998) and was developed from data in Keefer (1993), relating landslide concentrations to earthquake magnitude and outcrop physical properties (as delineated in the decision tree).

Finally, based on the calculated landslide concentration, each geologic unit was placed into a slope instability hazard category. Landslide concentrations of >2 LS/km^2 were assigned to the high hazard category, those of 1–2 LS/km^2 were assigned to the moderate hazard category, and those of <1 LS/km^2 were assigned to the low hazard category. Table 1 lists the landslide concentrations and hazard category ratings for the geologic units occurring on steep slopes in the Klamath Falls area. Detailed discussions of the geologic units can be found in Priest and others (in preparation).

The main steep-slope problem that exists in the Klamath Falls area is due to the lava flows that cap many of the ridge crests. The flows are relatively unweathered and are not expected to fail as large slide masses. They are highly jointed, however, producing individual blocks that range from a few tenths of a meter to several meters in diameter. Strong shaking could easily send individual boulders rolling downslope. A boulder of this type was responsible for a fatality in the 1993 Klamath Falls earthquake. Most of the areas of highest rock-fall susceptibility (maroon areas on the slope hazard map) represent this type of hazard.

Moderate slopes

The stability analysis for moderate slopes is based on the dynamic slope stability analysis of Newmark (1965) as verified and extended to regional-scale work by Wilson and Keefer (1983, 1985), Wieczorek and others (1985), Jibson (1993, 1996), and Jibson and Keefer (1993).

The process that assigns the soils mantling moderate slopes to one of several slope-instability hazard categories takes several steps. First, using infinite slope analysis, the static factor of safety (FS) is calculated for each grid element. This factor of safety is then used to calculate the *critical acceleration*, which is the acceleration required to overcome friction and initiate sliding in the soil mass. The critical acceleration is used in conjunction with earthquake input parameters to calculate the total displacement that is expected to occur during the design earthquake. Finally, the total displacement is used to assign each of these grid elements to a slope-instability hazard category. Hazard categories used for the Klamath

Table 1. *Landslide concentrations and hazard categories for geologic units occurring in the Klamath Falls area*

Geologic unit	Rock type	LS/km^2	Hazard category
Qls	Landslide	–	Very high (5)
Mf	Fill, not engineered	–	High (4)
Qal, Qs, Qc, Qac	Holocene alluvium, colluvium	–	High (4)
Mef	Engineered fill	–	Moderate (3)
Qoc	Older alluvium, colluvium	–	Moderate (3)
QTfs, Ths	Poortly indurated silt, sand	8.00	High (4)
Tm	Mudstone	12.40	High (4)
Ts, Tms, Tmsa	Tertiary sedimentary rocks	7.00	High (4)
Tpt	Nonwelded tuff	8.00	High (4)
Tla, Ta	Andesite	1.70	Moderate (3)
Qtwb, Thb, Tcba, Tba	Basalt and basaltic andesite	2.00	High (4)
Tbv, Tbtv, Tiba	Basalt and basaltic andesite	2.00	High (4)
Tg	Conglomerate	–	Moderate (3)

Falls study were (1) None—displacement <1 cm (0.4 in); (2) Low—displacement 1–10 cm (0.4–3.9 in); (3) Moderate—displacement 10–100 cm (3.9-39 in); (4) High—displacement >100 cm (>39 in); and (5) Existing—mapped landslides.

Factor-of-safety calculations depend on the thickness of the soil mass, the slope angle, the height of the water table, and physical characteristics of the soil mass. Such physical characteristics include unit weight, cohesion, and angle of internal friction. For the Klamath Falls area, the soil survey of Southern Klamath County (Cahoon, 1985) was used to obtain information on the distribution of soil units and their physical properties. Physical characteristics include grain size distribution (soil classification), thickness and degree of saturation during the period December to April, plasticity indexes, and unit weights.

Various sources were used to estimate cohesion and angle of internal friction for the various soil units. These included NFEC (1986), Hammond and others (1992), Das (1994), and USDA (1994).

Many assumptions were involved in the factor-of-safety (FS) calculations:

Failure: Failure is assumed to occur at the soil-bedrock interface during the period between December and April (the wettest months of the year).

Thickness: The soil survey (Cahoon, 1985) lists thicknesses for most soils. For some soils, however, the thickness is listed only as >60 in (152 cm). Based on conversations with USDA Natural Resources Conservation Service personnel, the thickness for those soils was assumed to be 96 in (244 cm).

Density: Soil densities in Cahoon (1985) are tabulated as "moist bulk density" and listed as a range. USDA (1996) notes that "moist bulk density" is the density measured at "field" moisture content. Because most field work is done in the summer, when the soils are thoroughly dried, it was assumed that the dry bulk density for FS calculations was the average of the "moist bulk density" range given in Cahoon (1985). Because it is assumed that the earthquake occurs during a wet period, the unit weights used in the FS calculations assume 90% saturation.

Cohesion: The following assumptions regarding cohesion were made: (1) For sandy and gravelly soils (SM, SW, GM, GW) with clay contents of <30%, cohesion = 2.4 kPa (50 psf). For these soils with >30% clay, cohesion = 4.8 kPa (100 psf). (2) For cohesive materials, a value of 28.7 kPa (600 psf) was assigned to soil types MH, ML, and CL. Note that silts (MH and ML) are considered to be cohesive materials. High-plasticity clays (CH) were assigned a cohesion of 22.5 kPa (470 psf). Neither the extra strength provided by tree roots nor the tree surcharge was considered in the analysis.

Water table: If the soil survey (Cahoon, 1985) described the soil as well drained, the water table was assumed to be below the soil-bedrock contact. If the depth to the water table for some period during the year was given as a range, the water table was assumed to be at the minimum depth in the range.

FS calculations were performed in MapInfo™ for all slopes.

Once the factor of safety for any slope element is known, it is possible to calculate the critical acceleration a_c (Newmark, 1965). The critical acceleration is the acceleration required to overcome frictional resistance and initiate sliding. It is calculated from the following equation (Newmark, 1965):

$$a_c = (FS - 1)g \sin(\alpha)$$

where a_c is the critical acceleration in terms of acceleration due to gravity, *FS* is the factor of safety, *g* is the acceleration due to gravity (equal to one in this equation), and α is the angle from the horizontal by which the center of the mass of the potential landslide block first moves. For a translational slide, assuming that the ground surface is parallel to the failure surface, α is the slope angle.

Once the critical acceleration is known, the design earthquake (M 6.5 at 10 km) can be used to predict the amount of expected displacement for the input ground motion. In a classic Newmark (1965) analysis, complete time histories of the earthquakes at specific locations are examined, and, for intervals in the time history where the acceleration exceeds the critical acceleration, the record is integrated twice to produce a record of displacement vs. time. However, a modified form of that technique was used in the Klamath Falls study. Arias (1970) developed a relatively simple method of expressing the severity of strong ground shaking, known as the Arias intensity. The Arias intensity (I_a) is the integration over time of the acceleration squared and has units of velocity. Wilson and Keefer (1985) developed an empirical equation that relates Arias intensity to earthquake magnitude and distance to the earthquake source:

$$\log(I_a) = M - 2\log R - 4.1$$

where I_a is the Arias intensity, M is the earthquake moment magnitude, and R is the earthquake source distance in kilometers.

Jibson (1993) and Jibson and Keefer (1993) developed empirical relationships between Newmark displacement (D_N, in cm), critical acceleration (a_c), and Arias intensity (I_a):

$$\log(D_N) = 1.460\log(I_a) - 6.642(a_c) + 1.546$$

This equation was used to determine the expected slope displacement for each grid point in the study area. Finally, the calculated displacement was used to assign each element of the slope grid to a hazard category (None, Low, Moderate, High).

In practical (GIS) terms, the procedure is time consuming but relatively simple. All calculations (factor of safety, Arias intensity, critical acceleration, Newmark displacement) are performed in MapInfo™. In addition, there are two digital files. One contains the soil map for the Klamath Falls study area. The second is the slope map (calculated from the DEM) on a 10-m (33-ft) grid spacing within the study area. Using MapInfo™, we mapped the location of each slope grid point within the soil map. A series of queries was used to assign hazard categories.

Digital files from the three slope methodologies (lateral spread, steep slope, and moderate slope) were combined to produce the final slope instability hazard map shown on the map sheet. When assigning a hazard category to a cell on this map, we used the highest hazard calculated by any one of the methods.

RELATIVE EARTHQUAKE HAZARD MAP

The *Relative Earthquake Hazard Map of the Klamath Falls Metropolitan Area* was created to show which areas will have the greatest tendency to experience damage due to any one hazard or a combination of hazards. Hazard maps were generated for each individual hazard (ground motion amplification, liquefaction, and slope instability). For the purpose of creating the final relative hazard map, the individual-map categories were assigned to zones 0, 1, 2, or 3, with 3 being the greatest hazard. For the ground motion amplification map, amplification of ≤1 ("Low hazard") was assigned to zone 1, amplification of 1.5 ("Moderate hazard") was assigned to zone 2, and amplification of 1.8 ("High hazard") was assigned to zone 3. For the slope instability map, the "No hazard" category was assigned to zone 0, the "Low hazard" category to zone 1, the "Moderate hazard" category to zone 2, and the "High hazard" category to zone 3. For the liquefaction hazard, the two categories, "No hazard" and "Low hazard" were assigned to zones 0 and 1, respectively. For every point (using a 30-m cell spacing) on the map, the zone rating of each individual hazard was squared, and the resulting numbers were added together. Then the square root of this sum was taken and rounded to the nearest whole number. A result of 4 was assigned to Zone A, 3 to Zone B, 2 to Zone C, and 1 to Zone D. While the production of the individual hazard maps is different from previous DOGAMI relative earthquake hazard studies (Wang and Priest, 1995; Wang and Leonard, 1996; Mabey and others, 1997; Madin and Wang, 1999, 2000a–c; Black and others, 2000), the method of production of the final relative hazard map is identical. Thus relative hazard maps produced for the Klamath Falls area are directly comparable to previous studies in the Siletz Bay area, Portland, Salem, Eugene-Springfield, and 28 other urban areas in western Oregon.

According to the way the rating system is designed, areas with a high hazard from a single local effect or areas with a combination of lesser single ratings are assigned to Zone B, the second highest hazard category. Zone A ratings occur as a result of two or more high ratings of local effects. The Zone B category should not be underrated, since it can result from a single very severe hazard.

USE OF THE RELATIVE EARTHQUAKE HAZARD MAP

The *Relative Earthquake Hazard Map of the Klamath Falls Metropolitan Area* delineates those areas where earthquakes present, on average, the greatest hazard. This information can be used to develop a variety of hazard mitigation policies, most of which were mentioned in the introduction. This information, however, should be carefully considered and understood, so that inappropriate use is avoided.

Emergency response and hazard mitigation

One of the key uses of this map is to develop emergency response plans. Areas indicated as having a higher hazard are areas where the greatest and most abundant damage will tend to occur. Efforts and funds for both urban renewal and strengthening or replacing older and weaker buildings can be focused on the areas where the effects of earthquakes will be the greatest. The location of future urban expansion or intensified development should consider earthquake hazards.

Requirements placed on development could be based on the hazard zone in which the development is located. For example, the type of site-specific earthquake hazard investigation that is required could be based on the hazard zone. When the relative earthquake hazard maps are incorporated into the Klamath Falls GIS, they can easily be combined with any of the other land use or hazard information in that system.

Lifelines

Lifelines include road and access systems, including railroads, airports and runways, bridges, and over- and underpasses as well as utilities and distribution systems. The *Relative Earthquake Hazard Map* and its component single-hazard maps are especially useful for expected damage estimation and mitigation for lifelines. The distributed character of lifelines precludes comprehensive site-specific evaluations. These hazard maps allow quantitative estimates of the hazard throughout a lifeline system. This information can be used for assessing vulnerability as well as indicating priorities and approaches for mitigation.

Engineering

The specific quantitative values of any single hazard that were calculated for this map are not a substitute for site-specific evaluations based on subsurface information gathered at a site. The calculated values may, however, be used to good purpose in the absence of such site-specific information, e.g., at the feasibility-study or preliminary-design stage. In most cases, the quantitative values calculated for these maps will be superior to qualitative estimates based solely on lithology or non-site-specific information. Any significant deviation of observed site geology from the geologic model used in the analyses indicates the need for additional analyses at the site.

Relative hazard

It is important to recognize the limitations of the *Relative Earthquake Hazard Map* which in no way includes information regarding the probability of earthquake damage occurring. Rather, it shows that when shaking occurs, the damage is more likely to occur, or to be more severe, in the higher hazard areas. The exact probability that such shaking would occur is yet to be determined.

Neither should the higher hazard areas be viewed as unsafe. Except for landslides, the earthquake effects that are factored into the *Relative Earthquake Hazard Map* are not life threatening in and of themselves. What is life threatening is the way that structures such as buildings and bridges respond to these effects. Locations are not necessarily unsafe or even less safe, but the structures there may be.

The map depicts trends and tendencies. In all cases, the actual threat at a given location can be assessed only by some degree of site-specific assessment. This is similar to being able to say, demographically, that a zip code zone contains an economic middle class, but within that zone there easily could be individuals or neighborhoods significantly richer or poorer.

In summary, some parts of the Klamath Falls area are more prone to earthquake effects than others. These maps provide one way this fact can be taken into account in planning, development, and decision-making.

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