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Earthquake Hazards in the Pacific Northwest of the United States

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APPROACHES FOR SEISMIC-HAZARD MITIGATION BY LOCAL GOVERNMENTS--AN EXAMPLE FROM KING COUNTY, WASHINGTON

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Foreword

This paper is one of a series dealing with earthquake hazards of the Pacific Northwest, primarily in western Oregon and western Washington. This research represents the efforts of U.S. Geological Survey, university, and industry scientists in response to the Survey initiatives under the National Earthquake Hazards Reduction Program. Subject to Director's approval, these papers will appear collectively as U.S. Geological Survey Professional Paper 1560, tentatively titled "Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest." The U.S. Geological Survey Open-File series will serve as a preprint for the Professional Paper chapters that the editors and authors believe require early release. A single Open-File will also be published that includes only the abstracts of those papers not included in the pre-release. The papers to be included in the Professional Paper are:

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Rogers, A.M., Walsh, T.J., Kockelman, W.J., and Priest, G.R., "Earthquake hazards in the Pacific Northwest: An overview

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Nelson, A.R., and Personius, S. F., "The potential for great earthquakes in Oregon and Washington: An overview of recent coastal geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia subduction zone"

Peterson, C. D., and Darienzo, M. E., "Discrimination of climatic, oceanic, and tectonic forcing of marsh burial events from Alsea Bay, Oregon, U.S.A."

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ABSTRACT

In areas of rapid development, local governments have the opportunity to achieve effective reduction of seismic risk by regulatory means. Basic risk-reduction strategies in hazardous zones either limit the intensity of land use or apply more stringent building requirements to the development that occurs. These two strategies can be implemented through a combination of methods, including policy-setting comprehensive plans, policy-implementing functional plans, building codes, and hazard-area delineation and regulation.

King County, Washington, has utilized all of these methods in addressing seismic hazards. The County's experience with hazard-area delineation and regulation, through its "Sensitive Areas Ordinance," is most instructive. Major weaknesses in its present effort include the poor data available from which to map hazard areas and the uneven quality of private consultants' site-specific reports. Recommendations for any local government contemplating a similar effort include a clear articulation of policies regarding basic strategy; zoning designations driven by functional plans that reflect the stated policy; regional hazard mapping that is conservative but credible; and sufficient on-staff geotechnical expertise to adequately establish and implement an effective program in cooperation with private geotechnical and design consultants.

INTRODUCTION

Local governments play a pivotal role in the mitigation of seismic hazards. They establish land-use policies, apply zoning, and review all new development within their jurisdictions. Whether intentionally or not, the policies and ordinances administered by these governments determine the vulnerability of all new development to damage from earthquakes. In established cities, this influence over new development may affect only a small proportion of the total number of structures. Here, risk reduction may require more aggressive efforts to upgrade existing buildings and insure post-earthquake function of utilities and emergency operations. In rapidly growing regions, however, new development may become a significant, or even the dominant, component of the built environment. We focus our attention on these situations, because here the opportunities for effective risk reduction are most promising and most attainable.

Once recognized, reducing seismic hazards for new developments can use one of two broad strategies. If the associated risk is perceived as severe and cannot be reduced, then intensive development can be prohibited through zoning regulations. If the risk is perceived as minor, or can be mitigated to that level, then development with appropriate conditions may be allowed. The choice of strategies reflects a social, rather than a purely technical, judgment about the ultimate severity of that risk. That judgment also is likely to be influenced by the size of the area affected, the certainty of the available hazard data, and the economic impacts of the alternative strategies. In general, even in the most hazard-prone areas of North America, only the strategy of development modification has been actively pursued.

Within either of the two conceptual strategies for hazard reduction, four distinct tools are available to local governments. They apply at different stages and in different ways to land development, but each may have a role as part of an overall effort to reduce seismic hazards.

1. **Comprehensive Plans:** These documents establish land-use and land-development policy throughout a region. They do not regulate land use, in and of themselves; indeed, the area of a comprehensive plan developed by a county may include incorporated cities over which the county has no jurisdiction. These plans are intended to establish the policy by which parcel-specific zoning decisions will subsequently be made. They therefore define which of the two basic strategies, prohibition or modification, will guide future efforts at seismic hazard mitigation.
2. **Functional Plans:** These documents apply zoning regulations over large regions of the issuing jurisdiction. They control allowable land uses and intensity of development for specific parcels within these regions. In theory, functional plans simply implement policies articulated in the comprehensive plan. In practice, they may post-date the relevant policy document to the extent that what is actually implemented reflects subsequent community or political evolution.
3. **Building Codes:** Most municipalities in the western United States have adopted the Uniform Building Code (UBC) as the basis for their building regulations. The seismic provisions of the UBC set standards for new structures. Where no other attention to seismic hazards is given, this measure is implicitly assumed to satisfy any stated (or unstated) policies regarding the minimum acceptable level of safety to be provided to the public. Yet the seismic design section of the UBC addresses only one element of seismic hazard, lateral

acceleration. Any seismic hazards aside from those related specifically to lateral forces on the building structure need to be addressed through other measures.

4. **Zoning Overlays:** Where a jurisdiction knows of, or suspects, the existence of specific areas with an enhanced risk of seismic damage, it may choose to control development in those areas. This approach requires the designation of specific hazard zones by means of an overlay (i.e. an area-specific change to established zoning restrictions) and a procedure to evaluate and condition development proposals that lie in the areas so designated. One such effort, King County's "Sensitive Areas Ordinance," is discussed in detail in the following section.

CASE STUDY--KING COUNTY, WASHINGTON

INTRODUCTION

In the Puget Sound region, unincorporated King County (fig. 1) has probably progressed furthest in specifically addressing seismic hazards on undeveloped land (see May, 1989). The County has used, to varying degrees, each of the four basic approaches to hazard reduction. Its ultimate goal is directed by two policies of the King County Comprehensive Plan, adopted in 1985:

"E-308 In areas with severe seismic hazards, special building design and construction measures should be used to minimize the risk of structural damage, fire and injury to occupants, and to prevent post-seismic collapse."

"E-309 Prior to development in severe seismic hazard areas, builders should conduct special studies to evaluate seismic risks and should use appropriate measures to reduce the risks."

These policies mandate at most modification but not prohibition of development, reflecting the prevailing local attitude towards seismic risk. This approach stands in contrast with the treatment afforded certain other types of geologic hazards, such as active landsliding or coal mine subsidence. In such areas, policies and subsequently adopted restrictions effectively prohibit most development on the constrained parts of the site. Subsequent functional plans have reiterated these two seismic-hazard policies and do not implement land-use restrictions on the basis of seismic risk.

King County uses both area-wide and site-specific approaches to reduce seismic hazards. These approaches predate the 1985 Comprehensive Plan, and thus the Comprehensive Plan policy does not guide but simply reiterates established practice. Area-wide control is provided by the seismic provisions in the Uniform Building Code. Site-specific risk-reduction measures for hazards not addressed by the UBC have been provided by the County's "Sensitive Areas Ordinance", adopted in 1979 and substantially revised in 1990. That ordinance also designates landslide, erosion, and coal-mine hazard areas and provides for studies and site-specific mitigation in an effort to avoid the worst consequences of development in geologically hazardous areas.

The Sensitive Areas Ordinance has proven far more complex in its administration and far-reaching in its implications than simple building codes. We therefore present its elements and its application in some detail, because such an approach to seismic hazard reduction is probably most feasible for a wide range of local governments.

There are several components necessary to any regulatory effort designed to mitigate seismic, or any geologic, hazard. These include:

--Definition of the hazard;
--Characterization of a hazardous set of site conditions;
--Delineation of the hazard zones on a map;
--Screening of proposed development; and
--Review and conditioning of developments in mapped hazard areas.

Each component is described below, both in a general context and in light of King County's specific experience.

HAZARD DEFINITION

Seismic hazards come in a variety of forms. They are generally divided first into the direct and indirect effects of earthquakes. The direct effects are those that result directly from ground shaking, and include displacement, ground rupture, differential settlement, and liquefaction. The indirect effects, often as or more damaging, include landslides, tsunamis and seiches (ocean and lake waves), floods from damaged dams or levees, and fire.

Planning efforts are typically motivated by past earthquakes, and so past experience usually guides the choice of relevant concerns in a particular region. In the Puget Sound area, the 1949 and 1965 earthquakes (Thorsen, 1988) suggest that direct effects, particularly shaking-induced ground failure and shaking on buildings, are of primary concern in this region. The indirect effects of landslides, seiches, and liquefaction were reported in several localities as well but were generally less severe.

CHARACTERIZATION OF HAZARDOUS SITE CONDITIONS

Characterizing hazardous site conditions, when applied to seismic hazards, is primarily the attempt to recognize those areas where the earthquake damage will be anomalously high. Any plot of earthquake damage after a single event shows regions where the damage is as high as in other areas much closer to the epicenter, and sites where those effects appear anomalously low relative to their neighbors (see, for example, Plafker and Galloway, 1989).

The conditions that will control the spatial variability of earthquake-related damage include:

--proximity to active faults,
--proximity to and characteristics of nearby water bodies,
--thickness, character, and stratification of surficial deposits,
--depth to groundwater, and
--site topography.

Any of these factors could in theory be made a part of the basis for seismic zonation of an area (i.e. the discrimination of areas of differing seismic hazard or risk). In practice, some of these determinants are more applicable or usable than others.

In King County, only soil conditions and slope are presently used to identify hazardous areas; other potential criteria are not applied. Historical earthquakes here are relatively deep-seated and no surface trace of active faults in this part of the Puget Lowland have been unequivocally identified, so proximity to known faults is not relevant (despite a few local examples of building setbacks from inactive Tertiary-age faults). Tsunamis and seiches have not caused significant damage in historic quakes.

Soil and substrate characteristics have been long accepted as primary determinants of earthquake damage. Areas underlain by thick deposits of low-strength, low-density soils have commonly been associated with severe earthquake damage (e.g., Bolt, 1988). Such damage may result from liquefaction or amplification of low-frequency seismic waves. In King County, most of the soil has been consolidated to a high density by multiple glacial episodes. The most extensive low-density deposits are therefore in areas where post-glacial sedimentation has filled valleys or depressions in the glaciated ground surface. The Sensitive Areas Ordinance therefore identifies "recent alluvium and organic soils" as indicators of high seismic hazard.

The presence of steep slopes introduces the potential for landsliding during and immediately following an earthquake. For this reason, the seismic provision of the Sensitive Areas Ordinance originally included all slopes steeper than 15 percent as seismic hazards. Unfortunately, the attempt to include areas of both low-density soil and potential slope instability as a single, undifferentiated hazard area on a single map has reduced the usefulness of the present mapping. For this reason, the 1990 revision to this ordinance deletes sloping areas, instead treating seismically triggered landsliding as a part of the landslide hazard review process.

MAPPING OF HAZARD ZONES

Ideally, the representation of seismic hazard zones would be based on complete topographic, hydrologic, geologic, and seismologic information. The risk from the direct effects of ground shaking might be quantified by the maximum horizontal ground acceleration for a quake of a given energy release. The result would be a contour map, based largely on soil and substrate properties. The effect of other, indirect effects could be overlain where relevant in order to define overall levels of risk.

In practice, the data and the resources are rarely available to make such detailed estimates. New mapping is beyond the means of most local jurisdictions; and existing soils and geologic mapping were not specifically prepared to identify seismically hazardous soils. Although a complete data source would show and identify the known types of seismic hazards, including artificial fills, recent alluvial soils, low-density organic soils, thick unconsolidated deposits, and landslide susceptibility, more commonly the information available consists of surface soil types (e.g., county soil surveys), topography, and patchy geologic mapping only. The result is a much more generalized hazard map, discriminating only "good" from "bad". This is true in King County's case (fig. 2), where the presence of either unfavorable soils (i.e. alluvial or organic) or slopes steeper than 15 percent solely define the hazard zone. About 10 percent of the land area within the actively developing parts of the County is so categorized.

Despite these deficiencies, the actual determinants of seismic response in most regions correlate fairly well with soils and slope information. Deep, unconsolidated deposits are most common beneath surfaces of alluvial sediment, which typically include areas of loose organic soil as well. Saturation of these sediments is also common. Steeper slopes correlate fairly well with landslide hazard. Yet use of soils maps may also identify areas where no increased seismic hazard exists, such as shallow pockets of peat on an undu- lating till surface or moderate-gradient hillslopes underlain by competent bedrock. Conversely, other seismic hazards may pass unnoticed, such as low-lying shorelines and areas of recent artificial fill.

SCREENING OF DEVELOPMENT PROPOSALS

Once a map is prepared, affected development proposals must be screened. In King County, that authority was created by the Sensitive Areas Ordinance, which required that virtually all proposals requiring a permit be checked against a map showing "hazardous" and "non-hazardous" areas. The process is quite straightforward; the location of the project is checked on a 1:62,500 map of the hazard zone by the intake permit technician (in the case of building permits) or lead planner (in the case of subdivisions or other large projects). If the project falls within the hazard zone, it is referred to a staff geotechnical specialist for further review.

REVIEW AND CONDITIONING OF PROPOSALS

Once a project has been identified in a seismic hazard zone, the geotechnical reviewer must typically choose among several alternatives:

--Because of the nature of the project, no concern is warranted (e.g., a kitchen remodel without a structural change to the building).

--Despite the project's apparent location within a mapped hazard zone, no concern is in fact warranted (e.g., not actually in the hazard zone because of known mapping error or map-reading error).

--The project lies in a seismic hazard zone, but the seismicity concerns will be adequately addressed in solving other, more severe site constraints (e.g., excessive depth to bearing soil or active landslide threat). This alternative is most commonly chosen for projects in the seismic hazard zones in King County.

--The seismic hazard is in fact a significant concern for the project and requires specific mitigation.

If authority is established, a local government will typically proceed in a similar fashion for either of the last two options, where conditions or requirements beyond the standard zoning and building codes are deemed necessary. The applicant will be directed to hire a professional consultant, typically a geologist or an engineer, to perform a detailed site evaluation and to design an appropriate solution, which will be submitted for review (usually) to the local jurisdiction. Detailed site evaluations are typically required because the existing information regarding site conditions seldom provides sufficient basis for developing appropriate mitigation. Site evaluations typically characterize the groundwater conditions and address the depth, density, and texture of the subgrade soils. For seismic hazards in King County, typical proposed mitigations have included subgrade replacement, alternative foundation systems, or improved site drainage. In many cases these represent engineering solutions to other, non-seismic problems at the site, which have the additional consequence of reducing the seismic hazard to a level equivalent to "non- hazardous" areas.

EVALUATION OF KING COUNTY'S MITIGATION EFFORTS

King County's primary effort to reduce seismic hazards has several key components. A zoning overlay has been established that defines a method for requiring geotechnical evaluation and so achieving additional engineering mitigation. No change (i.e., no reduction) in the intensity of land use is intended or achieved. Relevant seismic hazards have been identified, namely landsliding and ground failure. A map of these hazard zones has been prepared to screen development proposals. Special engineering studies, prepared by the applicant's consultants, offer an assessment of any seismic risk and necessary mitigation. Finally, geotechnical review by the County's own staff maintains consistency and minimum competency of the mitigation(s) finally adopted.

Of these elements, two are particularly weak. The first is the mapping of hazard areas. Critical by virtue of the sheer volume of development activity (over 10,000 permits processed in King County in 1989), the seismic hazard map is imperfectly correlated with zones of actual seismic hazard. King County's current seismic hazard map displays the extent of several Soil Conservation Services soil types that have been identified as being seismically sensitive (Rasmussen and others, 1974). In practice, it has become apparent that many areas designated as hazard areas on this map are not particularly hazardous. For this reason the County is planning to revise the seismic hazard mapping in conjunction with the 1990 update to the Sensitive Areas Ordinance, although the methodology to be used in this revision is still under discussion. Other potentially relevant determinants of seismic hazards have not been fully considered. For example, liquefaction potential is identified only by surface soil types; subregional variability in earthquake intensity, from focusing effects or particularly thick unconsolidated deposits, is nowhere identified. Other potential hazards, particularly seiches or dam breaks, are simply not included.

The second weak element is the reliance on special engineering studies for specific mitigation strategies. The structural and geotechnical engineering community spans a broad range of experience and sophistication in addressing seismic hazards. In the Pacific Northwest, there is little consensus in the geotechnical community on a standard of practice for evaluating site-specific seismic hazards. This is especially apparent in reviewing geotechnical reports for small to moderate-sized projects (residences or small commercial structures). The areas where geotechnical practice is most variable include selection of a design earthquake, the scope of adequate subsurface exploration, and appropriate mitigation measures for identified hazards. King County is fortunate in being staffed for review, but reliance on these outside studies for design is unavoidable. Currently, this County staffing consists of three engineering geologists for all aspects of geotechnical review of development proposals. However, over 25 years has passed since the last major earthquake in the region. Thus, the experience of local consultants is often limited, resulting in reports that vary widely in scope, analytical methodology, and design recommendations.

RECOMMENDATIONS

King County has over 10 years of experience in implementing a program of seismic hazard reduction through regulation of land use and building construction. The following recommendations are largely based on this experience and are offered for consideration by other local jurisdictions contemplating a similar program. Their value, however, will be known only after the next large earthquake in the Puget Lowland, followed by a review of developments that were built under this program.

1. **Establish Clear Policy**

   The jurisdiction's comprehensive land-use plan needs to define clearly the policy towards land development in seismically active areas. Without this foundation, subsequent efforts at hazard mitigation will either lack consistency or establish only *ad hoc* policy. At the level of a comprehensive plan, the existence and significance of the seismic threat should be stated clearly and the types of seismic hazard specific to the jurisdiction should be identified explicitly. Finally, a general framework for hazard mitigation should be laid out, for ultimate implementation through functional plans, building codes, and zoning overlays.

2. **Use Policy and Zoning Tools to Minimize Risk**

   Functional plans, which implement the land-use policies of the comprehensive plan, should reflect both the policy towards and the nature of the seismic hazards. If the hazard is one that can be mitigated during development, then the seismic hazard delineation should be considered a factor weighing against intensive land uses but not precluding all uses. This would apply to areas subject to liquefaction or settlement of uncontrolled fill, for example. Even hazards that can be mitigated should factor into decisions on locating intensive land uses, because of the additional cost of public service to such areas and the potential that mitigation may not be effective. If the hazard is one that cannot be effectively mitigated during development, such as inundation by tsunamis, this consideration should preclude intensive structural land uses (see, for example, Nichols and Buchanan-Banks, 1974). Such areas should be set aside for agriculture, recreation, natural resource production, or other uses that would minimize life and property risks.

3. **Map Accurately and Conservatively**

   Although maps associated with zoning overlays are vital to efficient implementation, community-wide seismic hazard maps are less detailed and less accurate than site-specific studies. For this reason hazard mapping should be represented and understood as a guideline to the general distribution of seismically sensitive areas, rather than a definitive delineation of such areas. Given that the mapping will be approximate, it should err on the side of including too much area in the hazard zone. Errors of this type can be identified during site-specific evaluations. The mapping, however, should not be biased so conservatively that it loses credibility as a useful predictor. It should also seek to incorporate data beyond soil surveys, and it should be updated as new information becomes available.

4. **Encourage Uniform Standards for Study Scope and Quality**
Jurisdictions should encourage a more uniform approach to seismic hazard evaluation by working with design professionals and technical experts to establish some baseline hazard evaluation criteria. In particular, these criteria may include designation of an appropriate design earthquake and establishment of a minimum scope of study for sites in designated seismic hazard areas. Recent revisions to King County's Sensitive Areas Ordinance provide that authority and also allow more stringent criteria for certain critical structures, such as schools, hospitals, and emergency centers.

5. **Provide In-House Expertise**
Effective implementation of a seismic hazard mitigation program requires geotechnical expertise on the part of the jurisdiction as well as on the part of the applicant's consultant. Larger governmental bodies, such as the City of Seattle and King County, can justify maintaining a full-time geotechnical staff. This staff is available to assist in all phases of permit processing in seismic hazard areas, from initial screening to review of construction inspection reports. Other, smaller municipalities will contract out geotechnical review to private consultants, whose overall role in permit processing typically will be more limited. The one step in the permit review process where geotechnical expertise is most clearly required is the evaluation of geotechnical studies submitted by the applicant. This is the stage at which adherence to a consistent minimum standard of practice must be assured. Yet without established, well-founded criteria for such a standard, the final results may fall far short of needs.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1. Location of King County.

Figure 2. An example of seismic hazard mapping, with the "Class III" areas defined and regulated under King County's Sensitive Areas Ordinance (King County, 1987). Maps are published at 1:62,500. This example covers an area of about 3.5 by 6 miles.

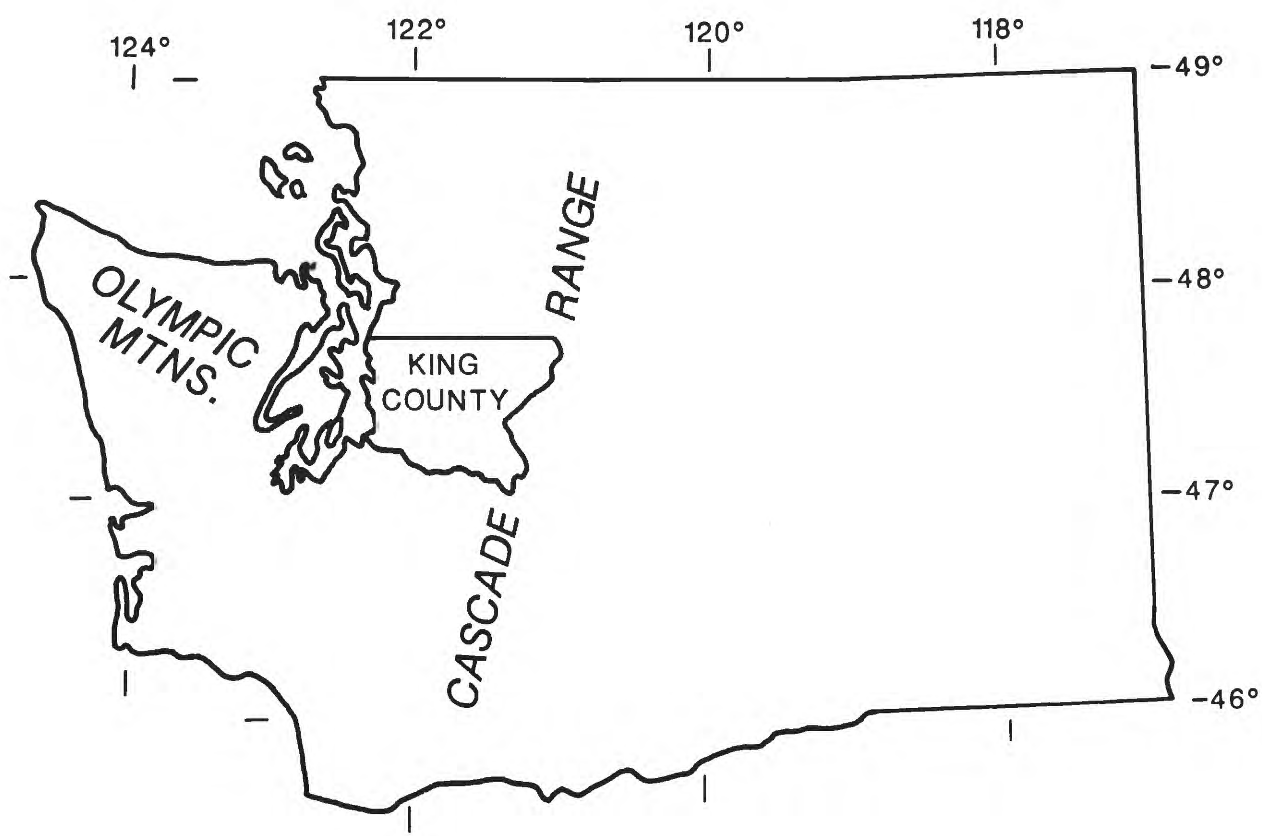
124°
122°
120°
118°
49°
48°
47°
46°
OLYMPIC MTNS.
KING COUNTY
CASCADE
RANGE

Figure 1

Class III Seismic Hazard Areas

Figure 2