BRITISH COLUMBIA

Ministry of Energy and Mines
Resource Development Division
Geological Survey Branch

EARTHQUAKE HAZARD MAPPING FOR LANDUSE AND EMERGENCY PLANNING:

SUMMARY OF CONFERENCE PRESENTATIONS

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EARTHQUAKE HAZARD MAPPING IN THE PACIFIC NORTHWEST: METHODOLOGIES, LAND-USE APPLICATIONS AND EMERGENCY PREPAREDNESS

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PREFACE

This volume is a compilation of papers dealing with the development and early application of earthquake hazard maps in the Pacific Northwest region of North America. The papers include articles from studies conducted in California, Oregon, and Washington states and the province of British Columbia.

The volume stems from an earthquake hazard mapping program that was initiated in British Columbia in 1993 and led to a conference on the subject in 1994. The Seismic Mirozonation Task Group, coordinated by the BC Geological Survey (BCGS), was established in September, 1992 and initially included representatives from the BCGS, the Geological Survey of Canada, BC Hydro, the University of Victoria and Public Works Canada. The first objective of the group was to develop standards and recommended procedures for earthquake hazard mapping in BC (Klohn-Crippen, 1994) and the second was to evaluate the usefulness of earthquake hazard maps for land use and emergency planning purposes (Levson *et al.*, 1994, 1998a, 1998b, this volume). The latter included hosting a conference in conjunction with the UBC Disaster Preparedness Resource Centre. The general purpose of the conference was to review earthquake hazard mapping methods and applications in the Pacific Northwest and to discuss the results of earthquake studies with land use and emergency planners (Levson *et al.*, this volume).

The papers included in this volume were initially presented at this conference but due to budget restraints the project was discontinued. However, on the impetus of the 10-year anniversary of the initiation of the British Columbia earthquake hazard mapping program, these papers have been compiled, edited and published here. Updates to the papers have been provided where possible but readers are referred to the individual authors for more recent information.

The conference consisted of presentations by scientists studying earthquake hazards as well as land use and emergency planners from the Pacific Northwest region. The meeting first focused on the geological and geotechnical aspects of earthquake hazards and hazard mapping and included presentations by the B.C. Geological Survey (Dr. Vic Levson and Paul Matysek), the Geological Survey of Canada (Dr. Dieter Weichert and Dr. Chang-jo Chung), Klohn-Crippen Consultants Ltd. (Bryan Watts) and the Oregon Department of Geology and Mineral Industries (Dr. Matthew Mabey). Examples of various types of applications of earthquake hazard mapping were provided in the second part of the meeting and included presentations by B.C. Hydro (Tim Little), the Portland, Oregon area Metro Planning Department (Dr. Gerald Uba), the City of Seattle (Cliff Marks), Spangle Associates from northern

California (Thomas Vlasic) and the University of Victoria (Dr. Harold Foster).

Participants included over 100 planners as well as geologists, geotechnical engineers and other researchers. Mainly in attendance were emergency and land use planners from municipalities and cities that occur in earthquake prone parts of the province including Burnaby, Vancouver, North Vancouver, Langley, Maple Ridge, Richmond, Surrey, Abbotsford, Parksville, Coquitlam, Lion's Bay, Tofino, Campbell River, Port McNeill, Terrace, Victoria, New Westminister, Nanaimo, Kelowna. Representatives were present from five Regional Districts (Matsqui, Fraser-Cheam, Sunshine Coast, Greater Vancouver (GVRD), Squamish), several provincial agencies (Provincial Emergency Program, B.C. Hydro, Ministry of Education, Ministry of Transportation and Highways, Ministry of Social Services, Ministry of Finance, Municipal Affairs, Ministry of Agriculture, BC Ambulance Service), the Vancouver School Board, several federal agencies (RCMP, Emergency Preparedness Canada, Geological Survey of Canada and Transport Canada) and universities (University of Washington, University of British Columbia, University of Victoria) as well as several geotechnical and other consulting firms.

The papers that follow in this volume provide a summary of some of the conference presentations. The development of one of the first comprehensive earthquake hazard mapping programs in the Pacific Northwest is described by Mabey and Madin (this volume) for the Portland Oregon area. The Portland mapping program includes evaluations of ground shaking amplification, liquefaction, and landslide hazards, that are combined into one relative earthquake hazard map for planning purposes. Subsequent mapping programs in Oregon and Washington states have built on this same approach (e.g. Mabey *et al.*, 1994, 1995, 1997; Palmer *et al.*, 1995; Madin and Wang, 1999, 2000a,b; Black *et al.*, 2000). Applications of earthquake hazard maps to land-use and emergency planning are illustrated in three papers from the Pacific Northwest states of Oregon (Uba, this volume), Washington (Marks, this volume) and California (Vlasic, this volume). Similar papers reviewing land use planning applications in the Portland metropolitan area are provided by Metro (1993, 1996).

The second part of this volume is focused more specifically on British Columbia. The first paper by Levson *et al.* (this volume) provides a review of earthquake hazard mapping in the province and the development of methodologies. A review of the status of current earthquake programs in different jurisdictions within the province including levels of funding, information needs, training needs, cost/benefit analysis information and data requirements is provided by Watts and Hollingshead (this volume). Monahan and Levson (this volume) subsequently describe a case study illustrating the large volumes of data required for earthquake hazard mapping, using the Chilliwack pilot mapping program as a specific example. A discussion of applications of hazard mapping for earthquake disaster exercises is provided by Foster *et al.* (this volume) using a simulation conducted in the city of Victoria for the B.C. Ministry of Health. Another case study, provided by Katrichak *et al.* (this volume), illustrates applications of hazard mapping for mitigating earthquake damage to the BC Hydro utility system on the West Coast of

Canada. The final paper by Chung *et al.* (this volume) discusses the use of quantitative techniques for zoning landslide hazards, a particularly important aspect of earthquake hazard mapping in high relief regions typical of many populated areas within the Cordillera in western North America and South America.

Subsequent to the development of the Siesmic Microzonation Task Group and the earthquake hazard conference in 1994, there were a number of developments in the earthquake hazard mapping program in BC. In 1995/96, a pilot earthquake hazard mapping project, evaluating liquefaction and ground-motion amplification hazards, was conducted in the Fraser River valley near Chilliwack (Levson *et al.*, 1996a,b, 1998a,b). The program included detailed geologic mapping, compilation of geotechnical data from 2400 test holes, field testing, subsurface geological modeling in a GIS, and production of liquefaction, amplification and generalized earthquake hazard maps for technical users and land use and emergency planners. A similar program was subsequently started in the Capital Regional District (Monahan and Levson, 1997, 2001; Monahan *et al.*, 1998) and the Victoria earthquake hazard map series was published in the millennial (Levson *et al.*, 2000; Monahan and Levson, 2000; McQuarrie and Bean, 2000, Monahan et al., 2000a,b,c). In the last few years, the B.C. Ministry of Energy and Mines has been working with the Universities of Victoria and British Columbia on evaluations of earthquake hazards in the Richmond area, especially in relation to dyke stability along the Fraser River. Readers are referred to the B.C. Ministry of Energy and Mines for more information on any of these programs.

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EARTHQUAKE HAZARD ASSESSMENT
THE LOCAL GEOLOGIC COMPONENT

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and
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INTRODUCTION

The factors which contribute to the earthquake hazard and risk at any location can be divided into three general components, which are: the regional earthquake sources and seismic wave propagation characteristics; the local geology's response to, and modification of, earthquake ground shaking; and the type and use of buildings and lifelines constructed at the location. A knowledge and interpretation of regional and local geology is essential for an assessment of the first two components. On a neighborhood-to-neighborhood scale the local geologic conditions contribute as much or more than any other factor to the hazard portion of a risk assessment. Various types of maps can be developed which aid in the assessment of the hazard and risk represented by earthquakes. The type of maps necessary and appropriate for a given area depends on the nature of present and future development. The earthquake hazards mapping program of the Oregon Department of Geology and Mineral Industries in the Portland area is presented as an example. The intended audience is an important factor in determining the final form in which the interpretation of the earthquake hazard is presented.

THREE COMPONENTS OF EARTHQUAKE HAZARD AND RISK

The regional sources of earthquakes are determined by analysis of both the past earthquake activity and through study and analysis of the geology of the region. An approximate estimate of the size, frequency and location of future earthquakes can be made from evidence gathered using both these approaches. The regional seismic wave propagation properties can be estimated by observations of past earthquake shaking. However, quantitative data for detailed analysis of seismic wave propagation is lacking for most of the world. The data available begins with historic records and seismograms of past earthquakes and specific studies of seismic sources. In some areas a brief historic record is all that is available.

Once the seismic waves arrive at a given location the local geology has great potential to modify the shaking and/or respond to the shaking in such a way as to increase the potential for damage and injury. The topography of the ground surface or of buried bedrock may amplify and focus the shaking. The soils (unconsolidated earth material, not bedrock) may also amplify the shaking. Saturated granular (non-clay) soils may liquefy and lose their strength, resulting in ground failure or foundation failure. Landslides or slope failures of various types may be triggered by the shaking. The type and distribution of different rock and soil types together with some information on their material properties is needed to assess the hazards. A standard geologic map is a commonly available starting point. Data on the material properties of the geologic materials may be available from previous studies such as foundation investigations.

The affect that all of the above has on a building or lifeline facility is a function of its design and construction. The injuries and economic impact are dependent on the use and occupancy of the building or facility. The tool necessary for assessing the hazard and risk for this component is an inventory of the buildings and lifelines in an area, which should include the geographic locations and as much detail as possible on the design, construction, use and occupancy. Tax records and building permits are two

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commonly available sources for this type of information.

THE INFLUENCE OF LOCAL GEOLOGY ON EARTHQUAKE EFFECTS

Knowledge and interpretation of regional and local geology is essential for understanding two of the three components which contribute to earthquake hazard and risk. On a neighborhood-to-neighborhood scale the local geologic conditions contribute as much or more than any other factor to the hazard portion of a risk assessment. Likewise, on a city or neighborhood scale the damage will generally be the worst in some areas, regardless of exactly how big and how close the earthquake was.

The most severe damage done by an earthquake is commonly concentrated within limited areas. The damage in these areas is generally caused by one or more of the following phenomena:

- Amplification of ground shaking by a "soft" soil column.
- Liquefaction of water-saturated sand, creating "quicksand" areas.
- Landslides triggered by earthquake induced shaking.

Potential effects at a location (Bolt, 1993) can be evaluated before an earthquake if good data are available on the thickness and nature of the geologic materials (rock and soils) The results of these locally-generated phenomena may range from people waking from their sleep to buildings collapsing or gas lines rupturing, depending on the size and location of the earthquake which causes the shaking. Holzer (1994) showed that 70% of the damage during the Loma Prieta earthquake was associated with amplification of ground shaking, 1.5% was due to liquefaction, 0.5% was due to landslides, while ground rupture or tsunami caused no damage. Only 28% was due to “normal” ground shaking. The liquefaction and landslide numbers are relatively small because these phenomena can only occur in very restricted (and mappable) parts of the area affected by the earthquake.

HAZARD MAPPING METHODOLOGIES

Various types of maps can be developed which aid in the assessment of the hazard and risk represented by earthquakes. The type of maps necessary and appropriate for a given area depends on the nature of present and future development. The simplest earthquake hazard map is a standard geologic map. By showing the distribution of hard rock versus soft rock versus soils, a geologic map delimits the areas where the damage-increasing modifications and responses to earthquake shaking are more or less likely. The general rule is that sites underlain by softer material will be more affected than the hardrock sites. From the starting point of a geologic map, more and more refined interpretations of the hazard are possible. Information on the material properties of the soil and rocks is necessary for refined interpretations. Information about the thickness and types of rocks below the ground surface is also useful. The more that is known about the nature and distribution of rock and soils, the more detailed is the analysis and assessment of the earthquake hazard that can be done.

The sophistication and detail of hazard mapping implemented in any particular area will be determined on the basis of several factors, most importantly the fiscal and personnel resources available to complete the mapping. The techniques based on simply interpreting a geologic map require the fewest resources but give a more uncertain assessment of the hazard. They may be costly in the degree to which they overestimate the hazard and unnecessarily increase the cost of mitigation, but underestimating the hazard is more costly in the event of an earthquake. Other factors include the value of existing or expected development or redevelopment. The availability of necessary data is also important in determining the difficulty in implementing any given methodology. If detailed geologic maps and extensive information on material properties are already available, the cost of producing sophisticated earthquake hazard maps is dramatically reduced. This type of information tends to be more abundant in urban areas.

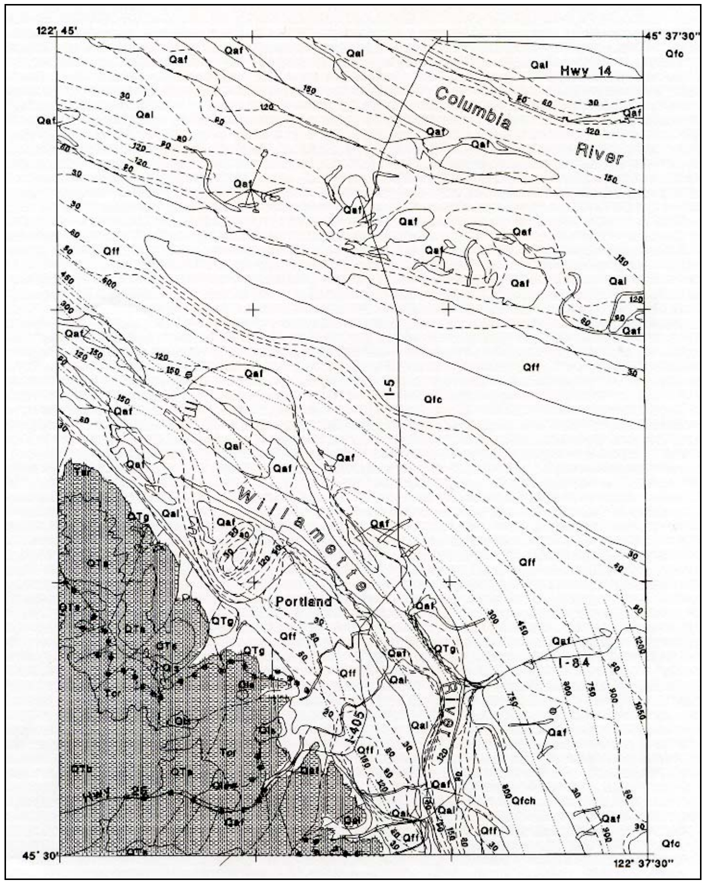

Figure 1. Geologic map of the Portland Quadrangle. (Dashed lines represent isopach intervals, dotted lines represent depth to basement contour intervals, Qaf = Artificial fill, Qal = Alluvium and catastrophic flood deposits, Qff = Fine-grained facies, Qfc = Coarse-grained facies, QTg = Troutdale formation gravels, Tcr = Columbia River basalt group, QTs = Sandy River mudstone equivalent, Qfch = Channel facies, QTb = Boring lavas)

THE PORTLAND EXAMPLE

The earthquake hazards mapping program of the Oregon Department of Geology and Mineral Industries for the Portland quadrangle is presented as an example of the process of earthquake hazard mapping. The understanding of earthquake hazards within the Portland area has been undergoing rapid change in recent years. Published geologic and seismologic studies have detailed the potential for earthquakes from three different sources (Weaver and Shedlock, 1989, Madin, 1990). In Portland, the most common are ***crustal earthquakes***, which occur at depths of 10-15 kilometres below the surface. The few moderate earthquakes that have originated in Portland in its brief recorded history have been this type.

Intraplate or ***Benioff earthquakes*** are the type that severely rocked the Puget Sound region in 1949 and again in 1965. Those who lived in Portland in 1949 may recall that the area suffered some damaging and frightening effects of that earthquake. Intraplate earthquakes occur within the remains of the ocean floor, which has been forced downward (subducted) beneath North America. It is believed that this type of earthquake could occur closer to Portland, perhaps 40-55 kilometres directly beneath the city.

Great subduction earthquakes occur around the world in subduction zones, where continent-sized pieces of the earth's crust are subducted to great depths. These earthquakes are consistently among the most powerful recorded, often having magnitudes of 8 to 9 on the moment magnitude scale. The Cascadia subduction zone, which has long been recognized off the coast of Oregon and Washington, has had no great subduction earthquakes during our short 200-year historical record. However, in the past five years, a variety of studies have found widespread evidence that these great events have occurred repeatedly in the past, most recently about 300 years ago in the latter part of the 17th century. The best evidence available suggests that these great earthquakes have occurred, on average, every 350 to 700 years, and there is every reason to believe that they will continue to occur in the future.

Portland is threatened by all three types of earthquakes, but there is currently uncertainty about exactly where, how often and how big future earthquakes will be. This uncertainty has made it difficult to rely on a traditional probability-based (probabilistic) approach to hazard mapping, which would provide information about absolute levels of ground shaking to be expected and how often such levels might be reached. When reliable probabilistic ground motion maps become available, they will be integrated with the relative hazard mapping presented here.

GEOLOGIC MODEL

The first step toward assessing the hazard in the Portland area was to construct a geologic map (Figure 1). The geology of the Portland quadrangle is relatively simple, with two distinct geologic domains. One domain consists of the Portland Hills, which rise to elevations more than 300 metres (1000 feet) in the southwest corner of the quadrangle. The second domain is comprised of the relatively flat Portland Basin, which extends to the north and east of the Portland Hills (Madin, 1990). In both domains, the local bedrock consists of relatively hard, dense basalt flows of the Columbia River Basalt Group. In the Portland Basin domain, this rock unit lies beneath several layers of younger, softer sedimentary rock composed of sand, silt, clay and gravel. The Sandy River mudstone lies directly above the basalt and is composed of soft siltstone, sandstone and claystone up to several hundred metres thick. Troutdale Formation gravel covers the Sandy River mudstone and is composed of pebble and cobble conglomerate up to 100 metres thick. The Troutdale Formation is covered with sand, silt and gravel deposited by catastrophic floods at the end of the last ice age. The flood sediments are divided into a lower gravel layer, and an upper sand and silt layer. The flood sediments are covered by alluvial sand, silt and clay along and adjacent to the channels of the Willamette and Columbia rivers.

In the Portland Hills domain, most of the geology is simple. The basalt bedrock is covered by wind-blown silt (called loess) up to 30 metres (100 feet) thick. In the southwest corner of the map, near Sylvan, there are deposits of siltstone and young Boring lava between the bedrock basalt and the wind-blown silt.

Thousands of boreholes drilled for water wells and foundation investigations etc. were used to determine the thickness of each of the six geologic units over the entire map area, and these data were entered into a GIS database. Where there were not enough boreholes, seismology was used to determine the thicknesses. This information defines the soil and rock beneath any location on the map so that their effect on earthquake damage can be assessed.

The results of this work were published in 1990 (Madin, 1990) for eight 1:24,000 scale quadrangle maps including the Portland quadrangle. The maps portray the distribution of the geologic units occurring at the surface and contours of the thickness of Quaternary units as well as depth to bedrock (Figure 1). The text accompanying these maps explains the general implications of the information for earthquake hazards.

To assess the effects of the local geologic materials, more than just their thickness is needed. Many of the required measurements are acquired in the normal course of a foundation investigation such as the standard penetration test (SPT). Thus, the needed information is available from many of the same sources as the thickness information.

In addition to the data acquired from existing borehole records, many of the assessment techniques require information on shear-wave velocities. Measurements of shear-wave velocity were made at twenty carefully selected sites. About half were within the map area and half were at other locations in the Portland area.

All this information combines to give a detailed computer map of what lies beneath the surface throughout the map area. With this information the response to earthquake shaking at a specific location can be assessed.

GROUND SHAKING AMPLIFICATION

Bedrock ground shaking caused by an earthquake can be modified by the soils and soft sedimentary rocks near the surface. This modification may increase the strength of shaking (or alternatively decrease it) or change its frequency. For example, the shaking could be changed from a rapid vibration (like a jet flying low overhead) to a long rolling motion (like being on a boat in a storm). The nature of these modifications is determined by the thickness of the geologic materials and their physical properties such as shear-wave velocity. A rough estimation technique has been proposed (Borcherdt, 1994) whereby an estimate of the local amplification could be mapped using information on average shear-wave velocities and either the surficial geology, or the three dimensional geology.

Using these same parameters, sophisticated computer programs can estimate the effects of the local geology on ground shaking with greater reliability. In this way, areas where the ground shaking will <u>tend</u> to be strongest have been identified. The computer program SHAKE 88 (Schnable, 1972) was used for the map of the Portland quadrangle (Mabey *et al.*, 1993).

Mapping of the amplification resulting from near-surface geology has been done previously in other areas such as San Francisco Bay and Mexico City. Damage to the Nimitz Freeway during the 1989 Loma Prieta or "World Series" earthquake was localized by near-surface amplification. Fortunately, the areas of the Portland quadrangle that are affected by large amplifications are small. The magnitude of the most severe amplifications in the Portland Quadrangle appears unlikely to be as great as has been found in other parts of the world. Unfortunately, one of the areas with the greatest amplification includes parts of downtown Portland.

The three amplification hazard categories were defined as follows:

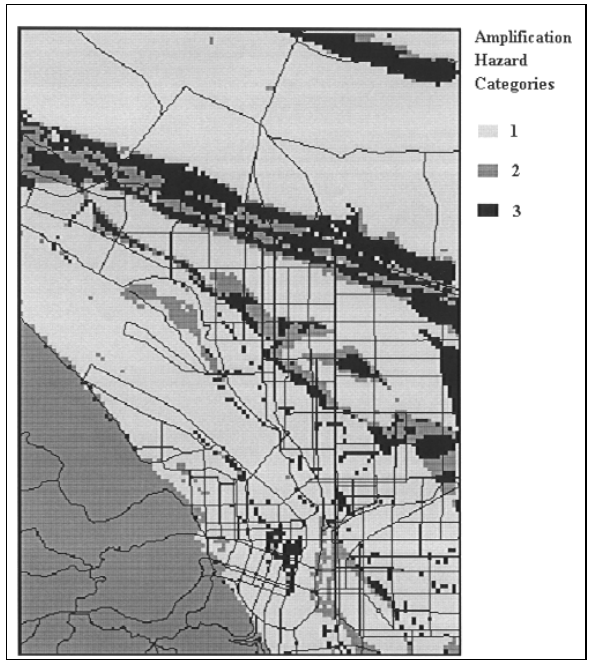

Figure 2. Relative ground shaking amplification hazard categories for the Portland Quadrangle.

1) Areas with amplification less than 1.25
2) Areas with amplification between 1.25 and 1.50
3) Areas with amplification greater than 1.50

Figure 2 is a three-category map of relative amplification hazard for the Portland quadrangle.

LIQUEFACTION ANALYSIS

Liquefaction is a phenomenon in which shaking, or otherwise disturbing, a soil causes it to rapidly change its material properties so that it begins to behave like a liquid. Soils that have this problem tend to be fairly young, loose granular soils (as opposed to clay) that are saturated with water (NRC, 1985). Unsaturated soils will not liquefy, but they may settle. If liquefaction is induced by the earthquake shaking, several things can happen. The liquefied layer of soil and everything lying on top of it may either move downhill or oscillate back and forth with displacements that are large enough to rupture pipelines, move bridge abutments, and pull buildings apart. Light objects such as underground storage tanks may float up toward the surface, and heavy objects, such as buildings, sink. These displacements can range from a few centimetres to several metres. Obviously, if the soil at a site liquefies, the damage caused by the earthquake is significantly increased from that resulting from shaking alone.

Soils that are subject to liquefaction can be identified, as can their thickness and their influence on the severity of the effects. The simplest approach is to identify the geologic units which are sufficiently loose and free enough of clay to liquefy. This information can then be combined with maps of depth to the water table and actual quantitative analysis of the susceptibility of the units to liquefaction. Finally, total thickness of liquefiable material found in boreholes can be used to map the hazard in still greater detail. This was done for the Portland Quadrangle (Mabey *et al.*, 1993).

Similar maps of liquefaction hazard have been produced in many areas including Seattle, Washington and Salt Lake City, Utah, where they have been incorporated into emergency response planning and development planning (Grant *et al.*, Anderson *et al.*, 1986).

The three liquefaction hazard categories were defined as follows:

1) Areas with materials that are liquefiable when they are intermittently saturated.
2) Areas with a thickness of liquefiable material (for the scenario earthquake) greater than 0 metres and less than 6 metres (20 feet) where the water table is 4.5 metres to 9 metres (15-30 feet) deep.
3) Areas with a thickness of liquefiable material (for the scenario earthquake) greater than 9 metres (30 feet) where the water table is 4.5 to 9 metres (15-30 feet) deep or areas with liquefiable material where the water table is less than 4.5 metres (15 feet) deep.

NOTE: Areas of 6 to 9 metres thickness are unmappably small and therefore do not appear on the map

Figure 3 is a three-category map of relative liquefaction hazard for the Portland quadrangle.

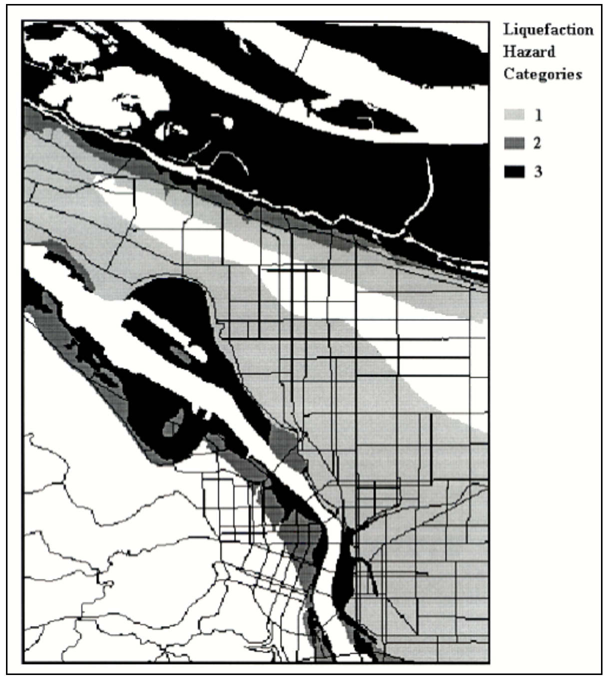

Figure 3. Relative liquefaction hazard categories for the Portland Quadrangle.

LANDSLIDE ANALYSIS

The shaking resulting from an earthquake tends to cause existing landslides to move, as well as generating forces that create new landslides. Because of this, known landslide masses have been identified as areas with a potential for severe damage during an earthquake. In addition, the steepness of a slope, and soil thickness, are indicators of the stability of a slope. These two factors have been used to estimate the risk of landslides in those parts of the hills that have no existing slides (Brabb, 1987, Varnes, 1978). In fact slope, which can be easily mapped using a simple topographic map, by itself is a fair measure of slope instability hazard. Using the slope and soil thickness information, a factor of safety against sliding was computed for the West Hills portion of Portland quadrangle (Mabey *et al.*, 1993). The hazard was rated based on these results.

This type of landslide mapping was pioneered in the San Francisco Bay area and has been applied in many areas of the world where landslides are common.

The three slope instability hazard categories were defined as follows:

1) A slope greater that 15% (8.5°)
2) A factor of safety against sliding of between 2.0 and 1.25, using a pseudo-static coefficient of 0.15 g.
3) A factor of safety against sliding of less than 1.25, using a pseudo-static coefficient of 0.15 g or the vicinity of an existing landslide.

Figure 4 is a three-category map of relative slope instability hazard for the Portland quadrangle.

OTHER HAZARDS

Other hazards have not been factored into the relative hazard map. Certainly bodies of water (*e.g.* the Willamette River) are subject to waves, known as seiches, being generated by the ground motion accompanying an earthquake. The effects of a seiche are limited to the immediate vicinity of the water body, but the size of the waves can be damaging and deadly. The effects of any tsunami generated in the ocean by an earthquake are likely to be small along the rivers in the Portland area but are of great concern elsewhere. Although many faults have been identified and mapped in the Portland area, the hazard represented by the rupture of specific faults is still unknown. The "activity" of these faults will be defined by studies in coming years. It should be noted that the magnitude 6 to 6.5 range is the threshold at which fault rupture begins to be commonly apparent (Bonilla *et al.*, 1984). Because 6 to 6.5 is the probable maximum magnitude for any crustal earthquakes in the area, fault rupture is likely to be absent altogether or will be of very limited extent. Therefore, the number of structures affected and the severity of the effects will also be limited.

The relative earthquake hazard map concept was created to show which areas will have the greatest tendency to experience damage due to any one of, or a combination of, these hazards. Hazard maps were generated for each of the individual hazards on which areas of the map were categorized as zones 0, 1, 2, or 3 with 3 being the greatest hazard. For every point on the map, the zone rating for each individual hazard (amplification, liquefaction and landslide) 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 is assigned to category A, a result of 3 is assigned to category B, a result of 2 is assigned to category C and a result of 1 is assigned to category D.

For example, suppose that the block on which your house sits had a ground shaking amplification rating of 2, a liquefaction rating of 2, and a landslide rating of 0. We would take the

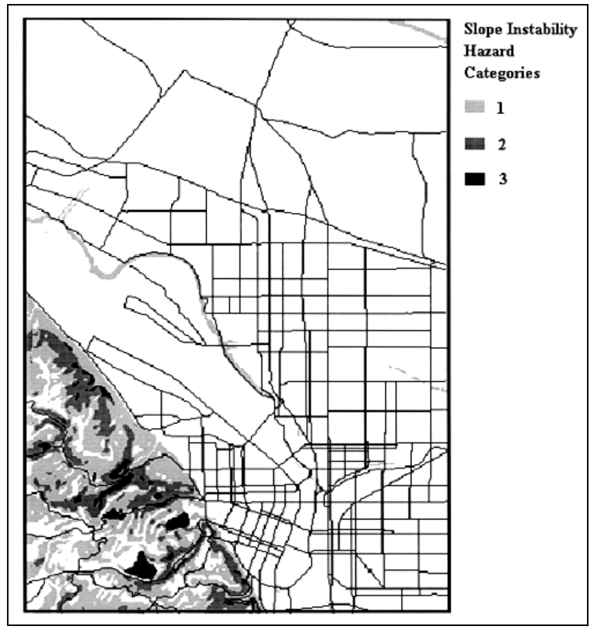

Figure 4. Relative slope instability hazard categories for the Portland Quadrangle.

ground shaking amplification rating of 2 and square it to get 4. We would do the same with the liquefaction rating and also get 4. Squaring the landslide rating of zero gives zero. So we add 4 + 4 + 0 to get a sum of 8. The square root of 8 is 2.8284, which rounds to 3 or a rating of B for this hypothetical block. As B is the next to the highest rating, this block is thus of greater concern, from an earthquake hazards standpoint, than would be a block a few miles away that has a rating of D.

It should be pointed out that, with this system, a numeric result of 0 or 5 is theoretically possible, but in practice neither is likely. If such a rating were to result, it would have been assigned to the D or A group, respectively.

The actual relative hazard map zones were smoothed using three iterations of a low pass filter in the GIS. Following each application of the filter, values of any cells which were reduced by the filtering process were increased back to their original value. The end result was a map with 12.0% of its area being in hazard zone A, 40.9% in hazard zone B, 35.5% in zone C and 11.5% in zone D. These numbers indicate a balanced distribution of the geographic area into the four hazard zones. There is a slight skew towards the higher hazard zones but because large portions of zone B are under water, this is justified and of little effect on land use and emergency response planning.

The result of this system is that areas with a high hazard from a single local effect are assigned the rating of B (next to highest overall hazard rating) as well as areas with a combination of lesser single ratings. The rating of A represents a combination of high ratings. The hazard category B should not be under-rated as it can result from a single hazard being very severe. This approach to arriving at a single relative hazard map is novel, but has the benefit of quickly delineating areas of greater earthquake hazard without requiring a detailed understanding of the individual hazards or how they are measured.

USE OF RELATIVE EARTHQUAKE HAZARD MAP

The Relative Earthquake Hazard Map (Figure 5) delineates the areas where earthquakes present the greatest hazard on average. This information can be used to develop a variety of hazard mitigation policies. It also can be used inappropriately, without careful consideration and a thorough understanding of the map and its basis. One of the key uses for this map is to develop emergency response plans. The areas indicated as having higher hazard will be the areas where the greatest and most extensive 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 certainly 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. As the Relative Earthquake Hazard Map is part of the regional government's Regional Land Information System (an ArcInfo based GIS), it can easily be combined with any of the other land-use or hazard information in that system. Digital maps and databases that display all the hazard analyses that have been done are planned for the future.

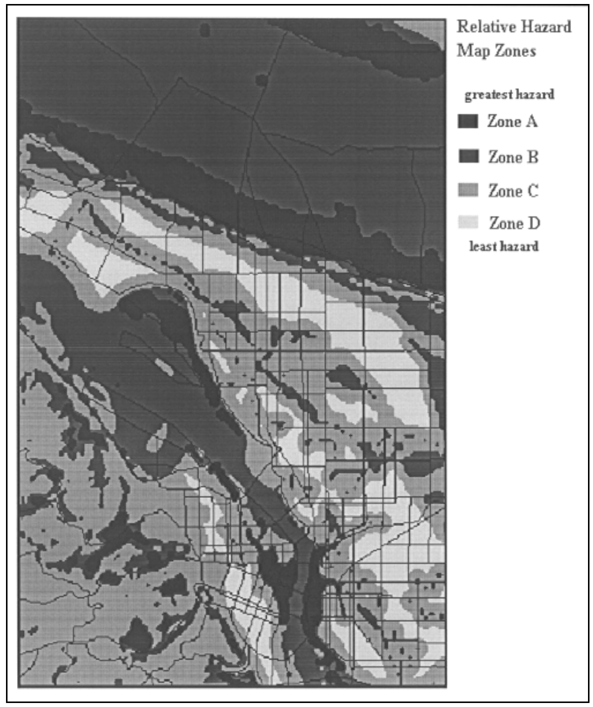

Figure 5. Relative earthquake hazard map of the Portland Quadrangle.

It is equally important to recognize the limitations of the Relative Earthquake Hazard Map. It in no way includes information with regard to the probability of damage occurring. Rather, it shows that when the area is shaken by an earthquake, the damage is more likely to occur or be more severe in the higher hazard areas. The exact probability of such shaking occurring 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 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.

CONCLUSION

In summary, just as some parts of the world are snowier than others, thus influencing the type of planning and development that occurs, some parts of any region, city or neighborhood are more prone to earthquake effects than others. These hazard maps provide one way this fact can be taken into account in planning, development and decision making. The specific methodology applied to any given area will depend on present patterns of development and expected future development and redevelopment. The high effort methodology that has been applied to the Portland quadrangle is being applied to the remainder of the Portland metropolitan area and other urban centres in Oregon as quickly as resources permit. Simpler techniques may be applied in less urbanized areas. All of the mapping is also being combined with assessments of seismic sources and wave propagation, and comprehensive inventories of buildings and lifelines to generate a detailed picture of the hazard and risk that earthquakes represent. This is done with confidence that it will facilitate the economic and efficient mitigation of earthquake hazards and that the reduction of future losses due to earthquakes will far exceed the cost of making the maps.

ACKNOWLEDGMENTS

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The countless organizations, companies and individuals made contributions of time, equipment, information, access, and expertise without which the Portland Earthquake Hazard Mapping project would have been impossible. To them I give my thanks.

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APPLICATIONS OF EARTHQUAKE HAZARD MAPS TO LAND-USE AND EMERGENCY PLANNING

EXAMPLES FROM THE PORTLAND AREA

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OVERVIEW

The extent to which we understand "below ground" (geological) and "above ground" (buildings and infrastructures) seismic risks is a key issue in developing appropriate earthquake mitigation and preparedness techniques, and policies that could minimize the effects of a major disaster event such as an earthquake. Cooperation among the urban and emergency management planners, developers, and owners of public and private structures is also vital for developing effective earthquake mitigation, preparedness, response and recovery strategies. Natural disasters, such as earthquakes, do not usually occur within the geographical boundaries of a local community or a service area of single utility agency. Costs associated with recovering from a major natural disaster are usually borne by more than the local community. Hence, rigorous disaster planning, such as seismic risk identification on a regional basis, and cooperative, integrated and comprehensive regional emergency planning can spread today's scarce disaster management funds across many jurisdictions.

The Oregon Department of Geology and Mineral Industries (DOGAMI) and Metro[1] embarked on the Regional Earthquake Hazard Identification Project to develop and provide an earthquake hazards data file system, based on a geographic information system (GIS) linking data concerning geology, buildings, lifeline systems and critical facilities, and capable of generating estimates of property damage and loss. This data file system will support all phases of earthquake disaster planning in the Portland metropolitan area. Metro's mission includes bridging the gap between information technology and policy decision-making at the regional emergency management level. The agency's effort is directed at: a) developing hazard data file systems with tools that can support earthquake mitigation, preparedness, response and recovery planning and real-time response; b) estimating possible property damage and loss; c) developing model land-use mitigation regulations that local governments can adopt and implement; d) assisting in the development of a regional emergency management plan and system; and e) involving public and private sector organizations in determining how to develop, maintain, and share the hazard data file systems.

In 1993, Metro collaborated with local governments in the Portland metropolitan area to form the Regional Emergency Management Group (REMG) for the Portland area through an intergovernmental agreement. The group is made of up of two bodies, the Regional Emergency Management Policy Advisory Committee (REMPAC) and Regional Emergency Management Technical Committee (REMTEC). The REMG has become the catalyst for initiating, developing and implementing disaster mitigation, preparedness, response and recovery strategies and plans in the region. Table 1 illustrates the issues and process that made the formation of REMG possible.

METHODS OF HAZARD IDENTIFICATION

Geologic hazards data for liquefaction, ground shaking amplification and slope instability were collected by the DOGAMI in the area described by the Portland 7½ minute U.S.G.S. quadrangle map. The methods of collecting and mapping these hazards are described in other reports (Mabey *et al.*, 1993) and (Mabey and Madin, 1993).

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1 Metro is the only directly elected regional government in the United States. About 1 million people live within Metro's boundaries. The geographic area of Metro is 1194 square kilometers (461 square miles) and includes 24 cities in the urban portion of three counties and 151 special districts. Metro's primary responsibilities include urban growth management, transportation, zoo and recreational facilities management, and green spaces and solid waste planning management.

Table 1. Formation of the Portland area regional emergency management group.

MAJOR ISSUES

1. Some emergency management issues are better dealt with at the regional level (and can be determined by separating local issues from those that are regional in scope).
2. There is no clear legal authority for coordinating emergency management planning at the regional level.
3. There is no organ of local government in the region to provide policy decision-making that would enhance disaster preparedness.
4. It is not known if the emergency management plans of local governments including the Red Cross are compatible and consistent.

PROCESS

1. Emergency managers in the four-county area around Portland recognized the major issue and expressed interest and willingness to find solutions to them.
2. Emergency managers developed a work plan that summarized existing emergency management programs and responsibilities in the region. The work plan also identified funding sources and defined the broader emergency management issues that are regional in scope, developed broader regional goals and proposed how a regional emergency management program could be developed, including the formation of the Regional Emergency Policy Advisory Committee and the Regional Emergency Technical Committee.
3. The work plan was used by emergency managers to educate elected officials and others of the need for developing a coordinated regional emergency management program and policy-making body.
4. Governing bodies of represented jurisdictions used resolutions (or ordinances) to: a) accept and recognize the work plan as the basis to formally address common policy issues faced in regional disasters by emergency management organizations in the Portland area, and b) signed an intergovernmental agreement that committed them to participate in the formation of the advisory committee to develop a regional plan and system.
5. The formal inaugural meeting of the new Regional Emergency Management Group (REMG) was held; the REMG is made up of the Regional Emergency Management Policy Advisory Committee (REMPAC) and Regional Emergency Management Technical Committee (REMTEC).
6. An annual work plan was developed with time line and project leaders for developing the regional emergency management elements identified earlier. This task includes identification of key policy recommendations for REMPAC to consider for adoption. Examples of policy actions include adoption of a regional emergency operation center and a regional process for activating the emergency broadcast system.

Metro's effort in hazard identification is devoted to assessment of buildings, lifeline systems and critical facilities, in the region for potential hazards. The assessment of buildings entails rapid visual screening of buildings, including specified critical facilities to identify those buildings that might pose potentially serious risk of loss of life and injury and severe disruption of community services in the event of a major earthquake.

Through the joint efforts of Metro, City of Portland Bureau of Buildings and Portland State University Civil Engineering Department, over 9000 nonresidential (commercial) buildings were assessed. Public and private utilities, the City of Portland, Multnomah County, hospitals and the Portland School District were very cooperative in collecting and mapping the major components of lifeline systems and critical facilities in the Portland quadrangle. Data have been collected for the following systems and critical facilities: electric power, sewer and storm drainage, telecommunications, bridges, water, hazardous materials storage, hospitals, ambulance, fire stations, police stations, schools and dams in the region.

The buildings, lifeline system and critical facilities data were integrated into Metro's GIS-based Regional Land Information System (RLIS). Maps displaying the geographic distribution of these structures were overlaid on geologic hazard maps and used for vulnerability analysis (Figure 1).

APPLICATION OF EARTHQUAKE HAZARD DATA FILES (AND MAPS) TO LAND-USE PLANNING

To obtain suggestions concerning how the earthquake hazard data files and maps may be used, a workshop was organized in January 1993 that brought together about 250 emergency planners, engineers, land-use planners, elected officials, citizens, and insurance and banking representatives. The workshop provided the following land-use related mitigation questions and answers concerning the uses of the hazard data files and maps.

<u>Land-use Planning Questions</u>

- Should all current comprehensive land-use plans be re-evaluated?
- Can the geologic hazards maps actually be used for zoning?
- How do you deal with properties at the boundaries of the geologic hazard zones?
- Is the Oregon statewide land-use planning Goal 7 (Areas Subject to Natural Disaster and Natural Hazards) adequate to cause any impact on the utilization of the geologic hazard maps?
- Should site-specific studies be required of land developers in the higher hazard areas?

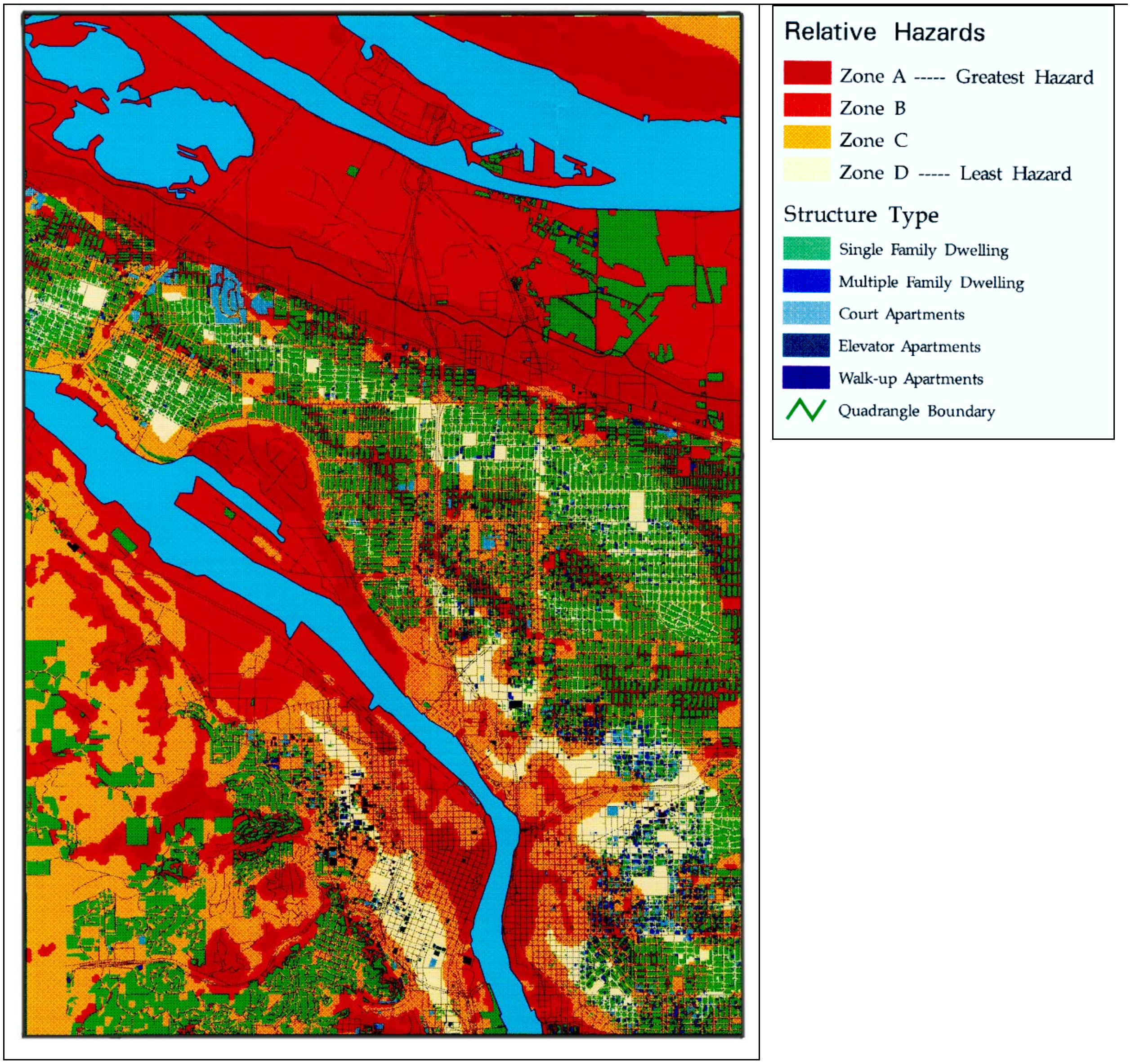

Figure 1. Residential buildings by structure and type and relative earthquake hazards.

Land-use Planning Answers

- Maps based on the individual geologic hazard should be utilized to guide land-use policy for that specific hazard, not a combined hazard map.
- Overlay maps with the floodplain map to get the overall picture of land-use hazards.
- Treat the maps as advisory only, because they are not adequate to mandate land-use actions and zoning. More information is needed.
- Use these hazard maps in the permitting process.
- Limit critical facilities such as hazardous facilities, schools and hospitals in the high hazard areas.
- Maps should be used to guide future development, especially of lifelines.

The above issues provided the guidelines used by Metro to initiate regional land-use planning efforts to mitigate seismic hazards in the Portland area. Subsequently, Metro and a land-use consulting firm based in California (Spangle Associates, 1996) worked with an advisory committee made up of land-use planners, building officials, developers and other interested partners to develop model land-use regulations for mitigating seismic hazards. The project purpose was to define the options for applying the earthquake hazards data files and maps directly to land development decisions in the Portland region. Development of regulations that could be used to mitigate seismic risks requires the correlation of geotechnical information (ground motion amplification, liquefaction susceptibility, and lateral spread displacement and dynamic slope instability) with existing land-use and building types.

Defining these correlations has helped to establish a reasonable procedure for justifying why and how earthquake hazard maps should be included in the range of factors considered by land-use. The fundamental concept that guided the team is as follows:

seismic hazard + land-use = risk

In other words, the risk of damage from an earthquake depends on the presence of land subject to failure from an earthquake and vulnerable land-use patterns (land plus its infrastructure, buildings, building content and function). Risk can be reduced by avoiding or modifying the land subject to failure by constructing buildings and facilities to withstand the effects of earthquakes, or by proscribing the development of a vulnerable land-use pattern.

The intent of this is to develop model regulations that are clear and flexible and that local governments can adopt and incorporate into land-use policies. Major features of these regulations include provisions and guidelines for action, such as adoption of the hazard maps as accepted maps of earthquake hazards for a local government, adoption of earthquake performance objectives and acceptable risk levels and matrices correlating land-uses to hazard zones, and refinement of hazard maps by property owners as required by a local community.

The issue of how local governments should be encouraged to use the model regulations and which agency should enforce the regulations will be explored by the advisory committee. Currently, there are very limited tools for enforcing any seismic safety regulation. One of the 19 goals of the Oregon statewide land-use planning laws (Goal 7) is to keep developments away from areas of natural disaster and hazards, or allow developments only with appropriate safeguards. The Oregon Land Conservation and Development Commission (LCDC) expect local governments to accommodate this goal as information on natural hazards (such as the earthquake hazard maps) becomes available. Periodic review of local governmental "Comprehensive Land-use Plans" by LCDC, to ensure that local plans include new information such as earthquake hazards and population changes, could be an opportunity to enforce land-use regulations for mitigating earthquake risks.

APPLICATION OF EARTHQUAKE HAZARD DATA FILES (AND MAPS) TO EMERGENCY MANAGEMENT

Another project initiated by Metro and DOGAMI (1993) is the use of the hazard data file systems to estimate property damage and loss from possible future earthquakes. A pilot study was conducted in a 60-square block area of Portland that includes 441 parcels of land with 185 buildings, railroad tracks and lifeline systems. The pilot study assessed building damage and casualties as a result of a hypothetical moderate earthquake. The study found that damage would equal approximately 12 percent of the total building value. It also provided an indication of the variations in expected loss by structural types of buildings, potential liability issues, and areas requiring greater emergency response priority following an earthquake. Damage and loss assessments will be evaluated throughout the region, at the county level, as additional data are collected.

Damage and loss estimation methodology could be used to support many aspects of emergency management planning and implementation. The methodology and results could be used to forecast demand on health care facilities, estimate shelter demand and amount of debris that will be generated, based on expected damage in buildings and infrastructure. The results could also be used to determine potential debris disposal and recycling sites, locate emergency transportation routes and potential utility outages. The data analysis could also support emergency resource allocation planning activities such as the pre-planned dispatch of building inspectors to areas where high damage and failure of facilities are likely to occur.

Disaster response planning (such as earthquake exercises and response drills) could also be guided by the maps. During the disaster recovery period, some of the major issues that communities have to deal with include tightening of existing ordinances and stricter enforcement of existing laws. The hazard data files can be used to evaluate the extent of likely disaster damage and suggest how existing ordinances should be modified.

CONCLUDING REMARKS

The success or failure of applying an earthquake hazard information system and map within a defined region may be dependent on factors such as the authority or responsibility of agencies supplying and using the information, information distribution techniques, status and structure of existing emergency management partnerships, potential for new partnerships, structure of existing land-use and emergency planning programs, and funding. However, the experience in the Portland area suggests that the following elements are also crucial: a) well known source of information and maps; b) availability of staff involved in the development of the maps to speak at public forums; c) ensuring equitable distribution of information and maps among all jurisdictions and agencies in the region; d) recognition of a lead agency that is responsible for articulating map application methods; and e) directing advisory committee efforts to develop a regionally balanced, cost-effective, technologically feasible, and publicly acceptable regional earthquake mitigation and emergency management system.

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APPLICATIONS OF EARTHQUAKE HAZARD MAPS TO LAND-USE PLANNING AND REGULATIONS IN SEATTLE

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BACKGROUND

This paper will discuss three types of mapping efforts conducted by the city of Seattle: 1) the incorporation of geologic hazard information into the city's land-use regulations; 2) the investigation of additional mapped geologic hazard information not yet incorporated into the city's hazard reduction efforts; and 3) the use of information on the location and condition of specific buildings and structures.

Two factors led the city of Seattle to become involved with seismic hazard mapping: 1) its development of Environmentally Critical Areas policies and regulations, including those dealing with geologic hazard areas; and 2) its reception of a grant from the United States Geological Survey, as part of the National Earthquake Hazard Reduction Program (NEHRP), to develop and coordinate policies and programs to reduce earthquake damage and loss of life.

As part of the NEHRP grant work the Seattle Planning Department proposed a model seismic hazard reduction process; this process provides an overall context for the discussion of seismic hazard mapping in this paper. The planning process has three basic phases which are described below and illustrated in Figure 1.

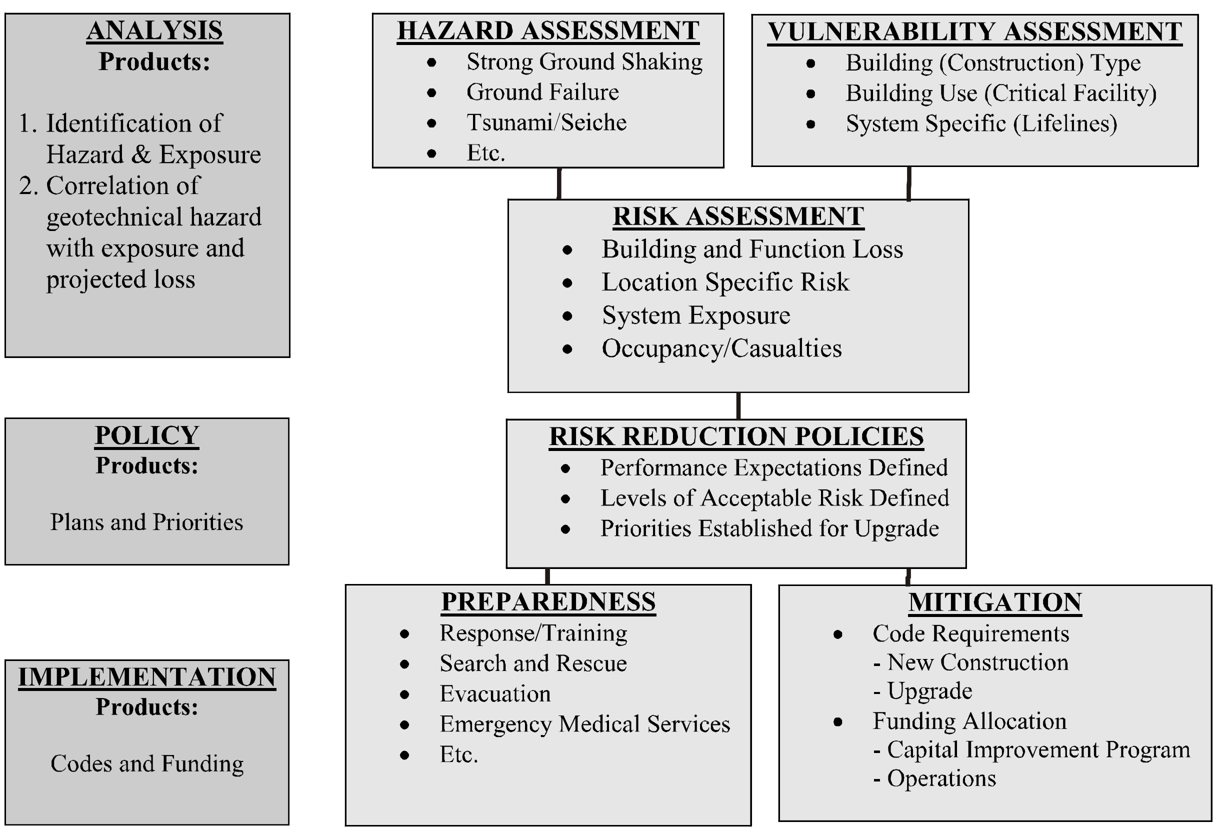

Figure 1. Seismic risk reduction process

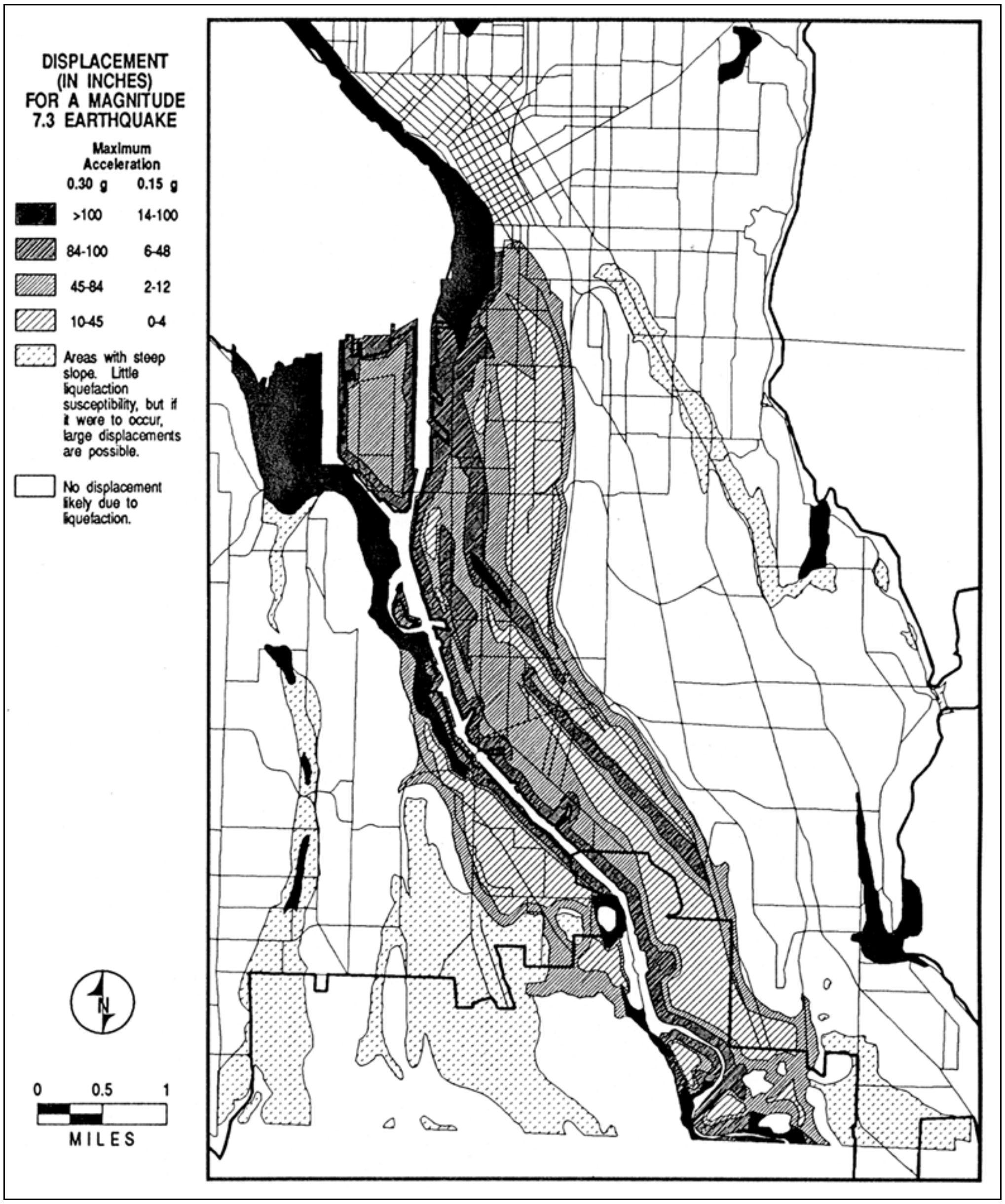

Figure 2. Maximum lateral displacement hazard for South Seattle (from Mabey *et al.*, 1991).

<u>**Analysis Phase**</u>

Hazard and Vulnerability Assessment

Two types of baseline studies are undertaken. One pertains to the geotechnical hazard which consists of the seismicity (the relative frequency and distribution of earthquakes) of the area and the distribution of expected effects from different magnitude earthquakes. It includes the distribution of direct ground motion effects and secondary effects such as liquefaction, tsunamis, and fire. (Note: The City of Seattle, 1992, produced a report, that summarized the latest seismic hazard scientific data and translated this technical information into terms that are understandable to both the general public and decision makers.)

The other component of baseline information pertains to vulnerability, or exposure. This vulnerability must be defined in relation to characteristics of:

- asset exposure (structures and classes of structures)
- occupancy/human exposure (of residents and employees)

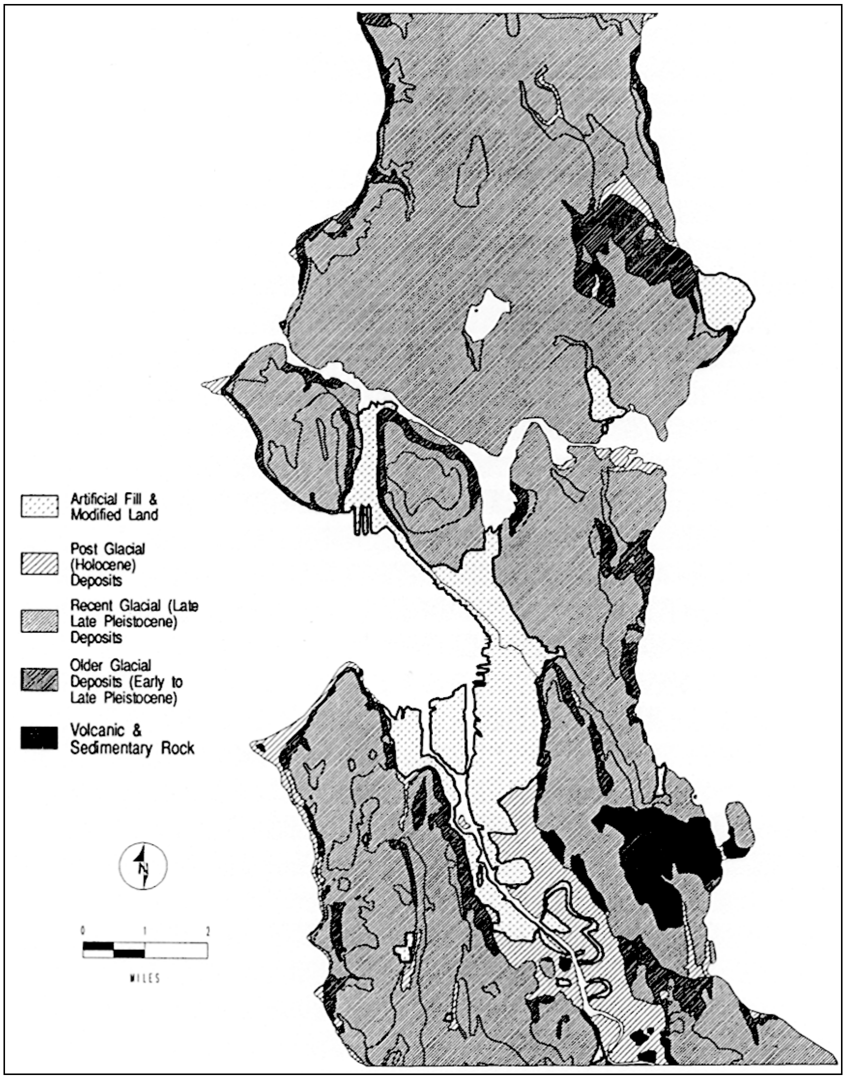

Figure 3. Geologic map of Seattle **(Source: U.S. Geological Survey).**

Risk Analysis

This analysis correlates vulnerability information and geological data with probabilistic assumptions pertaining to seismicity. Products of the correlation are estimates of property loss and probable casualties and injuries.

Policy Phase

Risk Reduction Policies

Once loss estimates are derived, decisions must be made regarding measures to reduce the earthquakes' impacts. Guidelines reflecting performance expectations for individual classes of structures are defined and the amount of "acceptable" risk is specified. Priorities are established with respect to the characteristics and magnitudes of risk identified as "acceptable" for given classes of structures. Cost estimates of measures bringing a structure to a desirable standard may also be undertaken.

Implementation Phase

Preparedness Programs

These programs deal mainly with disaster response planning. Information from seismic hazard planning can provide information regarding the type and magnitude of damage that may occur. Also, pre-earthquake planning for post-earthquake recovery should be included in any preparedness program.

Mitigation Measures

These measures include ordinances and codes pertaining to new construction and/or upgrade. This includes developing land-use regulations, discussed below. Also, funds must be allocated to implement the policies and priorities.

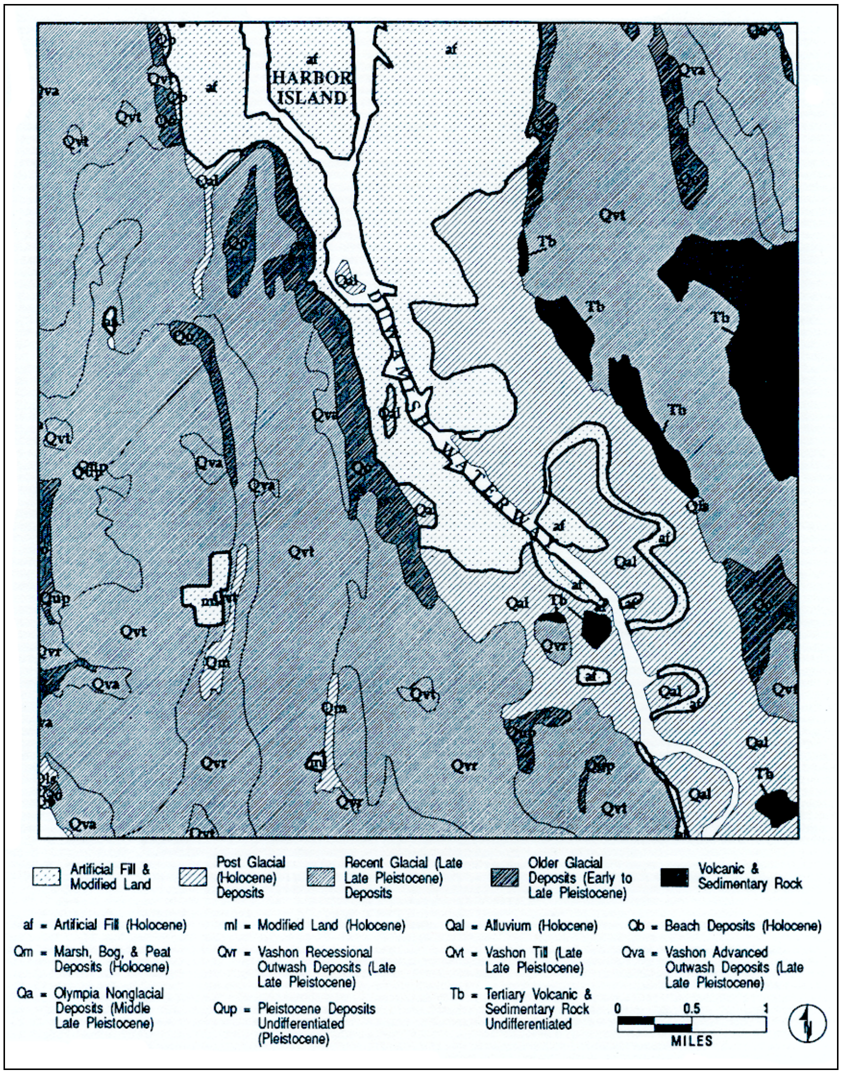

Figure 4. Enlarged portion of geologic map **(Source: U.S. Geological Survey).**

This process can be iterative and several different types of activities can occur at the same time. For example, codes can be developed at the same time that geologic information is being gathered and evaluated. If new scientific information becomes available the codes can be amended, if warranted.

SEISMIC HAZARD MAPPING ALREADY INCORPORATED INTO THE CITY'S LAND-USE REGULATIONS

The city of Seattle has already incorporated mapped geologic hazard information on liquefaction-prone and landslide-prone areas into the city's Environmentally Critical Areas policies and regulations. These policies and regulations are used in the review of specific development proposals. They do not prevent nor necessarily limit the extent or type of development, but are designed to ensure that development in these hazardous areas is constructed in a manner that minimizes property damage and eliminates injury and loss of life during an earthquake. This hazard information is the result of interpretive mapping from outside sources; the city did not develop this information itself, but did incorporate it into its land-use regulatory system.

The main provisions of the geologic hazard areas policies are summarized below. The full text of this section of the critical areas policies was described by the City of Seattle (1992). That report also contains maps of the liquefaction-prone and landslide-prone areas.

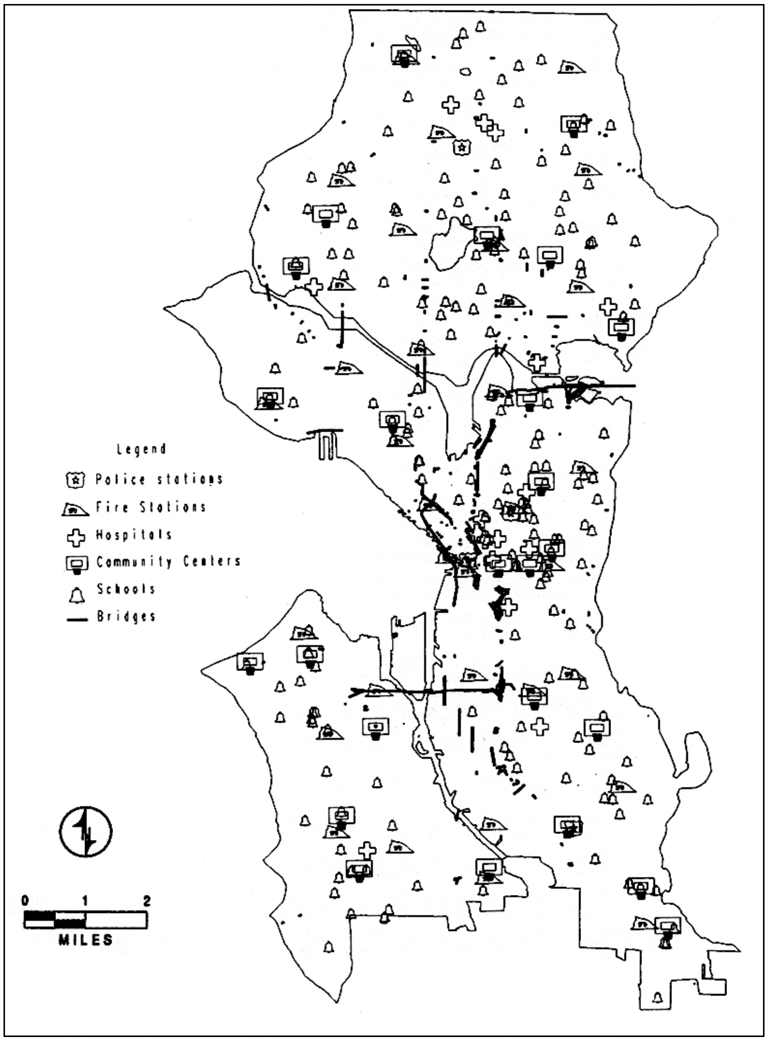

Figure 5. Critical facilities and community centers in Seattle.

LANDSLIDE-PRONE AREAS POLICY *

Development on areas subject to landslides shall be strictly regulated in order to protect the public health, safety, and welfare on both the development site and neighboring properties.

- The identification of landslide-prone areas shall include geologic, hydrologic and topographic factors.
- Maps identifying these areas are intended as a generalized description. The policies and regulations define areas based on specific criteria; whether or not a specific development proposal is subject to the regulations depends on whether or not the land on which it is located meets the definition of a critical area, not whether or not it is mapped as such.
- A staged review process shall be developed whereby a progressively restrictive set of requirements for geotechnical studies and engineering standards is instituted, based on site characteristics. More restrictive requirements shall be imposed on more hazardous sites.
- The city shall ensure that engineering solutions are adequate to prevent failure during high stress periods.
- Special engineering considerations may be required to be integrated into the structure's design to provide an acceptable level of risk.

* Editors note: Current development standards for landslide-prone hazard areas are provided in section 25.09.080 of the Seattle Municipal Code (Environmentally Critical Areas Ordinance, 1992).

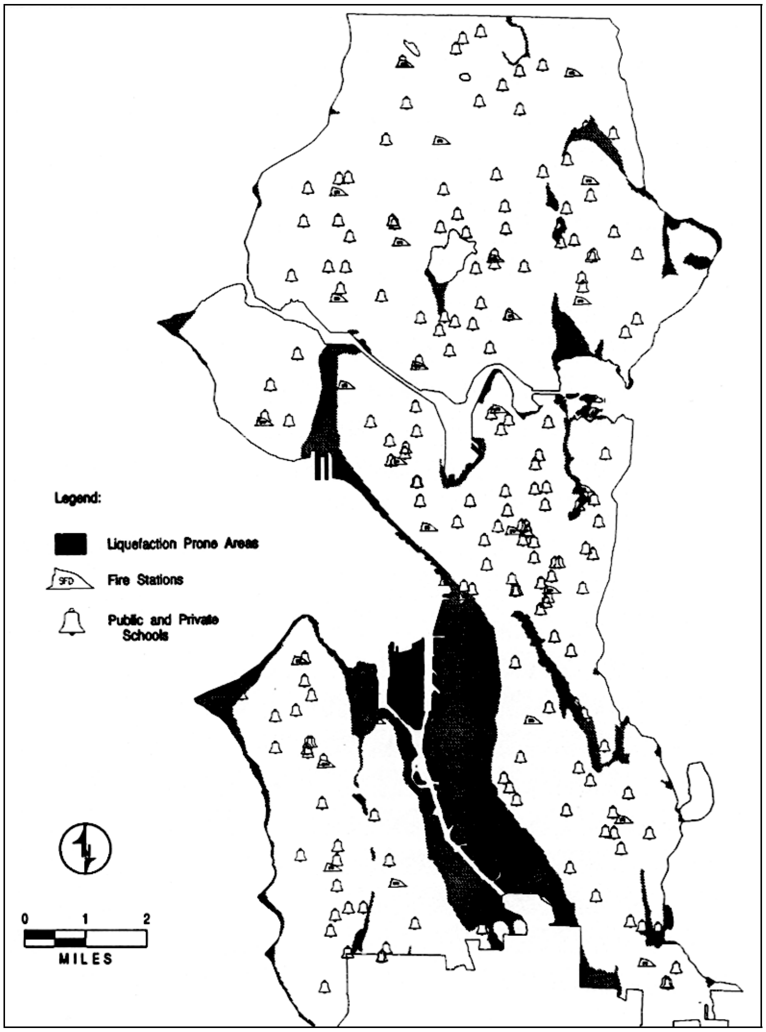

Figure 6. Relationship of fire stations and schools to liquefaction-prone areas.

LIQUEFACTION-PRONE AREAS POLICY*

The city shall identify areas prone to liquefaction during earthquakes and shall ensure that new development in these areas is constructed in a manner that minimizes property damage and eliminates injury and loss of life during earthquakes.

- Soils engineering studies shall be required for all proposed new development in areas subject to liquefaction to determine the physical properties of the surficial soils, especially the thickness of unconsolidated deposits, and their liquefaction potential.
- If it is determined that the site is subject to liquefaction, mitigation measures shall be recommended.
- The city shall ensure that adequate engineering studies are carried out and structural solutions, such as soil compaction or pile construction, are incorporated into project design.
- More detailed studies and more extensive engineering solutions shall be required in areas subject to high potential for liquefaction, and for critical and high-occupancy facilities such as fire stations, hospitals, and high-occupancy residential development.

*Editors note: Current development standards for liquefaction-prone areas are similar to these described here and are provided in section 25.09.100 of the Seattle Municipal Code (Environmentally Critical Areas Ordinance, 1992).

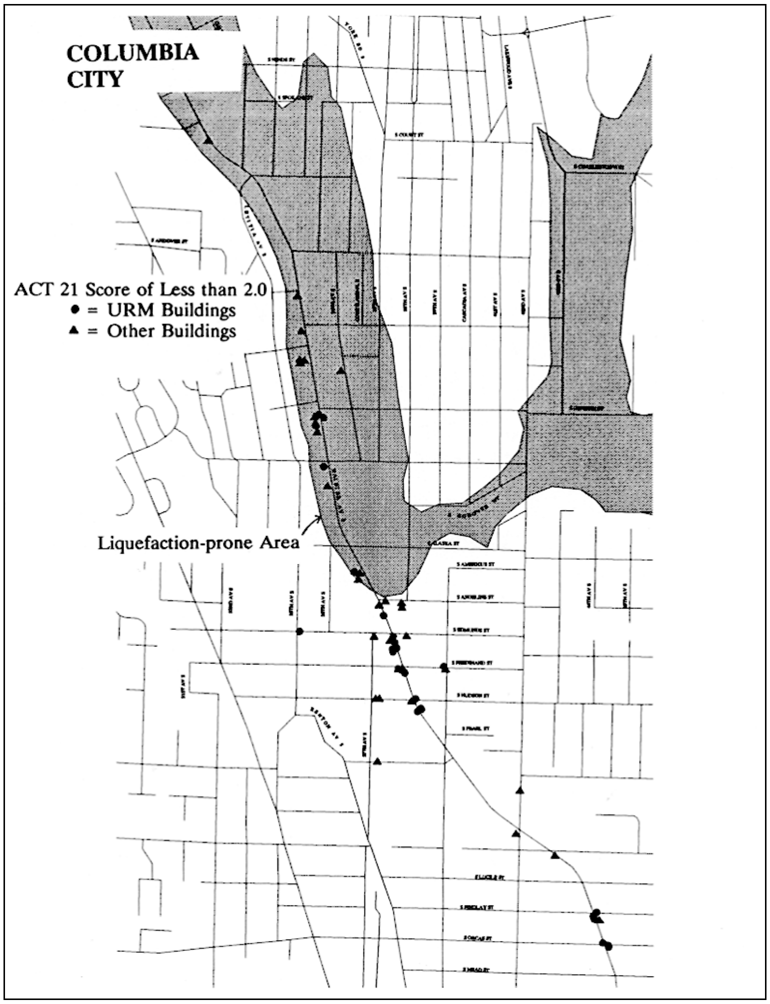

Figure 7. One portion of Seattle where existing buildings vulnerable to earthquake damage have been identified.

HAZARD MAPPING NOT YET INCORPORATED INTO CITY REGULATIONS

The second type of mapped information has not yet been incorporated into the city's hazard reduction planning, either for land-use regulation or disaster response planning purposes. This information includes the mapping of lateral spreading hazards in a portion of the city. This is shown on Figure 2. Lateral spreading is caused by the ground-shaking-induced liquefaction of an underground layer of liquefiable soil.

This triggers the movement of the overlying soils toward an unsupported surface or slope (not necessarily steep).

Ground shaking is the one type of hazard for which Seattle does not have adequate information, although we do have a basic geologic map on our Geographic Information System (GIS) that could someday be used in ground shaking hazard mapping. Figure 3 is a geologic map of Seattle; Figure 4 is a more detailed and enlarged portion of this map.

MAPPED INFORMATION ON BUILDINGS AND STRUCTURES

The third type of mapped information deals with buildings and structures. This information relates to the vulnerability assessment phase noted in the model seismic risk reduction process (see Figure 1). The city has included critical facilities such as schools, hospitals and fire stations in its GIS. Figure 5 shows fire and police stations, hospitals, schools and bridges in Seattle; community centres, which can serve as emergency shelters following an earthquake, are also shown.

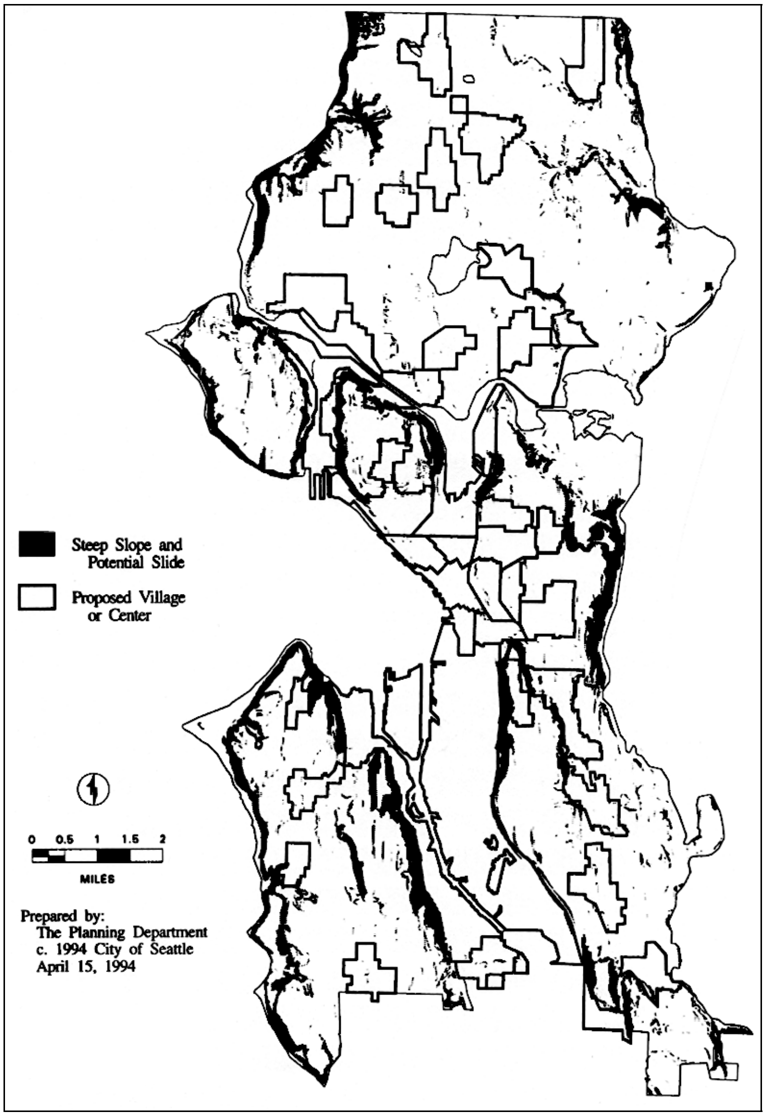

Figure 8. City of Seattle. Steep slope and slide prone areas and proposed villages/centres.

The location of these critical facilities has been compared to earthquake hazard areas for disaster response purposes. This is an example of the risk assessment phase of the model seismic risk reduction process (see Figure 1). Figure 6 shows the relationship of fire stations and schools to liquefaction-prone areas, for example. Policies and programs can be developed to address these vulnerable structures, to evaluate the specific risks involved, and to suggest and implement mitigating measures.

Seattle has also been gathering information on the condition of privately owned buildings for the purpose of disaster response planning, as well as to help determine the need for, and the potential impacts of, possible hazard abatement programs. Figure 7 shows one portion of Seattle where existing buildings vulnerable to earthquake damage have been identified, and illustrates where these structures are located on liquefaction-prone areas. The city is also in the process of mapping all the unreinforced masonry buildings within its boundaries.

FUTURE EFFORTS -- RELATIONSHIP TO LAND-USE PLANNING

Although seismic hazard information has been incorporated into Seattle's regulatory process, this information has not been a major factor in overall land-use planning, in determining where future development should locate. The approach to date has generally been that development could occur anywhere as long as it was designed and engineered to be safe. However, while not a major consideration, geologic hazards were taken into account to some extent in the designation of proposed of urban centers and urban villages, areas where future growth in the city is to be concentrated.

As can be seen in Figure 8, there is very little overlap between proposed urban centers and villages and potential slide areas and steep slopes (steep slope areas are, by definition, also considered to be potential slide areas).

When the city obtains better and more detailed ground shaking information in the future it might be worthwhile to investigate one other aspect of seismic hazard mapping and land-use planning. This involves the relationship of local subsurface conditions and building size. This is important as a building located on materials with a natural period of vibration similar to that of the building will suffer increased damage through resonance effects. It would be interesting to relate the height of typical structures in a given land-use category (such as highrise structures in downtown commercial zones, or single family homes in low-density residential areas), and relate these types of structures to soil conditions. Should these soil considerations be taken into account when designating areas for highrise commercial development, for example?

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LANDUSE APPLICATIONS OF EARTHQUAKE HAZARD MAPS CALIFORNIA EXPERIENCE

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INTRODUCTION

The focus of this report is primarily on the work done with earth scientists, including geologists and geotechnical engineers, in preparing and applying data that has guided land-use decisions for the Town of Portola Valley on the San Francisco Bay Peninsula. The report provides a brief overview of how State and regional hazard mapping has helped establish a context for applying data at the local level. It then reviews the Portola Valley experience, much of which is documented in a study by Mader *et al.* (1988) completed under a NSF grant.

OVERVIEW OF STATE, REGIONAL AND LOCAL PROGRAMS

During the past 20 to 30 years, earthquake hazard mapping has been increasingly used in effective land-use planning efforts at the state, regional, and local levels in California. At the state level, such actions as the Alquist-Priolo Special Studies Zones Act of 1972, and the requirement for local comprehensive plans to contain seismic safety elements have increased public and private awareness and prevented construction of buildings for human occupancy on an active fault. Under the Alquist-Priolo Act, the California Division of Mines and Geology (CDMG) identifies active faults and maps fault zones throughout the state. Applications for most development projects within these zones must include geologic studies prepared by a geologist. Local regulations must be consistent with the criteria of the Act, and the Act also allows cities and counties to establish more restrictive policies. A similar program is now under way with regard to liquefaction and slope failure. The seismic safety element provisions have resulted in many local jurisdictions acquiring seismic hazard mapping, using the mapping to identify levels of acceptable risk and applying the mapping and risk policy to local land-use, including zoning, decisions.

An example at the regional level is the cooperative work of the United States Geological Survey (USGS), the California Division of Mines and Geology, the Association of Bay Area Governments and the Bay Area Regional Earthquake Preparedness Project. These agencies have cooperated and relied on each other in ways that have led to the development of basic geologic data of the San Francisco Bay region. This information is presented in many maps and reports that have been used by all levels of government in the region as well as the private sector. The work of these agencies has resulted in an area-wide database that has facilitated regional planning, especially for infrastructure, and has provided a framework for local governments in dealing with their own unique problems. In particular, the USGS San Francisco Bay Region Study, which took place during the 1970s, described the seismic and nonseismic hazards of the Bay Area in products that have proven extremely useful for land-use planning.

At the local level, the "ground truth" of seismic hazard data has had significant impact in directing seismically safe development. The Town of Portola Valley has become a recognized leader in applying such data to local land-use planning decisions. In large part, as a result of our firm's work in Portola Valley, we have had involvement in many of the state and local efforts. It is this Portola Valley experience that is presented below. The brief review is intended to provide a perspective on Portola Valley and the kinds of problems the community has been dealing with in land-use decisions for almost 30 years. It must be emphasized, however, that of critical importance to this experience, and the success of the efforts has been an enlightened Town Council and knowledgeable citizen base. Further, capitalizing on the "window of opportunity" created by damaging earthquakes or landslides, has been important in terms of the willingness of decision makers to risk adopting new land-use regulations.

THE PORTOLA VALLEY EXPERIENCE

One of the first critical decisions of the Portola Valley Town Council was to establish the position of Town Geologist. Bill Cotton, Town Geologist for over 20 years, has played an essential role in the development of good planning programs and in educating local decision makers on the importance, and quality, of good geologic hazard mapping.

In Portola Valley, the geologic hazard reduction program is applied as shown in Figure 1. The figure shows the various steps in the planning and development processes, and the types of geologic data needed for informed decision making. It shows that less specific, mainly surface, data is needed at the general planning stage and that very precise and detailed subsurface data is needed at the subdivision, site development and building permit stages. The data must be usable by planners, decision makers and building inspectors. Thus, translation of information by the scientist for use by these individuals is essential.

For orientation, Portola Valley is located 45 kilometres south of San Francisco (Figure 2). It is a community of approximately 24 square kilometres (9 square miles; 5750 acres). It is located on the hillsides of the eastern San Francisco Peninsula. It has a population of approximately 4400 people and contains about 1650 dwelling units. There are a few small commercial and office use areas, and several large institutional uses including schools, churches, a retirement home, and lands belonging to Stanford University. The town is divided by the San Andreas fault zone (i.e., the Valley). The lands on the west side of the fault, are much more unstable than lands on the east side. This basic fact has been well documented and is recognized in the various plans and regulations of the town.

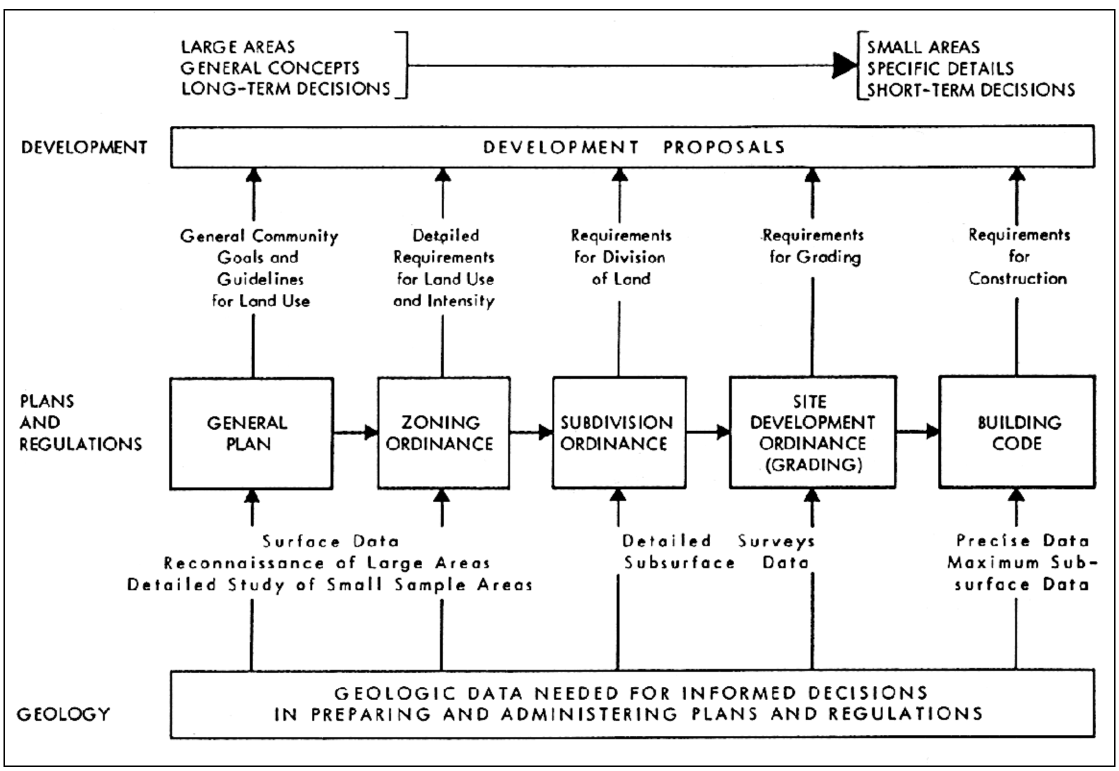


Figure 1. Geologic data are useful at every step in the planning-regulation-development process, with more data, and more precise data needed as consideration progresses from the general plan to building (Source: Mader and Crowder 1971).

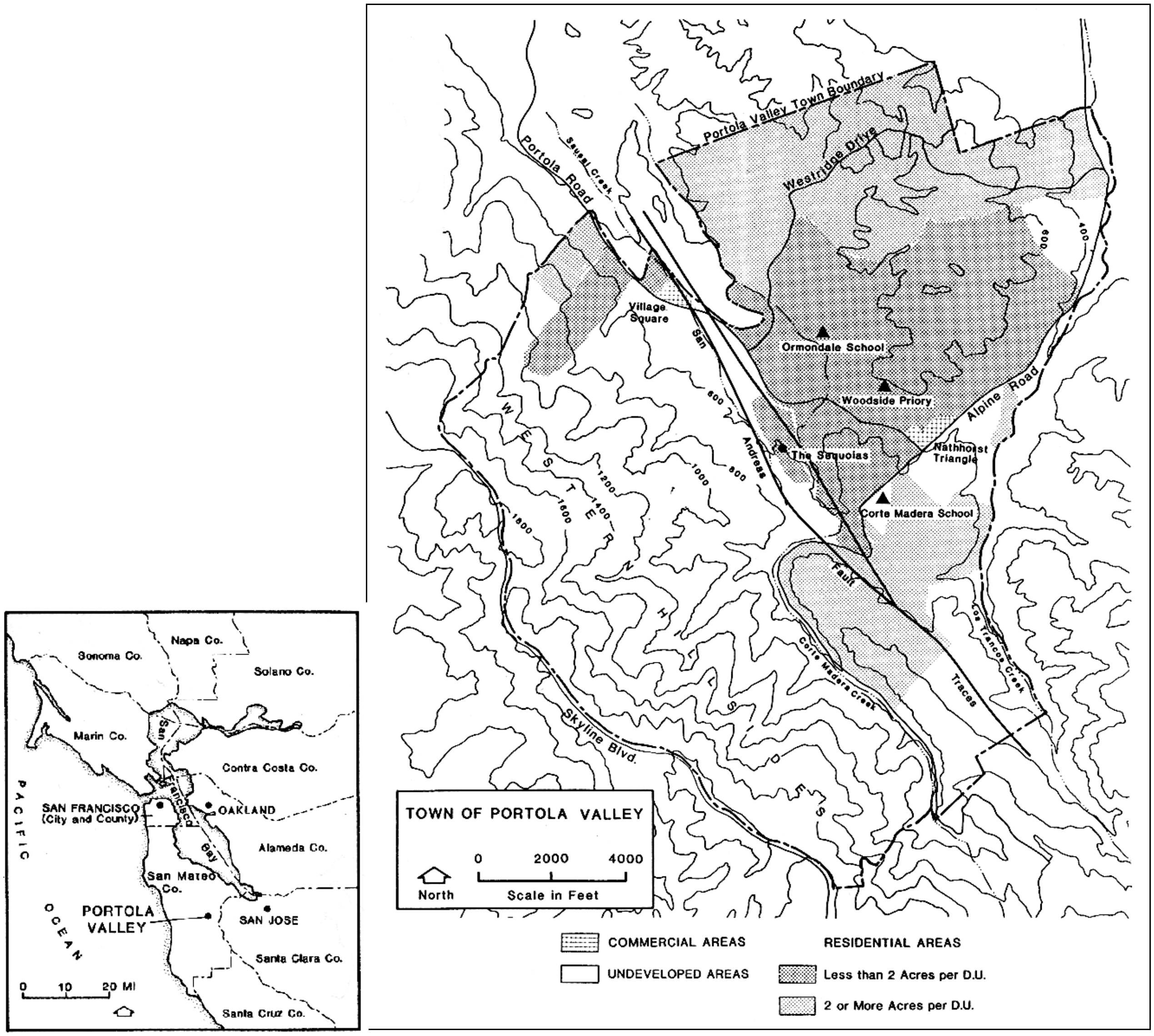


Figure 2. Location of Portola Valley and the existing Portola Valley community.

GEOLOGIC MAPPING, INTERPRETIVE MAPS AND LANDUSE REGULATIONS

Under the guidance of the Town Geologist the town embarked on a program to complete a detailed geologic map (Figure 3). This map, at a scale of 1:6000 and showing individual parcels, was drawn using surficial information and the few available subsurface studies. The cost of the mapping was controlled through the use of geology graduate students from Stanford University. The geologic map data were then interpreted for the purposes of determining the influence the data should have on land-use decisions. The interpretive map, also at a scale of 1:6000 is entitled "Movement Potential of Undisturbed Ground" (Figure 4). It characterizes all lands in the town in terms of relative stability.

Based on this mapping, the Town Council adopted Resolution 500 which established the "criteria for permissible landuse in Portola Valley" (Figure 5). This resolution and the geologic hazards mapping have been applied effectively since 1974 to increase seismic safety and reduce local risk from geologic hazards.

With the geologic and movement potential data, a land capability analysis was undertaken that resulted in changes to the town's General Plan. The western hillside area was the focus of mapped key geologic hazards. Once the constraints mapping was finished, the results were

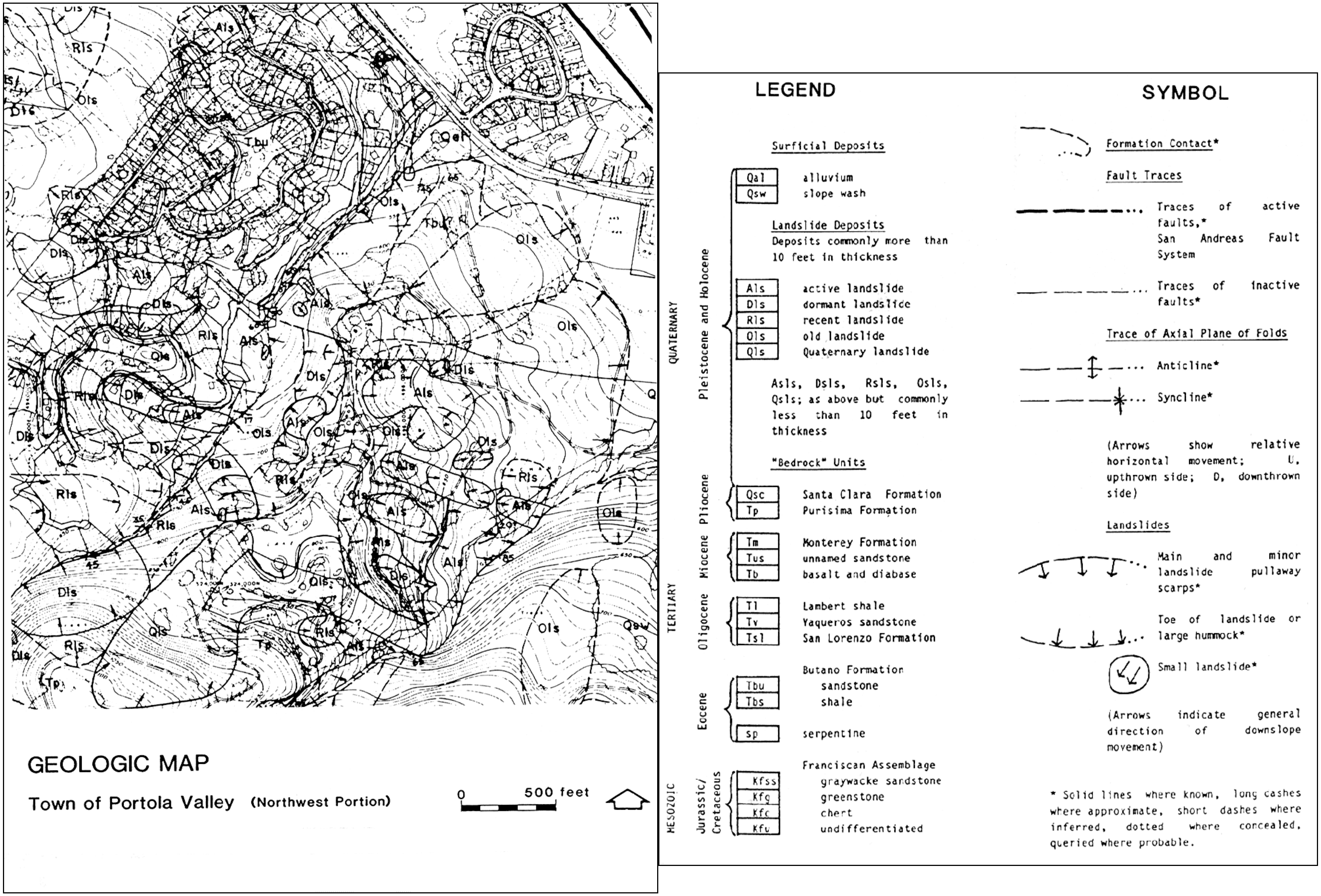


Figure 3. A portion of Portola Valley's geologic map with legend.

LEGEND

Relatively Stable Ground

Sbr	Level ground to moderately steep slopes underlain by bedrock within approximately three feet of ground surface or less; relatively thin soil mantle may be subject to shallow landsliding, settlement, and soil creep.
Sun	Unconsolidated granular material (alluvium, slope wash, and thick soil) on level ground and gentle slopes; subject to settlement and soil creep; liquefaction possible at valley floor sites during strong earthquakes.
Sls	Naturally stabilized ancient landslide debris on gentle to moderate slopes; subject to settlement and soil creep.
Sex	Generally highly expansive, clay-rich soils and bedrock. Subject to seasonal shrink-swell, rapid soil creep, and settlement. May include areas of non-expansive material. Expansive soils may also occur within other map units.

Areas with Significant Potential for Downslope Movement of Ground

Pmw	Steep to very steep slopes generally underlain by weathered and fractured bedrock; subject to mass-wasting by rockfall, slumping, and raveling.
Ps	Unstable, unconsolidated material, commonly less than 10 feet in thickness, on gentle to moderately steep slopes subject to shallow landsliding, slumping, settlement, and soil creep.
Pd	Unstable, unconsolidated material, commonly more than 10 feet in thickness, on moderate to steep slopes; subject to deep landsliding.

Areas with Potential for Surface Rupturing and Related Ground Displacements Associated with Active Faulting

Pf	Zone of potential permanent ground displacement within 100 feet of active fault trace.

Unstable Ground Characterized by Seasonally Active Downslope Movement

Ms	Moving shallow landslides, commonly less than 10 feet in thickness.
Md	Moving deep landslides, commonly more than 10 feet in thickness.

Contacts between map units: solid where known, long dashes where approximate, short dashes where inferred, queried where probable.

Figure 4. A portion of Portola Valley's interpretive geologic map, with legend, indicating categories of land stability.

CRITERIA FOR PERMISSIBLE LAND USE IN PORTOLA VALLEY

	Land Stability Symbol	Roads *Public*	Roads *Private*	Houses (*parcel acreage*) *¼-Ac*	Houses (*parcel acreage*) *1-Ac*	Houses (*parcel acreage*) *3-Ac*	Utilities	Water Tanks
MOST STABLE	Sbr	Y	Y	Y	Y	Y	Y	Y
	Sun	Y	Y	Y	Y	Y	Y	Y
	Sex	[Y]	Y	[Y]	Y	Y	Y	[Y]
	Sls	[Y]	[Y]	[N]	[Y]	[Y]	[Y]	[N]
	Ps	[Y]	[Y]	[N]	[Y]	[Y]	[Y]	[N]
	Pmw	[N]	[N]	[N]	[N]	[N]	[N]	[N]
	Ms	[N]	[N]	N	N	N	N	N
	Pd	N	[N]	N	N	N	N	N
	Psc	N	N	N	N	N	N	N
	Md	N	N	N	N	N	N	N
LEAST STABLE	Pf	[Y]	[Y]	(*Covered by zoning ordinance*)			[N]	[N]

LEGEND:
- Y Yes (construction permitted)
- [Y] Normally permitted, given favorable geologic data and/or engineering solutions
- N No (construction *not* permitted)
- [N] Normally *not* permitted, unless geologic data and/or engineering solutions favorable

- S Stable
- P Potential movement
- M Moving

LAND STABILITY SYMBOLS: (as used on geologic hazards map)
- br bedrock within three feet of surface
- d deep landsliding
- ex expansive shale interbedded with sandstone
- f permanent ground displacement within 100 feet of active fault zone
- ls ancient landslide debris
- mw mass wasting on steep slopes, rockfalls and slumping
- s shallow landsliding or slumping
- sc movement along scarps of bedrock landslides
- un unconsolidated material on gentle slope

Figure 5. Table from Resolution 500-1974.

compared with the development areas shown on the original general plan diagram. Development areas had to be reduced in scope to accommodate the results of the capability analysis. A new plan diagram was drafted and adopted and the density potential of the western hillsides significantly reduced as a direct result of the hazards mapping. Slope density zoning regulations were then adopted to implement the revised general plan.

In response to mapping of the San Andreas fault, specific conflicts with existing and potential future development were identified and fault-line zoning setback standards developed to reduce potential risk (Figure 6). Setbacks vary depending on whether mapping has resulted in “known" or "inferred" fault designations. Known designations are where subsurface work has allowed precise location of the fault, and setbacks are less than in areas where the fault is mapped as "inferred".

The fault traces and zoning setback areas extend along Willowbrook Drive, an area of existing developed and vacant parcels. Based on the fault-line zoning, land development has been carefully regulated along Willowbrook Drive. For example, the fault zoning resulted in the modification of a three-lot subdivision to a two-lot subdivision with the building sites located outside the fault zone.

REGULATION AND PLANNING OF A LARGE DEVELOPMENT -- PORTOLA VALLEY RANCH

Of particular interest is the experience of planning for use of 180 hectares of hillside land known as Portola Valley Ranch (Figure 7). The ranch area includes Coal Mine Ridge on the west side of the San Andreas fault and, the more stable terrain on the east side of the fault zone. The Portola Valley Ranch development is a well known project with design significantly influenced by geologic hazards mapping. Pursuant to the town regulations, the design of this residential development was adjusted to avoid San Andreas fault hazard areas, and unstable hillside terrain. During the process of project review, the town also determined that its own regulations needed further modification to allow for better adjustment of proposed development to the "ground truth" of the site. The result has been a well received project that avoids hazard areas and preserves much of the natural condition of the project site (Figure 8).

During the early stages of project planning in the late 1960s, basic, topographic, elevation, geologic and stability maps were prepared. These identified fault and landslide constraints. An initial attempt was made to design a 199 lot project that was responsive to geologic hazard mapping. Cluster areas were located, but the road system still had to cross the traces of the San Andreas fault. Various phases of the development were also identified.

It is interesting to compare the 1969 data with a development proposal originally suggested for the PV Ranch lands in 1956 (Figure 9). This earlier proposal called for 318 residential parcels spread over the San Andreas fault zones and the mapped landslide hazard areas. Fortunately for the town and future residents this development never materialized.

For a variety of reasons, the 1969 project design, although approved, did not move ahead to construction, and a new group of individuals obtained development rights to the ranch lands.

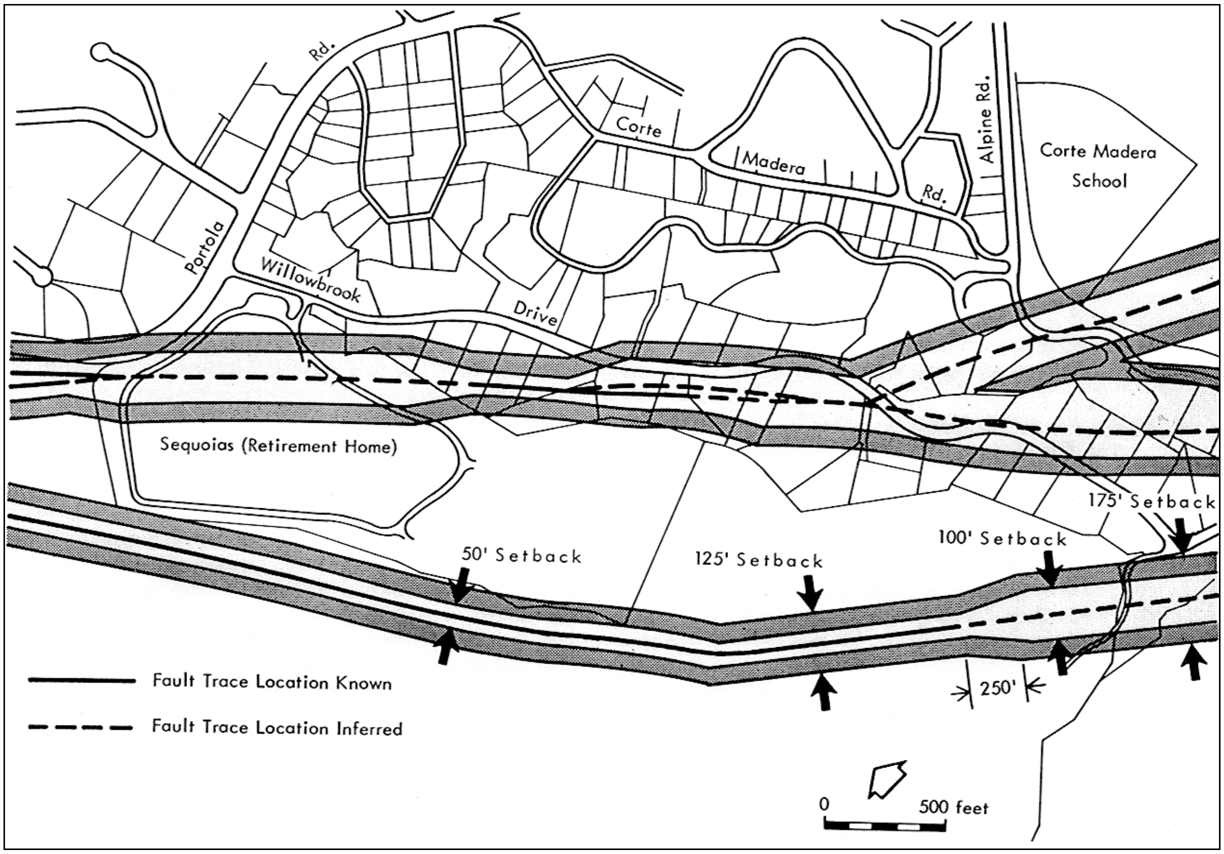


Figure 6. Simplified version of zoning map showing special building setback lines for earthquake faults.

This group decided from the outset that it would work closely with town planners and officials to develop a project highly sensitive to the natural site conditions and geologic hazard mapping. A new Planned Community (PC) zoning designation was adopted that increased opportunities for clustering.

A conceptual plan (Figure 10) and detailed cluster plans were developed that allowed for the Coal Mine Ridge area on the west side of the San Andreas fault to be left in open space and the 205 proposed residential units clustered on parcels on the east side of the fault. Common recreational facilities were planned along the fault zone.

The project was approved and construction started in 1975. Grading followed the natural land forms and houses were sited so that each has direct exposure to large open spaces. The houses range in size from 230 to 370 square metres (2500 to 4000 square feet). By the late 1970s, early 1980s development of the clusters was well under way. Figure 11 is an oblique photo showing the cluster areas in relationship to Coal Mine Ridge (*i.e.,* west side of the fault) and the San Andreas fault zone. The project design also included a valley area that resulted from fault-line zoning setback requirements.

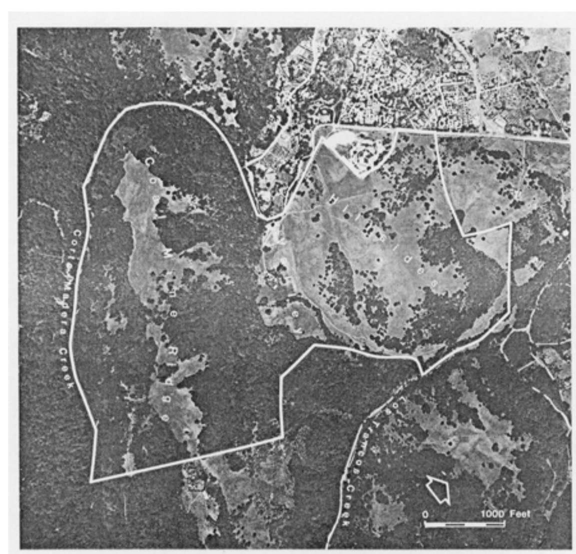


Figure 7. Aerial view of Portola Valley Ranch prior to development.

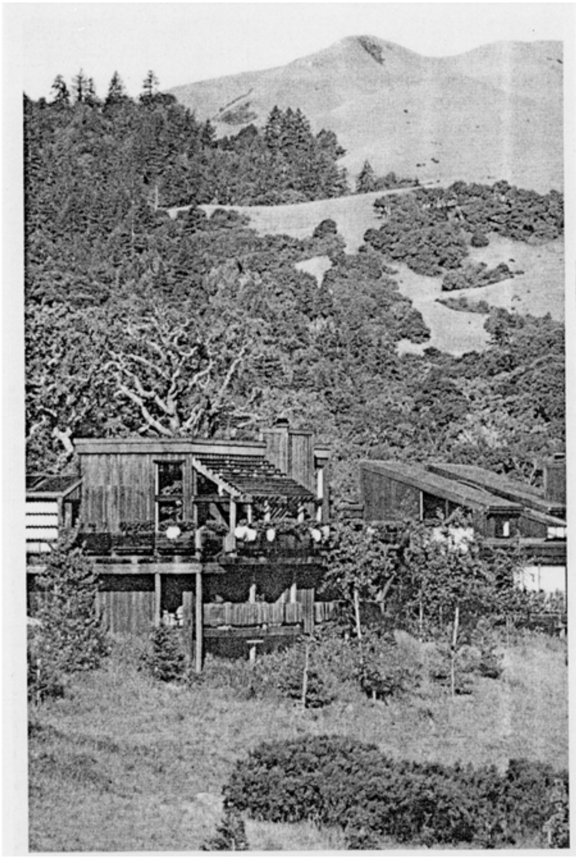


Figure 8. Portola Valley Ranch subdivision (Courtesy of Portola Valley Associates).

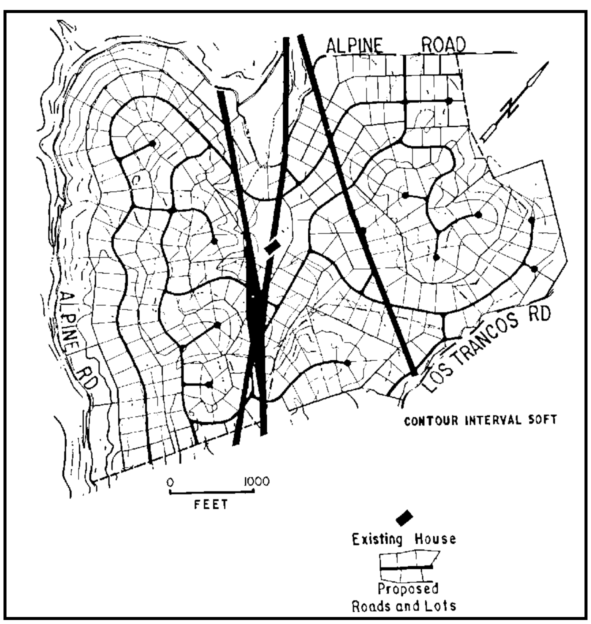


Figure 9. Map showing development proposed in 1956 (straight dark lines are faults).

This valley now contains pathways and has been used as the site for weddings and open air concerts.

Houses have been clustered to avoid the steeper and unstable hillsides of the Portola Valley Ranch lands. Pier and grade beam foundations have been used to avoid excessive grading and site disturbance (Figure 12). Every effort has been made to fit development to the natural conditions of the site. To the extent possible, the natural drainage system has been protected and native plants used in landscaping.

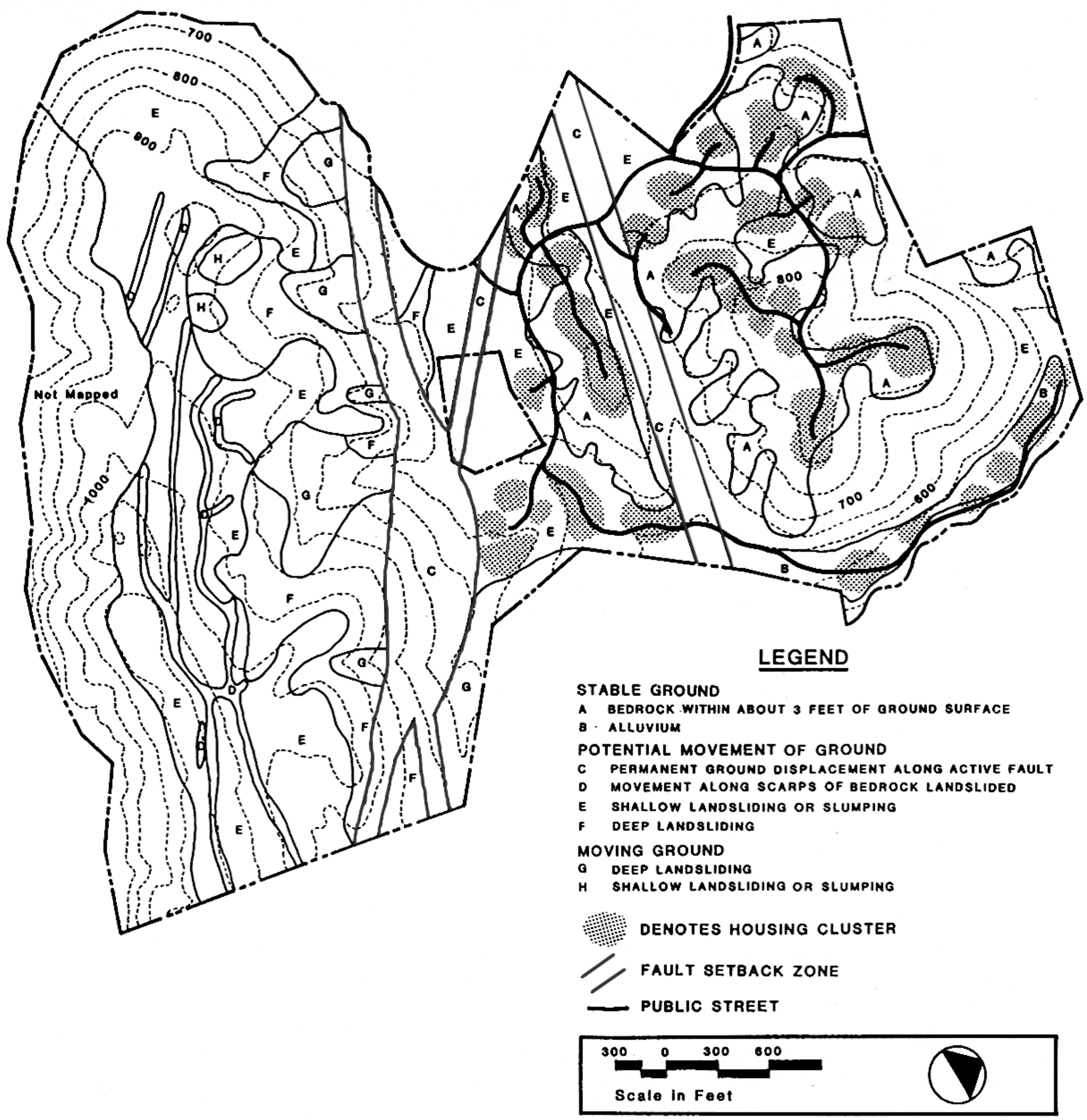
While Coal Mine Ridge, on the west side of the fault, has been left in open space, it does contain the water tank that serves the project. The tank was sited on stable land. However, the grading for the tank site was carefully planned so that the volume of earth removed to cut the tank into the hillside was equal in weight to the full water tank. Also, the grading and siting were carefully planned to minimize visual impacts.

Just to the south of the Portola Valley Ranch Development, the process of planning for new development started again. Trenching was completed and the fault located. Site-specific geologic and movement potential maps were drawn. Site plans were considered that conform with the town's General Plan diagram. Results of the Environmental Impact Report process appear to support the more general hazard mapping and planning that was done by the town.

CONCLUSIONS

Today, as we look beyond Portola Valley and the Bay Region, tremendous growth is occurring in California's Central Valley and Sierra Foothills. These areas are just beginning to face the problems that Portola Valley has come to grips with and are on the verge of significant growing pains. However, public awareness is placing pressure on local governments to acquire and make use of geologic hazards mapping and data.

While the experience of carefully applying geologic hazards mapping has been, for the most part, positive, and there are a number of success stories, the effort requires dedicated and enlightened public decision makers and patience and commitment on the part of the geologic and planning professionals. The scientists and technicians must be willing to patiently translate the technical data in a way that local decision makers can understand and use in making informed land-use decisions. This process must also include involvement of local users such as developers, engineers, architects and citizens. Frustration will come because of the different agendas of the various actors involved in the process. However, a commitment to application of data and consistency in application by staff, planners and local officials, will ultimately result in broad support for the process. Further, with each new earthquake, there is added support and recognition of the need for geologic hazards mapping and mitigation through proper land-use planning.



PORTOLA VALLEY RANCH
GENERAL DEVELOPMENT PLAN AND GEOLOGY

Figure 10. Portola Valley Ranch General Development Plan showing location of housing clusters and streets with respect to geology (Courtesy of Portola Valley Associates).

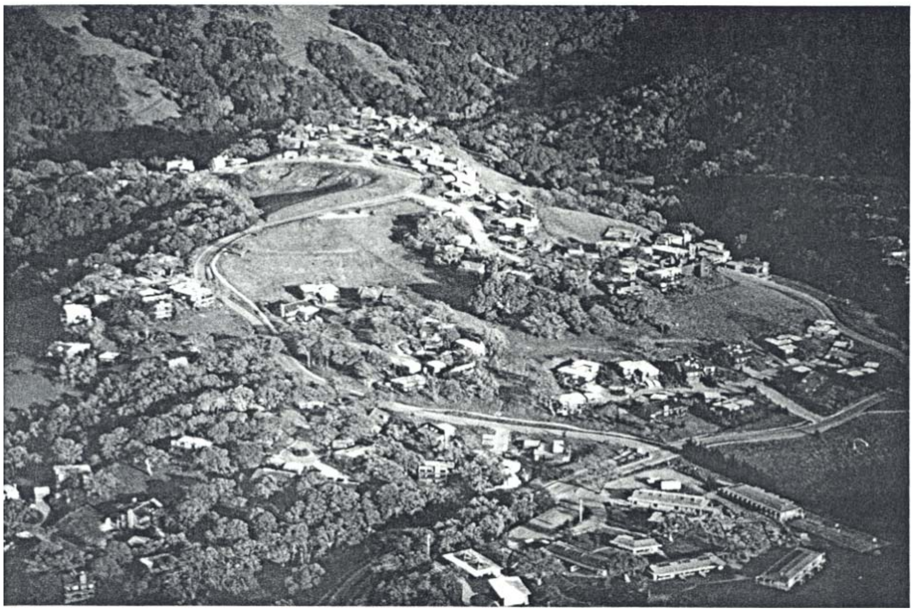


Figure 11. Portion of Portola Valley ranch subdivision as it appeared close to completion. (Courtesy of Portola Valley Associates)

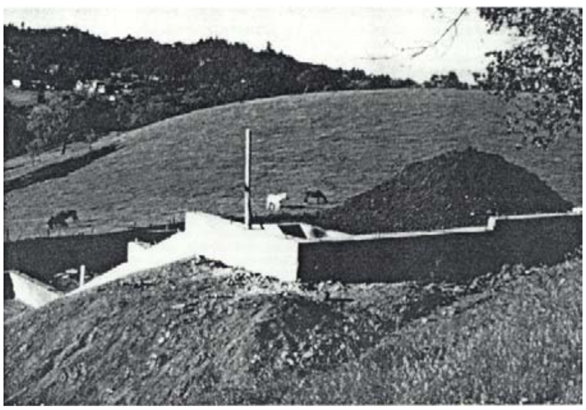


Figure 12. To minimize disturbance of the natural terrain, Portola Valley ranch houses were designed to fit existing ground conditions.

ACKNOWLEDGMENTS

I am pleased to have this opportunity to share my experiences from the "trenches" of applying seismic hazard mapping to land-use decisions in California. My firm has had the opportunity and pleasure to work with a number of jurisdictions whose decision makers have been willing, and even aggressive, in requiring the application of hazard data to land-use decision making. We have also been fortunate to receive grants from the National Science Foundation that have allowed us to document our experiences, research other experiences and share our findings with others concerned and involved with improving the ways in which hazard data are applied in land-use decision making.

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EARTHQUAKE HAZARD MAPPING IN BRITISH COLUMBIA: STATUS, DEMAND AND METHODOLOGY DEVELOPMENT

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INTRODUCTION

Earthquake hazard maps, also referred to as seismic microzonation maps, are detailed (generally 1:20000 to 1:50000 scale) maps that identify the relative potential for ground disturbance during an earthquake. Seismic microzonation is defined as "the process of determining absolute or relative seismic hazard at many sites accounting for the effects of geologic and topographic amplification of motion and of soil stability and liquefaction, for the purpose of delineating seismic microzones" (Earthquake Engineering Research Institute, Committee on Seismic Risk, 1984). Earthquake hazard maps are compiled from geologic and geotechnical data to reflect local site conditions, which in addition to earthquake source and magnitude, exert a major control on potential ground disruption. Records of historical earthquakes show that damage is largely controlled by site characteristics, which can be readily mapped. Earthquake hazard maps, based on site geology, can therefore be used directly as a predictive tool for land-use and emergency planning.

Although not yet widely used in Canada, earthquake hazard mapping has been completed and successfully applied in numerous parts of the United States including California (Youd *et al.,* 1972, 1975, 1978; Nilson and Brabb, 1979; Dupre and Tinsley, 1980; Power *et al.*, 1982, 1986; Kavazanjian *et al.*, 1985; Roth and Kavazanjian, 1985; Wieczorek *et al.,* 1985; Tinsley *et al.*, 1985; Youd and Perkins, 1987; Dupre, 1990; Leighton and Associates, 1990), Utah (Anderson *et al.*, 1982, 1986a, b; Mabey and Youd, 1988), central Mississippi valley (Obermeier, 1984, 1988), Missouri (Higgins and Rockaway, 1986), Tennessee (Sharma and Kovacs, 1980), South Carolina (Elton and Hadj-Hamou, 1990), New York (Budhu *et al.*, 1987) and Alaska (e.g. Combellick, 1984). Of particular relevance to British Columbia is mapping in the Seattle-Tacoma region in Washington State (e.g. Grant *et al.*, 1991; Shannon and Wilson Inc., 1990, 1993; Palmer *et al.*, 1994, 1995; Dragovich and Pringle, 1995) and in the Portland, Oregon - Vancouver, Washington region (e.g. Madin, 1990; Mabey and Madin, 1993; Youd and Jones, 1993; Mabey *et al.*, 1994, 1995). Earthquake hazard maps have also been produced in many other countries throughout the world including Japan (e.g. Ishihara and Ogawa, 1978; Kotoda *et al.,* 1988; Kusano *et al.*, 1990; Wakamatsu, 1992), Indonesia (Thenhaus *et al.*, 1993), Greece (Pitilakis *et al.*, 1982), Italy (Berardi *et al.*, 1990), Puerto Rico (Soto, 1987), Yugoslavia (Talaganov and Aleksovski, 1984), China (Fang *et al.*, 1980) and Argentina (INPRES, 1982, 1987).

The benefits of earthquake hazard mapping in British Columbia were investigated by the Seismic Microzonation Task Group of the Resources Inventory Committee (Klohn-Crippen, 1994). This paper summarizes some of the results of activities conducted by the task group between 1993 and 1995. The task group, consisting of representatives from the British Columbia Geological Survey Branch, Ministry of Energy, Mines and Petroleum Resources, the Geological Survey of Canada, B.C. Hydro, the University of Victoria, Public Works Canada, British Columbia Ministry of Environment, Lands and Parks and the geotechnical consulting community, conducted an analysis of earthquake hazards in the province and reviewed methods of seismic microzonation mapping for land-use planning purposes. Mapping standards, minimum data requirements, costs, benefits and potential users were also reviewed. This information was compiled under contract to Klohn-Crippen Consultants Ltd. (Klohn-Crippen, 1994) and the report is available from the Resources Inventory Committee Secretariat.

EARTHQUAKES IN B.C. AND ECONOMIC IMPACT

Southwestern British Columbia is in a seismically active area subject to crustal, subcrustal and subduction earthquakes (Rogers, 1992, 1994). The largest earthquake in Canada (M 8.1) occurred near the Queen Charlotte Islands in 1949. The 1946 earthquake (M 7.3) near Courtenay was the most destructive in western Canada. Although a number of damaging earthquakes have occurred in British Columbia and in nearby Washington and Alaska in historic times, most of these earthquakes occurred prior to extensive urban development. One of these earthquakes in 1965 in Seattle caused $12 million in damage. The estimated potential economic impact of a similar (M 6.5) earthquake on the Lower Mainland alone is $14.3 to $32.1 Billion (Munich Reinsurance, 1992).

The economic impact of earthquakes in British Columbia can also be measured in terms of the cost of seismic vulnerability studies and upgrading programs. Current earthquake related programs are mainly site specific or focused on agency-specific facilities. For example, the British Columbia Ministry of Education has, in recent years, allocated about $30 million per year to seismic upgrading of schools and British Columbia Hydro spent about $1 million per year on seismic studies of the electric system and about $8 million in total on upgrading and identifying areas of seismic vulnerability (Klohn-Crippen, 1994). Likewise, many different municipal government agencies are expending funds on seismic related projects. For example, the City of Vancouver spent approximately $4 million on Phases I and II of a seismic upgrading program of the Granville and Burrard Street bridges and the First Avenue viaduct, with an additional $6 million proposed for 1994-1996 for Phase III of the upgrade. In contrast, costs for producing earthquake hazard maps are relatively small. For example, the total cost of producing a liquefaction susceptibility map (B.C. Hydro, 1992) for parts of the Lower Mainland area was $110,000 in 1991-1992 dollars.

Due to the site-specific and facility-specific nature of present seismic evaluations and upgrading programs in the province, there is potential for duplication, poor regional coverage and inadequate prioritization of activities. A better understanding of geologic and geotechnical site conditions, through the production of earthquake hazard maps, would be particularly useful for landuse and emergency planning purposes. A regional approach may also be more cost-effective.

EARTHQUAKE HAZARDS IN B.C.

Earthquake hazards can be grouped into several categories including liquefaction, amplification, landsliding, tsunamis/seiches, subsidence and ground rupture. Liquefaction, resulting from loss of strength in loose, saturated, cohesionless soils during an earthquake, can lead to lateral spreading, flow slides and ground settlement and is one of the most important seismic hazards relevant to landuse planning in B.C., particularly in the Lower Mainland region where liquefaction susceptible soils are common (Watts *et al.,* 1992; Klohn-Crippen, 1994). Amplification of ground motions during an earthquake often occurs at sites overlain by thick, soft deposits of silt and clay such as are common in some coastal areas of the province (*e.g.* Victoria, Lower Mainland) as well as in the interior (*e.g.* Prince George -Vanderhoof region). Earthquake-induced landslides, especially large rock avalanches, are also a particularly important hazard in British Columbia because of the high relief in many areas of the province and because, on a world wide basis, landslides have been responsible for most earthquake-related deaths and large economic losses. Tsunami (sea wave) hazards are greatest on the west coast of Vancouver Island and Graham Island and along the central part of the mainland coast (Murty, 1992) but earthquake-induced, landslide generated waves in lakes (seiches) may occur in many different parts of the province. Subsidence and ground rupture hazards are generally considered less important in B.C. than other earthquake hazards.

Table 1. Estimated susceptibility to liquefaction of Chilliwack region soils (modified from Watts *et al.,* 1992); n.d. = no data.

Surficial Geological Units	Age	Distribution	Sediment Type	Water Table	Liquefaction Susceptibility Youd and Perkins (1978), Watts *et al.* (1992)	
River Channel	Very recent	Along present rivers	Sand & gravel	At surface	Very high	Very high
Overbank	Holocene	Floodplain widespread	Silt over sand & gravel	Near surface	Moderate	High
Fluvial fan	Holocene	Chilliwack River mouth	Gravel grading out to sand & silt	Variable	Moderate	Moderate
Bog	Holocene	Widespread	Peat, organic silt over fluvial seds.	At surface	n.d.	Nil but underlying sediments may liquefy
Lacustrine Deposits	Holocene to late Pleistocene	Sumas valley west of Vedder Canal	Silt to clay Sand and silt	Near surface	Low to high	n.d.
Till	Pleistocene	Ryder Upland	Diamicton	Variable	Very low	Extremely low

EARTHQUAKE HAZARD MAPS: DESCRIPTION, METHODS AND APPLICATIONS

Earthquake hazard maps are based on the local geology and geotechnical characteristics of the ground. They depict the severity of earthquake hazard that is expected in a map unit relative to other units. Although the size and location of future earthquakes are difficult to predict, the behavior of the soil at any one location relative to another can be estimated by evaluating local geologic and geotechnical site conditions. For example, certain types of soils may be susceptible to liquefaction during an earthquake and some may be prone to landsliding whereas others may be relatively stable. Thus, although exact predictions of when and where the next earthquake will occur are not possible, areas that are susceptible to ground disruption during an earthquake can be identified.

Earthquake hazard maps may include one or more of the earthquake hazards discussed above but the most common hazards evaluated are liquefaction, amplification of ground motion and landslides. Although most earthquake hazard maps focus only on one hazard type, some mapping programs have integrated several hazards into one map (*e.g.,* Mabey *et al.,* 1993, 1994, 1995). Maps of this type are developed to show the relative earthquake hazard in different areas due to variations in local geologic conditions at a city block or neighborhood scale. These maps are often produced for the purposes of providing information that can be used more effectively by landuse and emergency planners and the general public. More technical maps can also be produced separately for each hazard for geotechnical consultants and researchers.

Excellent reviews of earthquake hazard mapping methods have been provided by Aki and Irikura (1991), Finn (1991, 1994), Hansen and Franks (1991) and Youd (1991). Earthquake hazards can be mapped using a number of different methods, usually reflecting different levels of certainty or degrees of quantification of the data. The amount, quality and cost of information required for mapping, generally increases with increasing levels of certainty. For example, liquefaction hazard maps can be grouped into liquefaction susceptibility, liquefaction potential and liquefaction-

Table 2. Categories of Soil Susceptibility to Amplification (after Finn, 1993).

SOIL CATEGORY LABEL	GENERAL DESCRIPTION	SOIL CATEGORY DEFINITION	SUSCEPTIBILITY RATING
A	Competent/hard rock	V_{ave} > 750 m/sec	Nil
B	Deep cohesionless soils, stiff cohesive soils or mix of cohesionless with stiff cohesive soils, not soft clay	350 m/sec < V_{ave} < 750 m/sec	Low
C	Sands, silts and/or stiff/very stiff clays, some gravels; soft clay thickness < 3 m.	180 m/sec < V_{ave} < 750 m/sec	Moderate
D_1	Profile containing a small to moderate total thickness, H_∂ of soft to medium stiff clay	V_{ave} < 180 m/sec, and/or 3 m < H_c < 35m	High
D_2	Profile containing a large total thickness H_∂ of soft/medium stiff clay	V_{ave} <180 m/sec, and/or 15m < H_c < 35m	High
E_1	Peats or highly organic clays	H_p > 3m	Very High
E_2	Very high plasticity clays	H_{cp} > 7m and PI < 75%	Very High
E_3	Very thick soft/medium stiff clays	H_c > 3m	Very High

Notes:
1. Soft/medium stiff clays are those with normalized, average shear wave velocities less than 150 m/sec.
2. Soils classification terms are those in the Canadian Foundation Engineering Manual, Third Edition.

induced ground displacement maps (Youd and Perkins, 1978; Youd, 1991; Finn, 1994). Liquefaction susceptibility maps are based on surficial geology data such as sediment type, geomorphologic characteristics, relative density, deposit age, water table depth and geologic or historical evidence of liquefaction. Liquefaction potential maps indicate the probability of liquefaction actually occurring by accounting for the expected intensity of seismic shaking (based on past records of earthquakes) as well as soil conditions. Liquefaction potential can be estimated using a computer program called PROLIQ (Atkinson *et al.,* 1986) that combines Seed's (1979) method of liquefaction assessment with a probabilistic method of evaluating seismic risk (Cornell, 1968). Liquefaction-induced ground displacement or lateral displacement maps can be produced by accounting for ground movement (lateral spreading) on slopes and towards free faces such as a river banks (*e.g.*, Youd and Perkins, 1987; Mabey and Youd, 1991; Bartlett and Youd, 1992; Youd and Jones, 1993).

An important step in the production of earthquake hazard maps is the integration of geotechnical and surficial geology data. Tables 1 and 2 show how different types of surficial deposits (or soils, in the engineering sense) can be related to susceptibility to earthquake-induced liquefaction and amplification, respectively.

General applications of earthquake hazard maps to planning include: 1) identification of vulnerable lifeline systems (*e.g.* water, gas and power lines); 2) planning transportation and utility corridors; 3) setting priorities for seismic upgrading or remedial work on schools, hospitals, firehalls and other structures; 4) identifying good sites for new essential facilities (*e.g.* schools, hospitals, bridges, toxic waste containment facilities); 5) identifying areas requiring special study before development or high hazard areas with restricted development; 6) property insurance; 7) assessment of risk for financing new projects; 8) providing information on site effects for design of new structures; 9) establishing more stringent design requirements where needed (Klohn-Crippen, 1994).

LEGISLATION AND PREVIOUS WORK

The new *Emergency Program Act (S.B.C. 1993, c.41)* became effective November 1, 1993. The Provincial Emergency Program (Ministry of Attorney General) is the designated coordinating agency. Responsibility for seismic hazards is coordinated through the Inter-Agency Emergency Preparedness Committee. The act requires municipal government to create and maintain an emergency preparedness organization. A new need for geologic and geotechnical data related to earthquake hazards is expected to arise from this legislation.

Earthquake hazard mapping programs in seismically active jurisdictions near British Columbia, such as Washington and Oregon, have been conducted by government geological surveys in both states (Madin, 1990; Palmer, 1992; Mabey and Madin, 1993; Youd and Jones, 1993; Palmer *et al.,* 1994, 1995; Mabey *et al.,* 1994, 1995; Dragovich and Pringle, 1995). In general planning departments in large cities are well advanced in their use of this earthquake hazard mapping information for landuse and emergency planning (*e.g.* City of Seattle, 1992; Metro, 1993); Marks, this volume. A comprehensive bibliography of publications relating to seismic hazards in western Washington and adjacent areas was provided by Manson (1988). Like in Canada, past earthquake research has focused on understanding earthquake source areas and mechanisms for their generation. Fundamental research in earthquake hazard mapping has been provided by the United States Geological Survey and the Earthquake Engineering Research Institute (*e.g.* Ziony, 1985; EERI, 1991). Studies of relevance to microzonation mapping also have been conducted in the Lower Mainland region by the Geological Survey of Canada (*e.g.* Clague *et al.*, 1992; Hunter *et al.,* 1992, 1993; Luternauer, *et al.,* 1993, 1994).

The comprehensive earthquake hazard mapping program implemented in British Columbia was a pilot project in the Chilliwack area (Levson *et al*, 1995, 1996a,b; see description below; Figure 1). A number of independent studies conducted for specific purposes including a liquefaction hazard map of the lower mainland region focusing on B.C. Hydro's infrastructure (B.C. Hydro, 1992; Watts *et al.,* 1992) and a report on potential earthquake hazards and relative risk assessment of selected native communities in the province (von Sacken, 1992). Early versions of earthquake hazard maps in B.C. were also produced by Wuorinen (1972) for the Victoria area and Abrams (1979) for the lower mainland. Detailed maps of the Victoria area were completed by Monahan *et al.* (2000).

EARTHQUAKE HAZARD MAPPING CONFERENCE FOR LAND USE AND EMERGENCY PLANNERS

In an attempt to improve communication between planners and researchers a conference on earthquake hazard mapping for land use emergency planning purposes was organized by the Seismic Microzonation Task Force with the assistance of the UBC Disaster Preparedness Resource Centre. The general purpose of the conference was to review earthquake hazard mapping methods and applications in British Columbia and discuss the results of earthquake studies with landuse and emergency planners. The main objectives were to:

- communicate the purpose and use of earthquake hazard maps and develop a coordinated strategy for their production in British Columbia
- outline 'state of the art' methodologies for relative earthquake hazard mapping, currently being used in other seismically active jurisdiction such as Washington, Oregon and California
- explain the minimum data requirements for construction of earthquake hazard maps
- identify current needs for earthquake hazard mapping in the province and potential users
- identify areas of current duplication and possible collaboration
- determine preferred format and venue for release of earthquake hazard mapping information

Conference participants included individuals and agencies involved in planning seismic upgrading programs, earthquake related landuse zoning, public education and emergency planning and training. Time for questions and discussion was al-

Table 3. A summary of the survey results on earthquake hazard mapping.

EARTHQUAKE HAZARD MAPPING - QUESTIONNAIRE RESULTS						
QUESTION	**RESPONSE**					
		Strongly Agree			Strongly Disagree	
		1	2	3	4	5
Earthquake hazards need to be mapped in your jurisdiction	68%	26%	2%	2%	2%	
Your organization would use such maps if available	71%	24%	5%	0%	0%	
Your organization would contribute funds toward mapping	9%	18%	34%	24%	15%	
Your organization would collaborate by sharing human resources, data collection, data entry, GIS applications, etc.		34%	26%	21%	11%	8%
The scale of earthquake hazard mapping most applicable to your organization is:		1: 20,000 (city block)	1:50,000 (intermediate)	1:100,000 (municipal)	1:250,000 (regional)	
		35%	35%	18%	12%	
Past source of information for earthquake hazards:	Consultants	Municipal Gov.	Prov. Gov.	Fed. Gov.	Educ. Inst.	Other
	22%	12%	22%	19%	14%	11%
The major hurdle to implementing an earthquake hazard mapping program in your jurisdiction is:	Funding	Liability	Expertise	Political will	Other	
	63%	7%	2%	23%	5%	
					YES	NO
Is your agency involved in earthquake prevention (e.g. building codes, zoning, upgrading, legislation)?					66%	34%
Is your agency involved in earthquake preparedness (e.g. emergency plans, training, communication)?					87%	13%
Is your agency involved in earthquake response (activation of emergency operations, warnings) ?					73%	27%
Are you aware of any earthquake hazard maps for your jurisdiction?					46%	54%
Does your agency incorporate earthquake hazard data in zoning, land use and emergency planning?					60%	40%

located for each topic and input from conference participants was solicited.

CONFERENCE SURVEY RESULTS

To help define the direction of earthquake hazard mapping in the province a questionnaire was provided to all conference participants. A summary of the questionnaire results are provided in Table 3. A total of 94% of the respondents agree or strongly agree that earthquake hazard mapping needs to be conducted in their jurisdiction and 95% agree or strongly agree that they would use such maps if they were available (68-71% of these strongly agree). The preferred scale of mapping is 1:20,000 or 1:50,000 (35% each), with 18% favoring 1:100,000 and 12% 1:250,000. 60% of the respondents presently incorporate earthquake hazard information in land use, zoning and emergency planning but only 46% were aware of any earthquake hazard maps in their jurisdiction. 60% were willing to collaborate with an agency such as the B.C. Geological Survey Branch in an earthquake hazard mapping program in their jurisdiction by sharing human resources for data collection, data entry, GIS applications etc. and 27% indicated a willingness to contribute funds to such a program. Most people felt that the major hurdles to implementing an earthquake hazard mapping program are funding (63%) and political will (23%). Liability, technical expertise or other issues were not considered to be major hurdles (7%, 2%, and 5%, respectively).

Most of the individuals responding to the survey are involved in emergency planning (36%), land use planning (25%) or geological / geotechnical aspects of earthquake hazards (25%). A total of 66% of individuals responding, represent agencies involved in earthquake prevention, 87% in preparedness and 73% in response programs. Annual budgets for these programs have a wide range. The Vancouver School Board, for example, had $20-40 million / year for structural seismic upgrades (subject to Ministry of Education funding review / allocation) and $450, 000 / year for non structural upgrades. The Ministry of Transportation and Highways for 1994/95 budgeted $7 million for seismic retrofitting in the Greater Vancouver area and $10 million for Vancouver Island. The surveyed agencies have a total of about 50 personnel

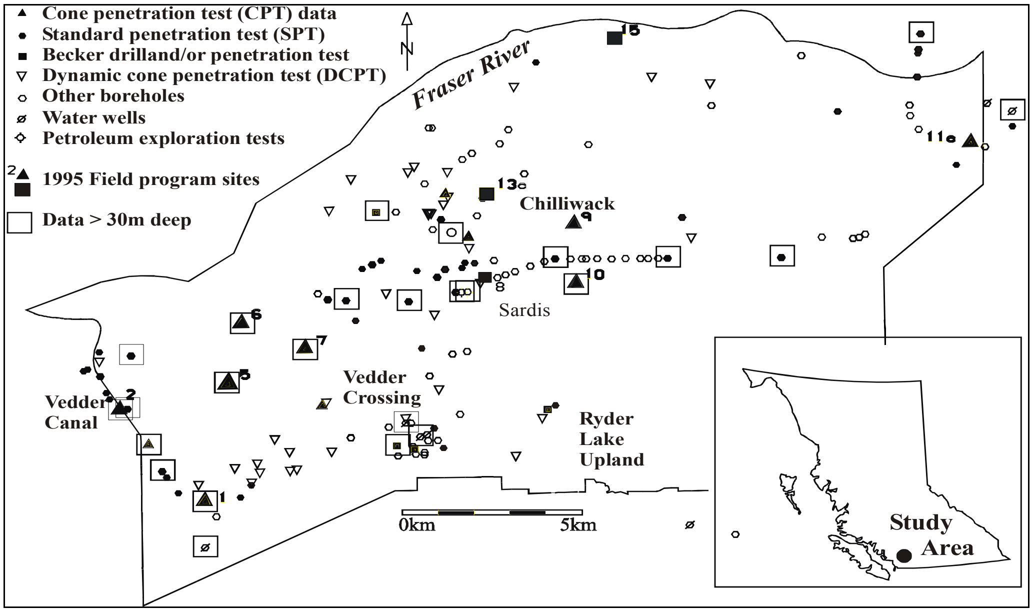


Figure 1. The Chilliwack District and parts of the Fraser-Cheam Regional District. Location of Subsurface Data.

involved in earthquake prevention programs (most with the Provincial Emergency Program), 25 personnel in preparedness, and 89 in response programs.

PILOT EARTHQUAKE MAPPING PROGRAM, CHILLIWACK AREA

A pilot earthquake hazard mapping program was initiated in 1994 in the Fraser River valley near Chilliwack, to develop and test methodologies for mapping earthquake hazards in British Columbia (Levson *et al.,* 1995). The project area (Figure 1) includes the Chilliwack District and parts of the Fraser-Cheam Regional District (contained within NTS mapsheet 92H/4W south of the Fraser River and north of 49° 3' N lat.). Liquefaction and amplification hazards were initially selected for consideration and, after discussions with community planners, a decision was made to not include landslide hazards.

The first step in the hazard mapping program was the compilation of existing geotechnical borehole data from private and public agencies including municipal, provincial and federal government offices, such as the District of Chilliwack, District of Chilliwack, Chilliwack School Board, B.C. Ministry of Transportation and Highways, B.C. Ministry of Environment, Lands and Parks, CFB Chilliwack and geotechnical consultants. The resulting database includes information on sediment type, stratigraphy, depth to bedrock, moisture content and a variety of geotechnical characteristics (*e.g.* penetration test data, liquid and plastic limits, shear wave velocity, shear strength, water table). The database includes over 1700 testholes concentrated along the Trans-Canada Highway, in the Chilliwack, Sardis and Vedder Crossing areas, along the Fraser River and Vedder Canal dykes, and along B.C. Hydro's Main Transmission Line (Figure 1). The database also includes accurate location information for each geotechnical hole or data collection site, the agency that collected the data, the client and the date of collection (see Monahan and Levson, this volume).

The database was supplemented by a field program to obtain new high quality geotechnical data. Three types of field tests were conducted at eleven different locations. Seismic cone penetration tests (SCPT's) were conducted by Conetec Investigations Ltd. at 10 sites (numbered locations on Figure 2) with sandy or silty soils where the method is most suitable. Closed Becker penetration tests (BPT's) and spectral analysis of surface waves (SASW) tests were conducted at three locations in gravel rich areas to assess the liquefaction susceptibility of these deposits. Open Becker tests were also conducted at two of these sites (8 and 13 on Figure 2) to penetrate the near surface gravels and allow for deeper

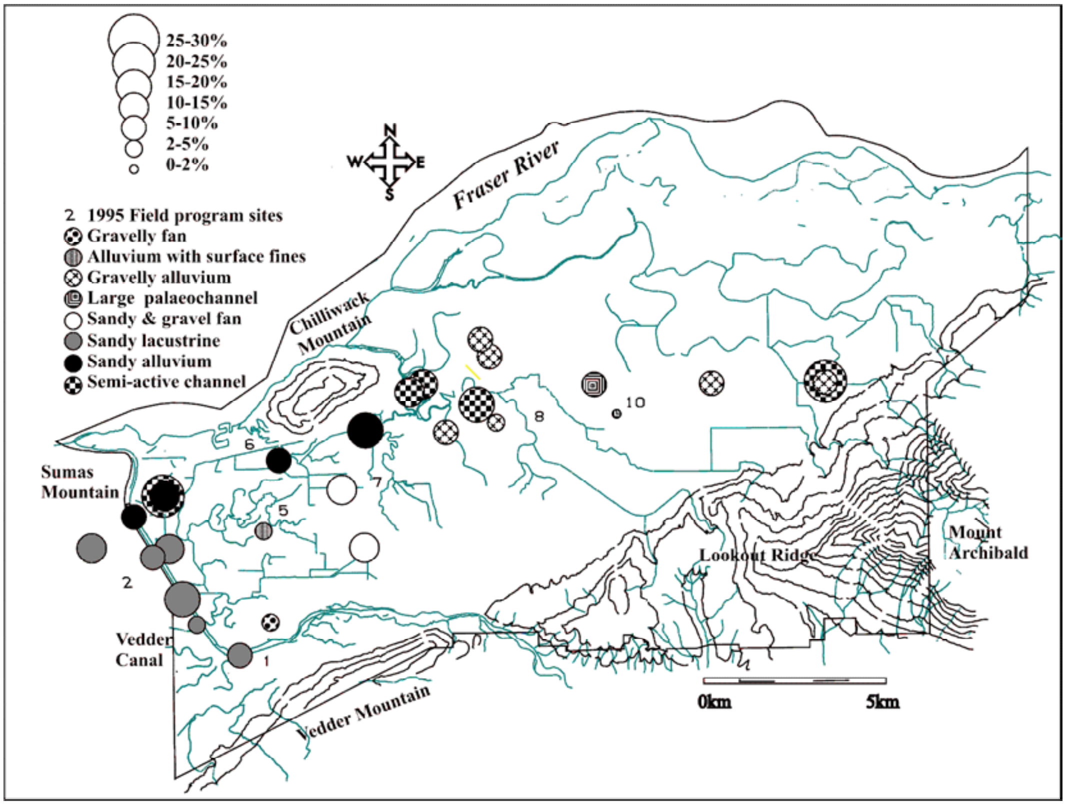


Figure 2. Depositional Environment vs. PLS.

SCPT's and to collect lithologic samples from the gravelly parts of the section. Sample logs of cone penetration and down-hole shear wave data are provided in Figures 3 and 4, respectively.

The surficial geology of the Chilliwack study area was described and mapped at a scale of 1:50,000 by Armstrong (1960, 1980a, b; 1984). These compilations have been integrated with geotechnical borehole data collected during the pilot program (see below and Figure 1), to produce a subsurface geological model of the area (Monahan and Levson, this volume). The Fraser River floodplain, which dominates the study area, is underlain by about 50 metres of sand and gravel interbedded with silt and peat that is interpreted to represent a prograding deltaic and overlying fluvial sequence. These deposits are underlain by Holocene and/or earlier glaciomarine (?) silts, clays and sands that locally extend to depths of over 400 metres. The Fraser River floodplain deposits pass laterally into Holocene lacustrine sands, silts and clays in the Sumas Valley (Cameron, 1989). Gravels deposited in an alluvial fan where the Chilliwack-Vedder River enters the Fraser Lowland are over 35 metres thick at the mountain front and have prograded over older deposits in the Sumas and Fraser River valleys (Dakin, 1994). A large area of landslide debris that overlies glaciogenic deposits and is capped by up to 10 metres of soft silt, peat and marl, occurs in the eastern end of the study area (Figure 2). Upland areas, such as the Promontory Heights-Ryder Lake Upland, are mantled by glacial deposits and locally are capped by up to several metres of loess.

The next step in the program was the compilation of a chronostratigraphic surficial geology map focusing on the Fraser Lowland and Promontory - Ryder Lake upland area. The map was compiled at a 1:20,000 scale from existing sources, aerial photographic mapping and field studies. Data collected for each map unit included information on the type, geomorphic characteristics, age, genesis and thickness of surficial sediment that dominates each map unit.

Surficial geology and geotechnical data were then digitized and inputted into a GIS format to integrate the two types of data and to allow further analysis. Liquefaction and amplification hazards were evaluated by Klohn-Crippen

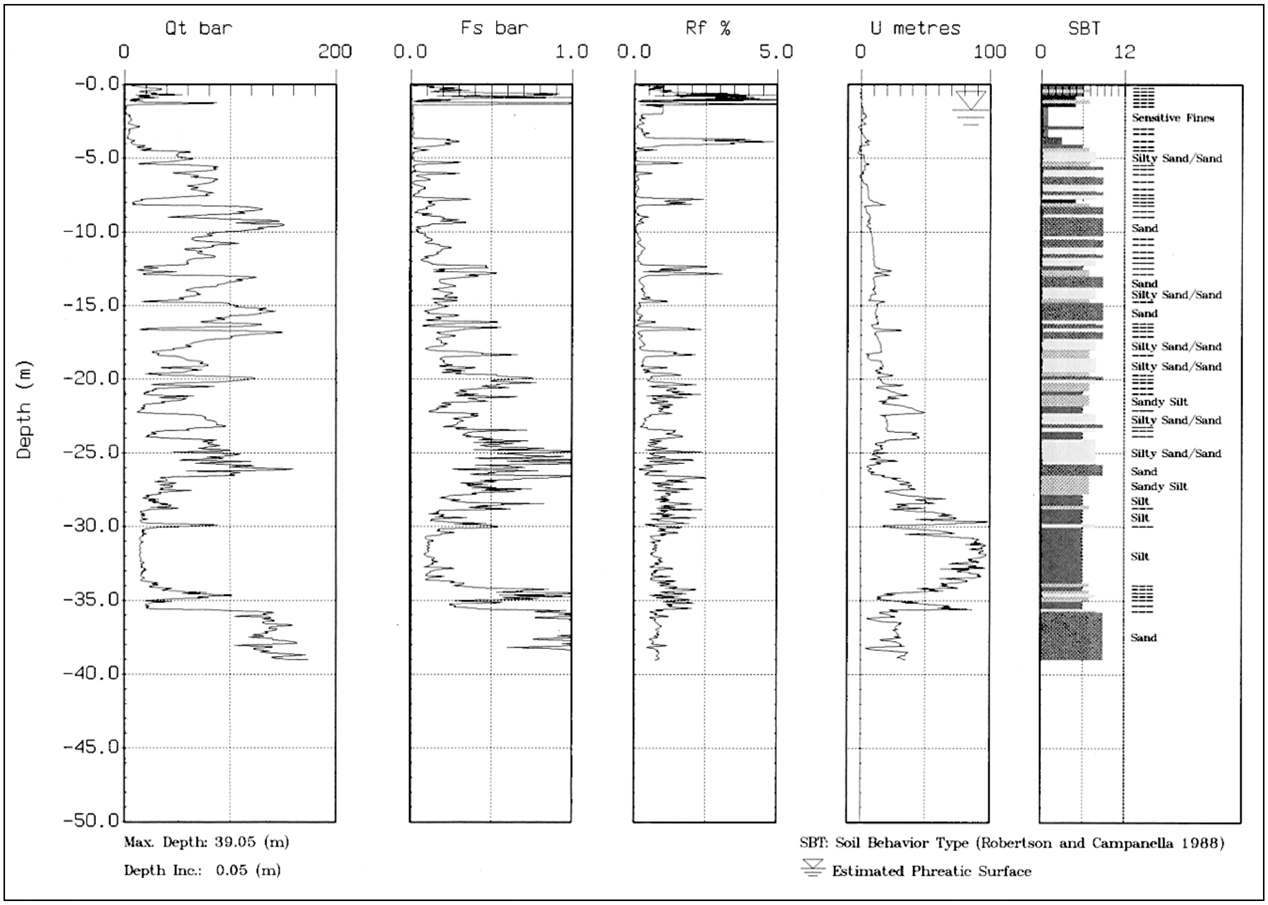


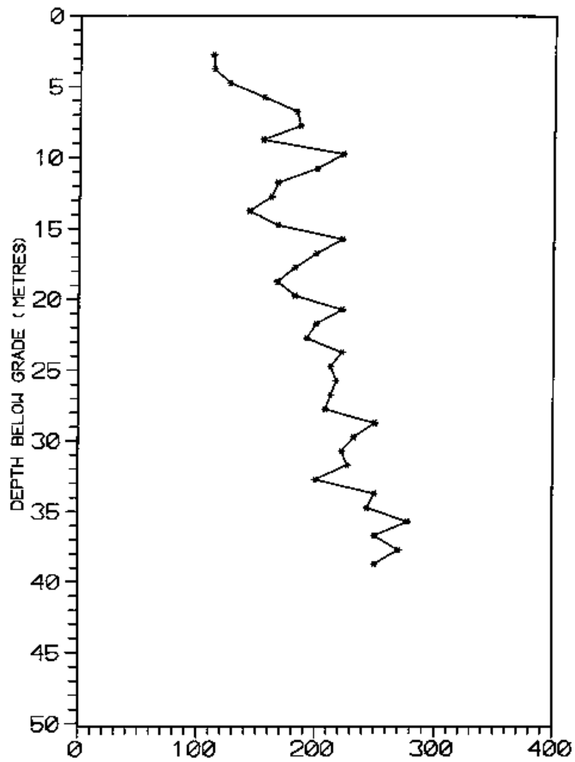
Figure 3. Sample cone penetration test log showing cone bearing (Qt), sleeve friction (Fs), fuction ratio (RF), pore pressure (U) and soil behavior type (SBT).

Consultants Ltd. at specific sites within the map area where good quality geotechnical data was available. Liquefaction potential was estimated by assessing the probability of liquefaction occurring at a number of sites in a 50 year period, based on the NBCC seismicity model and the local geologic and geotechnical site conditions. Preliminary results of this analysis are shown in Figure 2. The liquefaction probability for each site includes a measure of severity of surface disruption (PLS), which is a function of the depth and thickness of each liquefiable unit. Dot size on the map corresponds to liquefaction potential and sites with similar surface and subsurface geology are coded with the same pattern. The figure also illustrates the relationship between surficial geology and liquefaction potential. For example sequences along partially abandoned channels on the Fraser River floodplain have the highest PLS whereas coarse alluvial fan deposits have the lowest mean PLS in the map area.

Compilation of an earthquake-induced liquefaction hazard map of the study region showing liquefaction ‘susceptibility’ (Level 1 map) and liquefaction ‘potential’ (Level 2 map), at a scale of 1:20,000, is currently in progress. Mapping standards are following the general guidelines previously published by the Resource Inventory Committee (RIC Report 017). To complete the ground-motion amplification hazard assessment, additional geophysical data are needed to estimate the total thickness and velocity structure of the Holocene section. Further work on the project may include a variety of geophysical methods such as reflection seismic or ground penetrating radar lines in selected areas where borehole data are lacking (Monahan and Levson, this volume) or where specific issues need to be addressed.

CONCLUSIONS

Earthquake hazard maps are essential tools for effective emergency and landuse planning. The results of a survey, given at an earthquake



SHEAR WAVE VELOCITY (METRES/SEC)
SCPT-95-1

Figure 4. Shear Wave Velocity vs. Depth B.C.G.S.B.

hazard mapping conference for planners, demonstrate that there is a strong need for these maps in British Columbia. These maps can be used to aid in setting priorities for seismic upgrading or remedial work on existing facilities. For emergency planners they are useful for identifying critical facilities that are geologically the most vulnerable including lifeline systems, transportation corridors and emergency centres such as fire halls or medical facilities.

Relative earthquake hazard maps can be produced from surficial geology data and from the large geotechnical database that exists for most urban areas. They may reflect one or more hazards, most commonly including liquefaction and amplification hazards. Susceptibility to liquefaction and ground-motion amplification are related to site geology. In general, loose sandy or silty soils are susceptible to liquefaction and thick clays or peats with low shear wave velocities pose an amplification hazard.

A pilot earthquake mapping program in the Chilliwack area is the first of its kind in the province. The first phases of the program have focused on collection of geotechnical data, 1:20,000 scale surficial geology mapping, a field program of seismic cone and Becker penetration tests, and integration of geologic and geotechnical data to produce liquefaction susceptibility and ground motion amplification (Level 1) hazard maps. Probabilistic assessments of liquefaction that reflect the relative severity of ground disruption at a number of sites in the Chilliwack region demonstrate the relationship between geology and the liquefaction hazard and provide a more quantitative determination of the liquefaction hazard in each map unit (Level 2 map).

Although standards and methods for earthquake hazard mapping exist, few mapping programs have been implemented in British Columbia. Earthquake hazard mapping in the province should initially emphasize liquefaction, amplification and landslide hazards, although other hazard types will also be important in some regions. A comprehensive earthquake hazard mapping program will provide the information necessary for effective landuse and emergency planning, will allow for better allocation of funds for seismic upgrading programs and, through policy development and mitigative measures, may help prevent loss of life, injury and property damage in an earthquake.

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SEISMIC MICROZONATION ASSESSMENT AND MAPPING FOR LAND-USE PLANNING: DATA AVAILABILITY, SURVEY RESULTS AND REVISED DATA MODEL

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INTRODUCTION

This paper presents the results of work carried out under contract to the Ministry of Energy, Mines and Petroleum Resources, Geological Survey Branch. Results of a survey of selected British Columbia communities regarding availability of data suitable for seismic microzonation mapping are described. A revised version of the data model presented by Klohn-Crippen (1994) is also presented. Data requirements for liquefaction hazard and ground-motion amplification hazard mapping, which were first presented in the report noted above, are also summarized.

DATA AVAILABILITY SURVEY

GENERAL

The goal of the survey was to assess the availability of data suitable for seismic microzonation mapping in selected communities across British Columbia. A copy of the questionnaire developed in conjunction with the Geological Survey Branch to guide the survey is included as Figure 1. The results of the survey, combined with the results of an independent study on data availability in Richmond, British Columbia by the Geological Survey of Canada (Monahan and Lutemauer, 1994 are summarized below.

Agencies contacted in the survey included municipal engineering departments, local Ministry of Transportation and Highways (MOTH) offices and at least one geotechnical consultant in each community. Names and phone numbers of those contacted are summarized in Table 1. The targeted communities were: Victoria, Nanaimo, Chilliwack, Prince Rupert, Kelowna, Kitimat, Prince George. Locations of the targeted communities are shown on Figure 2, which also indicates relative seismic hazard across the province in terms of estimated peak ground accelerations for 1000-year ground motions.

MOTH branch offices in Terrace (which serves the Prince Rupert and Kitimat areas) and Burnaby were also contacted. Most of the survey participants were contacted by phone, with questionnaires being filled out based on their verbal responses. In some cases, questionnaires were faxed to the participants so they could complete the survey at their convenience.

Other potential sources of geotechnical data, not surveyed as part of this assignment, include other provincial and federal ministries and Crown corporations, such as BC Hydro and the Geological Survey of Canada, regional districts and private industry (*e.g.* pipeline, mining and forestry companies).

SURVEY RESULTS

This section summarizes responses to the data availability survey and the GSC Richmond Pilot Project. Most municipalities have geotechnical records on file, typically in hard-copy format, which are publicly available, though not necessarily easily accessed by a catalogue system. The number and type of projects for which geotechnical data are retained may be limited however (*e.g.* municipal structures only), especially in smaller communities.

At the two extremes, Richmond has a considerable amount of geotechnical data collected in the building permit application process, whereas Prince Rupert has almost none. Despite its size, the City of Victoria also claims to have little geotechnical data, except for some shallow information along city streets. The GSC study indicated that not all municipalities in the Greater Vancouver area require geotechnical data to be submitted with building permit applications and thus would not be able to provide as much data as Richmond.

MOTH retains geotechnical data for many existing and proposed highway corridors throughout the province. The files are typically stored in hard-copy format in the head office in Victoria and in various branch offices. All factual data are publicly available through the Freedom of Information Act;

release of data interpretation is not legally required.

MOTH typically collects data from drill holes, test pits and cone penetration tests (CPT), as well as airphoto coverage and geophysical surveys in selected areas, all related to highways projects. MOTH has also recently completed seismic microzonation mapping along highway corridors in the South Coast region and part of Vancouver Island, and has similar projects planned for the remainder of Vancouver Island and central British Columbia. All geotechnical data retained by the ministry is catalogued under its own system, which was referred to by some as "difficult", and generally dates back to about the early 1960s.

Geotechnical consultants across the province have typically retained ground information since their inception, with the oldest firms dating back to the early 1950s. Some firms have branch offices which concentrate on projects in specific communities (*e.g.* Nanaimo, Prince George) whereas others retain records for a variety of projects throughout the province in a central office. The data are typically catalogued, but not publicly available. Most consultants stated that their clients' permission would be required for release of any geotechnical data, and even then some reluctance was expressed.

Results of the GSC Richmond Pilot Project indicate that data can be categorized as either immediately available (*e.g.* data acquired by public agencies such as MOTH, Vancouver International Airport Authority, BC Hydro and the Geological Survey of Canada), potentially available (*e.g.* data acquired by consultants for public structures such as schools, municipal buildings and wastewater treatment plants) or not currently available (*e.g.* data acquired by consultants for private clients). The amount of data falling into the latter two categories was estimated by reviewing geotechnical engineering reports for a selection of building permit applications for projects of high monetary value. The amount of immediately available data was assessed by contacting the responsible agencies directly.

Organization: ______________________
Contact Name: ______________________
Position: ______________________
Phone Number: ______________________
Address: ______________________
____
____

1. Do you retain records of local geotechnical data?
   If no, what is the best source of local geotechnical data?
   If yes, continue with survey...
2. For what area?
3. Since when have records been kept?
4. For what kinds of projects?
5. Where or by whom are records retained?
6. What form are records stored in? e.g. hardcopy, microfiche, GIS (details on software/hardware used), other
7. What kinds of data are retained? Do you have data collection standards or QC?
   e.g. water well logs
   water well or piezometer levels
   drill hole logs
   test pit logs
   airphoto coverage (with or without interpretation)
   geophysical surveys
   in situ testing
   e.g. cone penetration tests
   dynamic cone penetration tests
   pressuremeter tests
8. Estimate of number of test points available: total number or number per unit area.
9. Right of access to records?
10. Ease of access to records? e.g. catalogued? record keeper in charge?
11. To what percent/portion of the total geotechnical work done in your area do you have access and/or records?
12. Would your organization be interested in seismic microzonation maps for your area.

Figure 1. Seismic Microzonation Data Availability Survey.

Geotechnical test holes identified during the study included about 1650 drill holes, 275 cone penetration tests and 160 dynamic cone penetration tests at 280 sites on Sea Island and Lulu Island west of No. 6 Road. Of these, approximately one-half of the drill holes and one-third of the penetration tests representing two-thirds of the identified sites were classified as immediately available. Geotechnical data acquired by public agencies and for public structures was considered to provide good overall coverage of

Table 1. Data Availability Survey Contacts.

COMMUNITY	MUNICIPAL OFFICE	LOCAL MOTH[1] OFFICE	CONSULTANTS
Victoria	D. Leslie	D. Lister	J. Sobkowicz Thurber Engineering
Nanaimo	V. Scheltgen	W. Janusson	B. Musgrave HBT Agra
Chilliwack	D. Basu	M. Oliver (MOTH, Burnaby)	None locally
Prince Rupert	B. Thompson	F. Maximchuk (MOTH, Terrace)	D. Hawkes Levelton (Richmond)
Kitimat	D. Harrison		R. Lapointe Lapointe Engineering
Kelowna	W. Barton	None locally	B. Carlson Golder Associates
			B. Evans UMA Engineering
Prince George	D. Halldorson	N. Polysou	C. Workman HBT Agra

NOTE: (1) MOTH = British Columbia Ministry of Transportation and Highways

the area, with the data acquired for private clients being concentrated mainly in the commercial core.

DISCUSSION

The greatest amount of currently 'available' geotechnical data resides with public agencies, including municipalities, federal agencies such as the Geological Survey of Canada and Public Works Canada, crown corporations and provincial ministries such as MOTH and the Ministry of Environment, Lands and Parks. An equal or probably greater volume of data is retained by local geotechnical consultants, who often have better data filing and retention than the clients they work for. However, consultants are typically reluctant to make geotechnical data available because of concerns related to the following issues:

- Data ownership *(i.e.* does data 'belong' to the client who paid for the consultant's services?).
- Liability (*i.e.* will the consultant be subject to threat of legal action from anyone in possession of data obtained or supplied by the consultant?).
- Competitive advantage (*i.e.* will the consultant lose advantage over competitors by releasing geotechnical data?).

In our opinion, these concerns can probably be resolved to the benefit of both the public and the consulting companies. One option may be to invite the geotechnical community to help develop guidelines for release of geotechnical information to a central database. Liability concerns could be addressed by assuring that any release of data from the database is done so anonymously.

This central database could capture much of the site investigation results from the past four decades of geotechnical engineering in the province. The costs of retrieving data from various agencies and setting up and maintaining the database would be offset by the potential costs of duplicating site investigation work already done. Provisions should also be made for frequent or ongoing updating of the database to ensure it remains current, and given the errors discovered in the Vancouver database, Monahan and Luternauer (1994) also suggest retention of test-hole logs in hard-copy format for future reference.

The Vancouver database, which contains geotechnical data from the period 1913 to 1973 in a DOS database format (Geological Survey of Canada Open File 2532), is the only attempt identified to date in British Columbia to compile existing geotechnical information. The goal of the Richmond Pilot Project referred to above was to assess data availability for updating the Vancouver database.

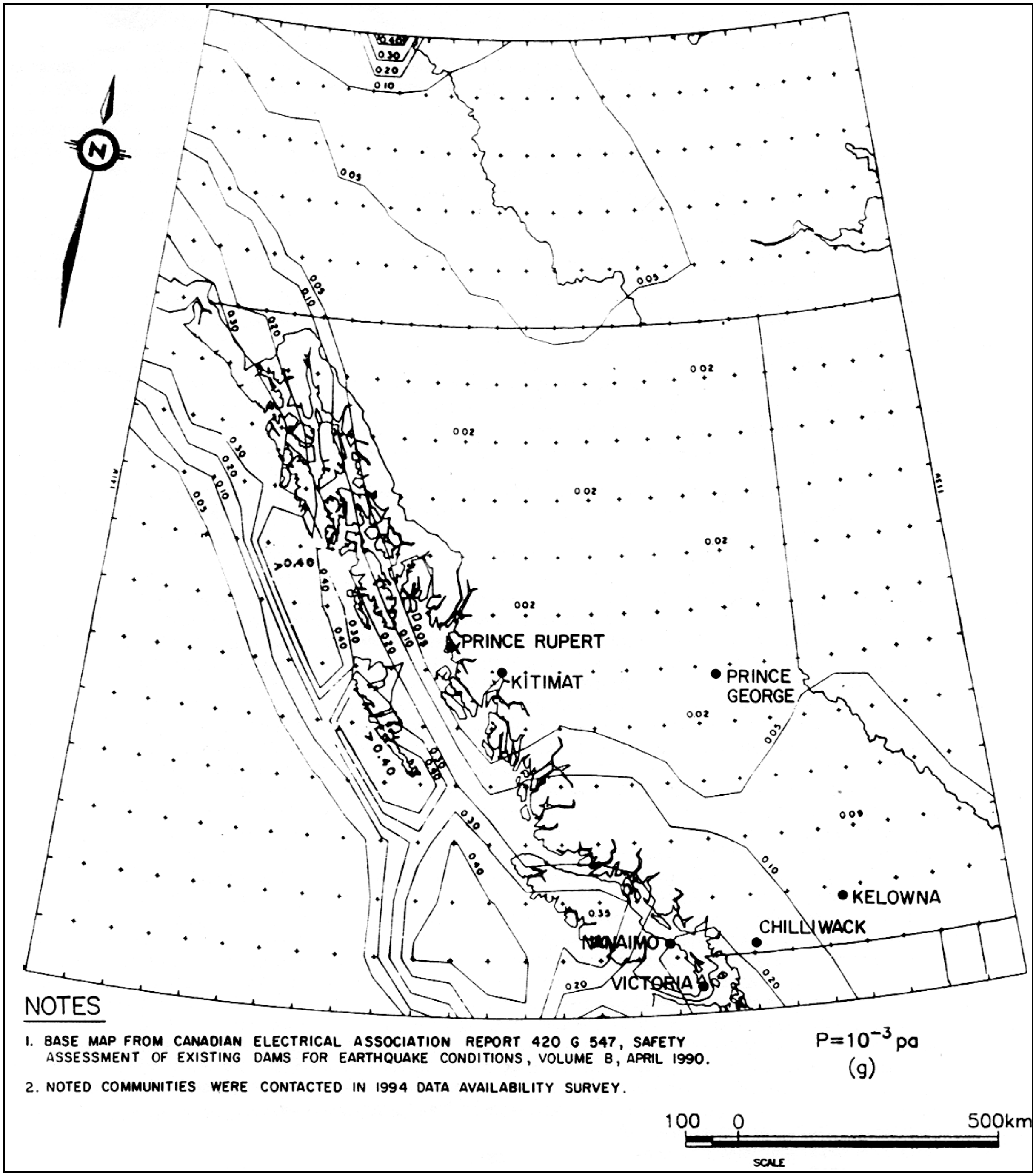

Figure 2. Locations of Targeted Communities.

Assessment of the suitability of information contained in the Vancouver database for seismic microzonation mapping is outside the scope of this assignment.

The scope and format of the data availability survey precluded thorough investigation of data quality, which would require inspection of a large sample of the actual data. However, our experience indicates that data quality varies widely with time and the practitioner. Not all available data will be useful for the higher levels (i.e. Level III) of seismic hazard mapping particularly, although most of the data will be use- ful for the more basic maps (i.e. Level I and perhaps Level II).Some data, such as results of standard penetration tests, are influenced by a number of factors, all of which are not necessarily recorded on, or apparent from, test-hole logs and the accompanying reports. Therefore, engineering judgement will be required to

Table 2. Revised Data Model

NAME	LIQUEFACTION HAZARD			GROUND MOTION AMPLIFICATION HAZARD		
DEFINITION	LEVEL			LEVEL		
ATTRIBUTES	I	II	III	I	II	III
Entered by	-	-	-	-	-	-
Date of entry or update	-	-	-	-	-	-
Regional district	-	-	-	-	-	-
Municipality	-	-	-	-	-	-
Location (other description)	✓	-	-	✓	-	-
Latitude	-	✓	✓	-	✓	✓
Longitude	-	✓	✓	-	✓	✓
Estimated positional accuracy	-	-	-	-	-	-
NTS map reference (e.g. 92 G 3 a)	-	-	-	-	-	-
UTM grid northing	-	-	-	-	-	-
UTM grid easting	-	-	-	-	-	-
Surface elevation (geodetic, metric)	✓	✓	✓	✓	✓	✓
Bottom of test-hole elevation	-	-	-	-	-	-
Description of test hole:						
drill or test type	✓	✓	✓	✓	✓	✓
mud type	-	-	-	-	-	-
instrument description	✓	✓	✓	✓	✓	✓
hole diameter	-	-	-	-	-	-
Test hole completion date	-	-	-	-	-	-
Test hole data source:						
document title	-	-	-	-	-	-
document author	-	-	-	-	-	-
document date	-	-	-	-	-	-
intended use	-	-	-	-	-	-
Comments on data limitations	-	-	-	-	-	-
Estimated accuracy of vertical positions	-	-	-	-	-	-
Subsurface conditions						

NAME	LIQUEFACTION HAZARD			GROUND MOTION AMPLIFICATION HAZARD		
DEFINITION	LEVEL			LEVEL		
ATTRIBUTES	I	II	III	I	II	III
Atterberg limits:						
sample elevation	-	-	-	✓	✓	✓
plastic limit	-	-	-	✓	✓	✓
liquid limit	-	-	-	✓	✓	✓
Shear wave velocity	-	-	-	-	-	✓
elevation	-	-	-	-	-	✓
Grain size						
sample elevation	-	-	✓	-	-	-
D_{10}	-	-	-	-	-	-
D_{50}	-	-	✓	-	-	-
Percent fines (i.e. passing # 200 sieve, <0.075 mm dia.)	-	✓	✓	-	-	-
clay fraction	-	-	-	-	-	-
sample elevation	-	✓	✓	-	-	-
CPT results: (required in absence of SPT results):						
elevation	-	✓	✓	-	-	-
tip resistance	-	✓	✓	-	-	-
pore pressure (behind cone tip)	-	✓	✓	-	-	-
friction	-	✓	✓	-	-	-
Shear strength	-	-	-	-	-	✓
elevation	-	-	-	-	-	✓
description of test	-	-	-	-	-	-
Water level elevation	✓	✓	✓	-	-	✓
top of measurement zone, elevation	✓	✓	✓	-	-	✓
bottom of measurement zone, elevation	✓	✓	✓	-	-	✓
date	-	-	-	-	-	-
instrument type/ description	-	-	-	-	-	-
List of any other test data available	-	-	-	-	-	-

(repeat as many layers as required) Soil Layer 1:							Bedrock elevation	-	-	-	✓	✓	✓
bottom elevation	✓	✓	✓	✓	✓	✓	rock type/ description	-	-	-	-	-	✓
USCS[2] classification	-	-	-	-	-	-	Inventory number (references to original test hole log)	✓	✓	✓	✓	✓	✓
material description	✓	✓	✓	✓	✓	✓	Test results (repeat as many of each type as required)						
geologic interpretation or name	-	-	-	-	-	-	Moisture content	-	✓	-	-	-	✓
SPT blowcount for final 30 cm or 45 cm drive (uncorrected)	-	✓	✓	-	-	-	sample elevation	-	✓	-	-	-	✓
mid-test elevation	-	✓	✓	-	-	-							

CURRENT SOURCES: Ministry of Transportation and Highways; Ministry of Energy and Mines, Geological Survey Branch; Ministry of Environment, Land and Parks; Municipalities; Ministry of Education; Regional Districts; Geological Survey of Canada; Private Industry; Consultants; Other public or private agencies

CUSTODIAN AGENCY: Ministry of Energy and Mines, Geological Survey Branch

GEOMETRY: Point

COMMENTS: This entity summarizes surficial geology information which can be used to help assess site specific seismic hazard levels for liquefaction and ground motion amplification.

NOTE: (1) Data model follows format established by the British Columbia Resources Inventory Committee
(2) Unified Soil Classification System

incorporate these data into the seismic microzonation mapping process.

REVISED DATA MODEL AND DATA REQUIREMENTS SUMMARY TABLE

Klohn-Crippen (1994) presented a data model for recording geotechnical test-hole data consistent with the format developed by the British Columbia Resources Inventory Committee. The data model has been revised to indicate which data attributes are required for each level of liquefaction hazard and ground-motion amplification hazard mapping (see Table 2). Note that this data model has not yet been tested in an actual geographic information system mapping application, and that refinement of the model with experience will be required.

The data model is intended for recording information from geotechnical test holes, which is only one type of information necessary for seismic microzonation mapping. Other types of data required for mapping (*e.g.* topography, surficial geology) are summarized in Table 3.

Table 2 indicates only the minimum data requirements for each mapping level and is not intended to serve as a guide to what information should be recorded in a database. For example, while date of drilling is not required for mapping purposes, it should be recorded for future reference, if available. Similarly, Table 2 is not intended as a guide to what information should be acquired in an investigation program. Some geotechnical information not considered necessary for a particular map type/level should be obtained in an investigation program regardless, especially where it can be obtained economically and will add considerably to the understanding of ground conditions. For example, although not required for all mapping levels, soil moisture content should generally be determined and recorded.

Minimum data requirements have been tabulated for the three levels of liquefaction hazard mapping and ground motion amplification hazard mapping described in Part II, Sections 2 and 3, of the 1994 report by Klohn-Crippen. These data requirements are presented in Table 3.

Table 3. Minimum Data Requirements for Liquefaction Hazard and Ground Motion Amplification Hazard Mapping

MINIMUM DATA REQUIREMENTS	LIQUEFACTION HAZARD			GROUND MOTION AMPLIFICATION HAZARD		
✓ = minimum requirements	Level I	Level II	Level III	Level I	Level II	Level III
	Liquefaction Susceptibility	Liquefaction Potential	Permanent Ground Displacement	Qualitative (after Finn 1992)	Quantitative (after Finn 1993)	Site Specific SHAKE Analyses
Topography (elevation contours)	✓	✓	✓	✓	✓	✓
Groundwater table elevation	✓	✓	✓			✓
Surficial geology map, confirmed with limited (Level I) to wide (Level II and III) coverage of geotechnical test holes						
Soil stratigraphy, including: type; thickness; depth		✓	✓	✓	✓	✓
Seed's level ground liquefaction assessment; data required includes: SPT[1] blow counts, CPT[2] or shear wave velocity; soil types, thicknesses and depths; unit weights						
Cornell seismic hazard assessment; data required includes; longitude/latitude of site; regional attenuation function; geometry or surrounding seismic source zones; magnitude/recurrence parameters for each seismic source zone; focal depth (if applicable)		✓	✓		✓	✓
Bartlett & Youd permanent ground displacement model; data required includes; earthquake moment magnitude; horizontal distance from seismic source; SPT blow counts; fines content; mean particle size; ground surface slope; free face height to distance ratio			✓			
Acceleration time-histories for SHAKE input; must be compatible with: earthquake magnitude range; source to site distance; acceleration/velocity ratio; peak ground acceleration						✓
Soil index properties with depth, including: unit weight; Atterberg limits; water content; penetration resistance (cohesionless soils); undrained strength (cohesive soils); maximum shear modulus, variation with strain; damping ratio, variation with strain; shear wave velocity profile						✓

NOTE:
(1) SPT = Standard Penetration Test
(2) CPT = (electric piezo) Cone Penetration Test
(3) Other potential data sources; Bedrock geology maps; Air photographs; Geophysical surveys; Site reconnaissance work; Urban landmarks (e.g. roads, dikes, major structures); Geographic features (e.g. lakes, rivers); Terrain maps (e.g. glacial landforms, fluvial landforms)
(4) Refer to Klohn-Crippen report dated February 1994 for references and further discussion of map types.

REFERENCES

Klohn-Crippen (1994): Preliminary Seismic Microzonation Assessment for British Columbia. Resource Inventory Committee, Report 17, 108 pages.

Luternauer, J.L., Barrie, J.V., Christian, H.A., Clague, J.J., Evoy, R.W., Hart, B.S., Hunter, J.A., Killeen, P.G., Kostaschuk, R.A., Mathewes, R.W., Monahan, P.A., Moslow, T.F., Mwenifumbo, H.W., Olynyk, H.W., Patterson, R.T., Pullan, S.E., Roberts, M.C., Robertson, P.K., Tarbotton, M.R. and Woeller, D.J. (1994): Fraser River Delta: Geology, Geohazards and Human Impact. *Geological Survey of Canada,* Bulletin 481, pages 197-220.

CHILLIWACK SEISMIC MICROZONATION PROJECT - DATA COLLECTION AND GEOLOGICAL OVERVIEW

P.A. Monahan[1] and V.M. Levson[2]

INTRODUCTION

The Chilliwack Seismic Microzonation Project was initiated by the Geological Survey Branch of the Ministry of Energy, Mines and Petroleum Resources in order to map local variations in the potential for seismically induced liquefaction and amplification of ground motion in the Chilliwack area. The project area was defined as all of the District of Chilliwack and adjoining parts of the Regional District of Fraser Cheam west of 121° 45' W in the Fraser Lowland, the adjoining Promontory - Ryder Lake Upland and the Cheam Plateau (Figure 1).

The objectives of the data collection phase of the project were to generate a database of existing geotechnical and other geological data relevant to the assessment of the liquefaction and amplification hazards and to recommend areas where additional work would be required to complete regional coverage. Data collection commenced August 5, 1994 and a field investigation program was conducted in March 1995 to fill in some of the data gaps. These data have been used by the authors to prepare a subsurface geological model of the area, by Thurber Engineering Ltd. to assist in the preparation of a surficial geologic map, and by Klohn-Crippen Consultants to assess liquefaction and amplification hazards (see Levson *et al.,* 1995).

The purpose of this paper is to report on the results of the data collection and fieldwork and to present an overview of the Quaternary geology of the area based on these data.

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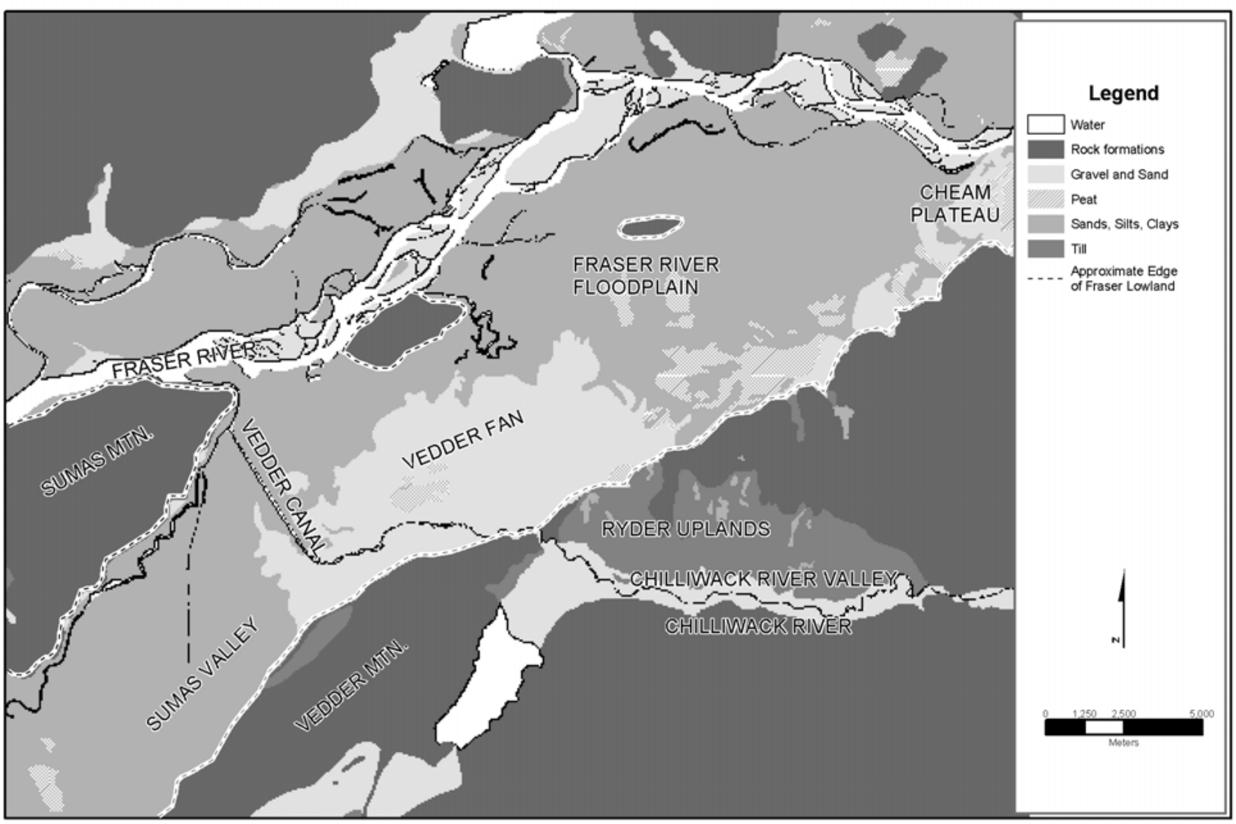

Figure 1. Chilliwack Seismic Microzonation. Principal Geologic Environments modified from Armstrong (1980a, b).

Table 1. Summary of Borehole Data.

	Standard Penetration Tests					Dynamic Cone Penetration Tests					Becker Penetration Tests					Cone Penetration Tests					Other Boreholes				
	0-10m	**10-20m**	**20-30m**	**30+ m**	**TOTAL**	**0-10m**	**10-20m**	**20-30m**	**30+ m**	**TOTAL**	**0-10m**	**10-20m**	**20-30m**	**30+ m**	**TOTAL**	**0-10m**	**10-20m**	**20-30m**	**30+ m**	**TOTAL**	**0-10m**	**10-20m**	**20-30m**	**30+ m**	**TOTAL**
MOTH	12	26	58	27	**123**	4	8			**12**						1	2	25		**28**	234	39	5	3	**281**
Total B.C.Hydro	1				**1**	3	27			**30**	1				**1**	1	2			**3**	1				**1**
Total Other Prov	16	55	7	11	**89**	45	20	2		**67**						12	1			**13**	183	23	2	1	**209**
Total CNR	3	3			**6**	1				**1**											1				**1**
Total District	11	4	3		**18**	15	6			**21**	4	3	5	3	**15**						87	4			**91**
Water Wells	2				**2**																7	58	25	41	**131**
Private Data						4	6	1		**11**											60		1		**61**
Petroleum Expl.																					2				**2**
School Board						38	2			**40**	5	2	2		**9**						116	1			**117**
CFB Chilliwack	12				**12**	76	6			**82**	9	21		1	**31**						134				**134**
Other Sources	2				**2**	4	1			**5**	1	4			**5**	9				**9**	47	2			**49**
Total	53	88	74	38	**253**	190	76	3		**269**	18	27	12	4	**61**	21	3	4	25	**53**	**869**	**128**	**33**	**47**	**1077**

PROCEDURES

Data collection focused on information obtained by or for public agencies rather than private information for the following reasons (Monahan and Luternauer, 1994):

- Data generated by public agencies are easier to obtain, because there are relatively few public agencies that must be contacted to approve release of data, compared to the large number of private developers. Furthermore, public agencies readily authorize release of data to projects that are in the public interest.
- Data generated by public agencies generally provide better regional coverage. Private data tend to be concentrated in the downtown and commercial areas of urban centres.

Data were obtained from the following public agencies:

- District of Chilliwack;
- School District 33, Chilliwack;
- Regional District of Fraser Cheam;
- Chilliwack Hospital;
- University College of Fraser Valley;
- B.C. Ministry of Transportation and Highways (MOTH), Geotechnical and Materials Branch;
- B.C. Ministry of Energy, Mines and Petroleum Resources, Energy Resources Division, for petroleum industry data;
- B.C. Ministry of Environment, Lands and Parks, Groundwater Section. Over 700 water wells are included in its computer database in the area and logs for many of these are available on the Internet. Additional recent well data was on file at the Surrey office of the Groundwater Section;
- B.C. Ministry of Environment, Lands and Parks Water Management Division; in addition to geotechnical data for the dikes and the Barrowtown Pump Station, these files include extensive records of flood levels, erosion and sediment transport in the Fraser and Vedder rivers;
- B.C. Hydro;
- B.C. Buildings Corporation;
- Geological Survey of Canada;
- Canadian National Railway;
- Public Works and Government Services Canada; and
- Canadian Forces Base Chilliwack, Engineering and Environmental Sections.

Data were also obtained from the following private organizations:

- Southern Rail of British Columbia; and
- developers identified in a review of the District building permit files and who

were requested by the District to release their data to the database.

The data were obtained either directly from the agencies or from engineering and architectural consultants who were authorized by their clients to release them. In all cases in which geotechnical consultants provided data, they were informed that they were for the sole use of the Geological Survey Branch and its contractors and would not be part of a public database. In addition, researchers at Simon Fraser University and the University of British Columbia were contacted to determine what research they had conducted in the area.

Data were collected beyond the limits of the project area in order to better understand the regional geological framework of the area.

Because of the large volume and the purely descriptive nature of the water-well data obtained from the Ministry of Environment, Lands and Parks Groundwater Section, the only well logs from this source included in the following discussions are those that provide lithological information from areas in the Fraser lowland where geotechnical data are sparse.

RESULTS OF DATA COLLECTION

The data obtained include 253 standard penetration tests (SPTs), 269 dynamic cone penetration tests (DCPTs), 61 Becker penetration and density tests (driven with either open or closed casing, but with a continuous penetration record), 53 cone penetration tests (CPTs) and 1077 other testholes (those with lithological descriptions only, including test pits, water wells and petroleum tests) (Table 1). For the locations of subsurface data sites, see Figure 1 in Levson *et al.* (this volume). CPT data are restricted to the western part of the project area because there is too much gravel elsewhere. CPTs that include shear wave data (SCPTs) have been conducted at only three sites.

The geotechnical testhole data are unevenly distributed across the project area. The data obtained from MOTH are located primarily along the Trans-Canada Highway. This is the most valuable dataset obtained for the following reasons: it includes the majority of the geotechnical testholes deeper than 20 metres; the largest number of SPTs and most of the CPTs, and it provides a line of section that transects the project area. Geotechnical data from other sources are concentrated in the urban and suburban areas of Chilliwack, Sardis, Vedder Crossing (including CFB Chilliwack) and Promontory Heights and along the Fraser River and Vedder Canal dikes. Most testholes from these sources are shallower than the MOTH data. As a result, the subsurface shallower than 10 metres is reason-ably well documented in these built-up areas but the deeper section is not well controlled. A series of DCPTs along the B.C. Hydro main transmission line provides a useful line of data across the southern part of the Fraser River floodplain. Few geotechnical data are available for the Yarrow, Greendale and Rosedale areas.

Water-well data are in general deeper than the geotechnical data and, although descriptions are often cursory and inconsistent, they do provide lithologic information where geotechnical data are not available. The deepest water well in the Fraser Lowland reached a depth of 512 metres.

Two petroleum exploratory tests are located in the project area: a 345 metre stratigraphic test hole and a 1885 metres exploratory well located adjacent to each other. However, the wireline logs in the well were only run below 640 metres and sample descriptions from these holes are ambiguous.

In addition to geological maps and reports published by the Geological Survey of Canada and other agencies (Armstrong, 1960, 1980a, b, 1984; Halstead, 1961, 1986; Dakin, 1994) several other regional reports relevant to the assessment of liquefaction and amplification were obtained. These include:

- a gravity survey that extends from the Fraser delta to the western margin of the study area (Wild Rose Exploration, 1988);
- a geological investigation of the Cheam Plateau (Smith *et al*., 1991);
- a ground water evaluation of part of the Vedder fan (Dakin and Holmes, 1989);
- a geological investigation of the Sumas Valley based on borehole data (Cameron, 1989);
- soil surveys of region by Comar *et al*. (1962) and Luttmerding (1981). The former covers the entire study area and the latter covers only the western part.

FIELD PROGRAM

A field program to fill some of the data gaps was completed in March, 1995 (ConeTec, 1995). Eight SCPTs were conducted to depths of 8 to 45 metres, with an average depth of 34 metres. They are concentrated in the western part of the project area because there is too much gravel elsewhere.

Becker penetration tests, both open and closed, were conducted to the base of the near surface gravels at 20 metres depths at two sites in the vicinity of the urban area of Chilliwack. SCPTs were conducted below that depth in the cased and open Becker holes. A final site on the Fraser River dikes was evaluated by a closed Becker penetration test to a depth of 12 metres. Spectral analysis of surface waves (SASW) tests were also conducted at the Becker sites to obtain shear wave data.

GEOLOGICAL OVERVIEW

Five principal Quaternary sedimentary environments are recognized in the project area (Figure 1; Armstrong, 1980a, b).

CHEAM PLATEAU

The plateau is underlain by diamicton that is up to 40 metres thick and overlies glaciofluvial sand and gravel, clay and till. The diamicton has been interpreted as a slide deposit (Armstrong, 1980b; 1984), although recently it has been reinterpreted to include till, at least in part (Smith *et al.*, 1991; R. Gerath, personal communication, 1992). In the central part of the Cheam Plateau, the diamicton is overlain by soft silt, peat and marl up to 10 metres thick. Smaller areas mapped as slide deposits by Armstrong (1980b) are located to the southwest, on the southern margin of the Fraser River floodplain.

FRASER RIVER FLOODPLAIN

Quaternary deposits deeper than 50 metres are known from the petroleum exploration tests and a water well 8 kilometres to the east, where they extend to depths of 400 and 500 metres, respectively. They consist largely of silt and clay, with sand being predominant in the upper half of the section at the water well. These deposits are undated, although a tentative correlation with similar deposits in the Sumas Valley suggests that they may be in part postglacial or late glacial glaciomarine.

The deposits below 50 metres are overlain by a unit of Holocene sand up to 30 metres thick (Figure 2). In the western part of the study area, the top of this sand unit dips south and west beneath a unit of interbedded silt, sand and clay that extends into the Sumas Valley. The sand unit is interpreted to be partly deltaic, as suggested by the dipping upper contact in the western part of the study area. Elsewhere the sands are overlain by a unit of sand and gravel capped by silt and peat that extends to the surface. This sand, gravel, silt and peat unit is commonly organized into one or more decametre-scale fining-upward sequences, interpreted to represent formerly active channel-fill and floodplain deposits of the Fraser River. Thick abandoned channel-fill silt deposits occur locally and the gravel content decreases to the west.

SUMAS VALLEY

The maximum known thickness of Quaternary deposits in the Sumas Valley is 186 metres, as recorded in a water well on the northwest side of the valley which did not reach the base of the Quaternary section. A pronounced gravity low (Wild Rose Exploration Services Ltd., 1988) confirms the presence of thick Quaternary fill. Below 60 metres, Quaternary deposits consist primarily of silt and clay which are at least in part normally consolidated. Consequently they are interpreted to be postglacial or late glacial glaciomarine sediments.

The silt and clay sequence is overlain by a unit that is equivalent to the sand unit interpreted to be in part deltaic in the Fraser River floodplain (Figure 2). As this unit descends to the southwest from the Fraser River floodplain, it changes facies from sand to interbedded sand and silt, and is interpreted to be a deltaic bottomset deposit. The latter deposits are overlain by a generally coarsening upward sequence of interbedded silt, sand and clay that extends to the surface in most of the Sumas Valley; this

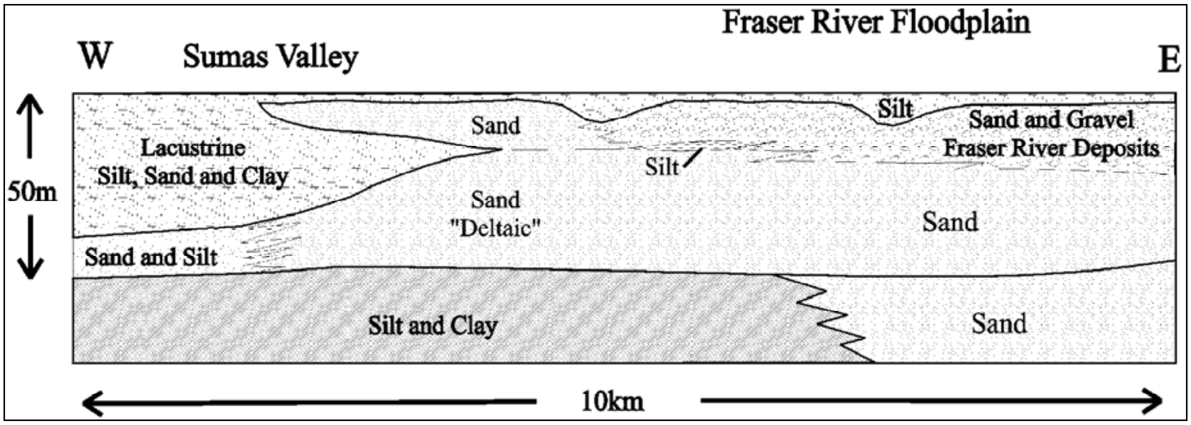

Figure 2. Schematic east-west cross-section illustrating the Holocene stratigraphy of the Chilliwack area.

sequence is interpreted to represent the gradual filling of a lacustrine basin by sediment supplied from the Chilliwack and Nooksack rivers (Cameron, 1989). A lake persisted in the Sumas Valley until historic times. Lacustrine silt, sand and clay are overlain by Fraser River channel sand in the transitional area between the Sumas Valley and the Fraser River floodplain (Figure 2).

VEDDER FAN

A gravel-rich fan extends into the Fraser Valley from the point where the Chilliwack River enters the Fraser Lowland (Armstrong, 1980a, b, Figure 3). The fan has prograded over silt and clay equivalent to the lacustrine deposits of the Sumas Valley and, to a lesser extent, over Fraser River floodplain deposits (Dakin and Holmes, 1989; Dakin, 1994). The gravelly fan deposits are more than 35 metres thick and are an important aquifer. The water table in this aquifer is below the level of the Chilliwack River, indicating that the river is perched (Dakin and Holmes, 1989; Dakin, 1994). The total thickness of Quaternary sediments in this area is unknown.

PROMONTORY HEIGHTS - RYDER LAKE UPLAND

This area is underlain by Late Pleistocene Sumas drift and is locally capped by loess (Armstrong, 1980b). The depth to bedrock commonly exceeds 30 metres.

DISCUSSION

Quantitative determinations of liquefaction susceptibility are usually based on SPT, CPT or shear wave data to depths of 20 metres (Ishihara, 1985; Seed *et al.* 1985; Seed and de Alba, 1986; Robertson *et al.*, 1992; Klohn-Crippen, 1994). In some investigations in the Chilliwack area, DCPTs have been used to approximate SPT "N" values. Becker tests, which are less sensitive to grain size variations than SPTs, have also been used to provide continuous penetration records at gravel-rich sites in the Chilliwack area. However, standardized procedures to calibrate Becker penetration values with the SPT "N" values have only recently been developed (Stewart *et al.*, 1990; Sy and Campanella, 1993, 1994).

Assessment of amplification is usually based on the lithology and shear wave velocity structure of soils to a depth of 35 metres (Finn, 1993, 1994; Klohn-Crippen, 1994). However, a more thorough assessment requires the knowledge of the shear wave velocity structure of deeper sediments, particularly for long-period seismic waves. Furthermore, three dimensional effects may be significant in the Fraser Lowland (Reiter, 1990; Harris *et al.*, 1995).

Significant gaps remain in the regional coverage of geotechnical data that are adequate to assess seismic hazards in the upper 35 metres of the Holocene section. This is particularly true of the gravel-rich parts of the study area including: the northern part of the urban area of Chilliwack, the Fraser River floodplain east of Chilliwack, both north and south of the Trans-Canada Highway, and the Vedder fan. Only water-well data are available for large parts of these areas.

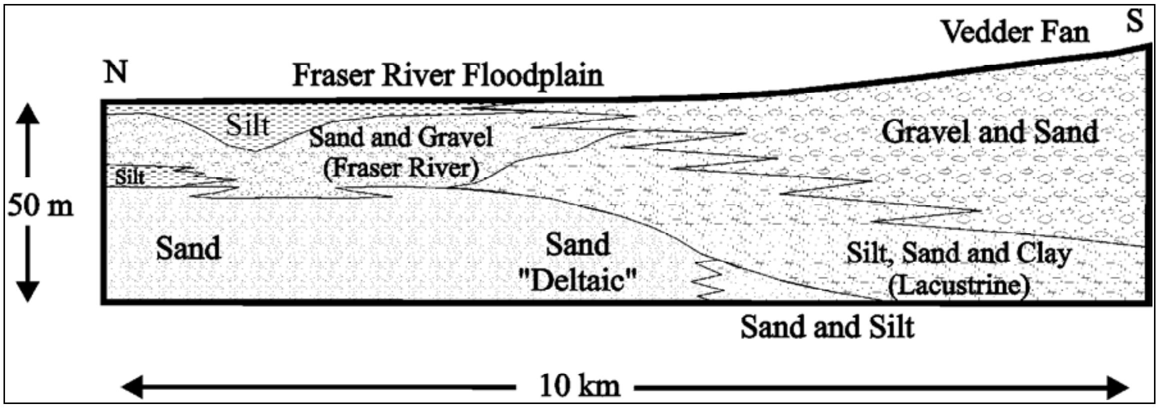

Figure 3. Schematic north-south cross-section illustrating the Holocene stratigraphy of the Chilliwack area.

Furthermore, the stratigraphy and shear wave velocity structure of the deeper part of the Holocene and Pleistocene section remains almost unknown.

RECOMMENDATIONS

Additional field investigations in the gravel-rich parts of the study area would be useful to complete regional coverage of the upper 20 metres of the Holocene section in order to fully evaluate the liquefaction hazard. The most critical areas are the following in the Fraser River floodplain, where the water table is high: the northern part of the Chilliwack urban area, the community of Rosedale, the roads adjoining major sloughs where lateral movements could possibly occur and the Fraser River dikes, which are not built to earthquake standards (Fraser Basin Management Program, 1994). Field investigations could include SASW and Becker penetration tests.

The total thickness and velocity structure of the Holocene and Pleistocene section underlying the Fraser River floodplain, the Sumas Valley and the Vedder fan should be determined in order to more thoroughly assess the amplification hazard. A combination of regional gravity data, selected seismic reflection and deep refraction sites and a program of SASW and deep SCPTs would provide a cost-effective means of estimating the velocity structure of these sediments (J.B. Harris and J.A. Hunter, personal communication, 1995).

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THE ROLE OF EARTHQUAKE HAZARD MAPPING IN DISASTER SIMULATIONS AND EXERCISES: CASE STUDIES FROM BRITISH COLUMBIA

Harold D. Foster,[1] Norman E. Hardy [2] and Colin J.B. Wood [1]

INTRODUCTION

Computer-based damage simulations have a wide variety of potential uses. For example, they are utilized by insurance companies to establish premium rates needed to cover expected average annual damage losses (Friedman, 1984). Computer simulations also have a role to play in land-use planning and the production of disaster plans, where they can be used to reduce vulnerability to hazards (Foster, 1980). They are particularly valuable immediately after major disasters, such as large magnitude earthquakes, as they permit very quick estimates of damage, loss of life and injury, allowing a rapid, yet realistic response. For this reason, computer-based damage simulations are also valuable training tools that can be used to develop realistic and challenging exercise scenarios. This paper describes the development of computer-based earthquake-damage simulations for the municipalities of Victoria and Oak Bay, and discusses their use as a training tool by the British Columbia Ministry of Health and Ministry Responsible for Seniors.

METHODOLOGY

STEP 1

The simulation of earthquake damage and life loss and injury involves five basic steps. The first of these is the production of an earthquake hazard map. Fortunately such maps are available for both Victoria and Oak Bay, having been produced in the 1970's by Wuorinen (1976, 1979). These maps were based on interviews with people that experienced the June 23, 1946 earthquake, a survey of bedrock outcrops, an examination of pre-settlement drainage patterns and reviews of borehole and trenching records. They subdivide Victoria and the Saanich Peninsula into three hazard zones (Figure 1).

Type C zone represents areas where fill has been used extensively in shoreline reclamation and where marshy ground existed prior to development. These areas experienced the highest ground motion amplitudes during the 1946 earthquake. Type A zone includes all areas where bedrock reaches to within 3 metres of the surface. Intensities tended to be lowest in this zone during the 1946 earthquake. All of Victoria and Oak Bay not placed in either zone A or C was assigned to Zone B, thought to represent the "average" seismic hazard zone for the region. It would seem, therefore, that Wuorinen's maps (1976, 1979) should be considered Level 1 (Watts, 1994).

The role of such earthquake hazard maps in computer-based damage simulations is to distinguish spatial differences in the intensity of impact. In southern Vancouver Island, for example, experience seems to indicate that Modified Mercalli intensities are likely to be two classes higher during an earthquake in Zone C than in Zone A. This means that if Greater Victoria was to fall within the regional intensity VIII isoseismal, the Zone C areas might be expected to experience intensity IX, while Zone A areas would be subjected to only intensity VII (Wuorinen, 1976).

STEP 2

To predict the damage such an uneven distribution of intensities might be expected to cause, it is necessary to know the characteristics and geographical location of the infrastructure that is at risk. In 1976 one of the authors was involved in a computer simulation of potential earthquake damage in Victoria (Foster and Carey, 1976). To achieve this, 24 significant categories of land-use and building type were established by a detailed survey of the literature of past seismic disasters.

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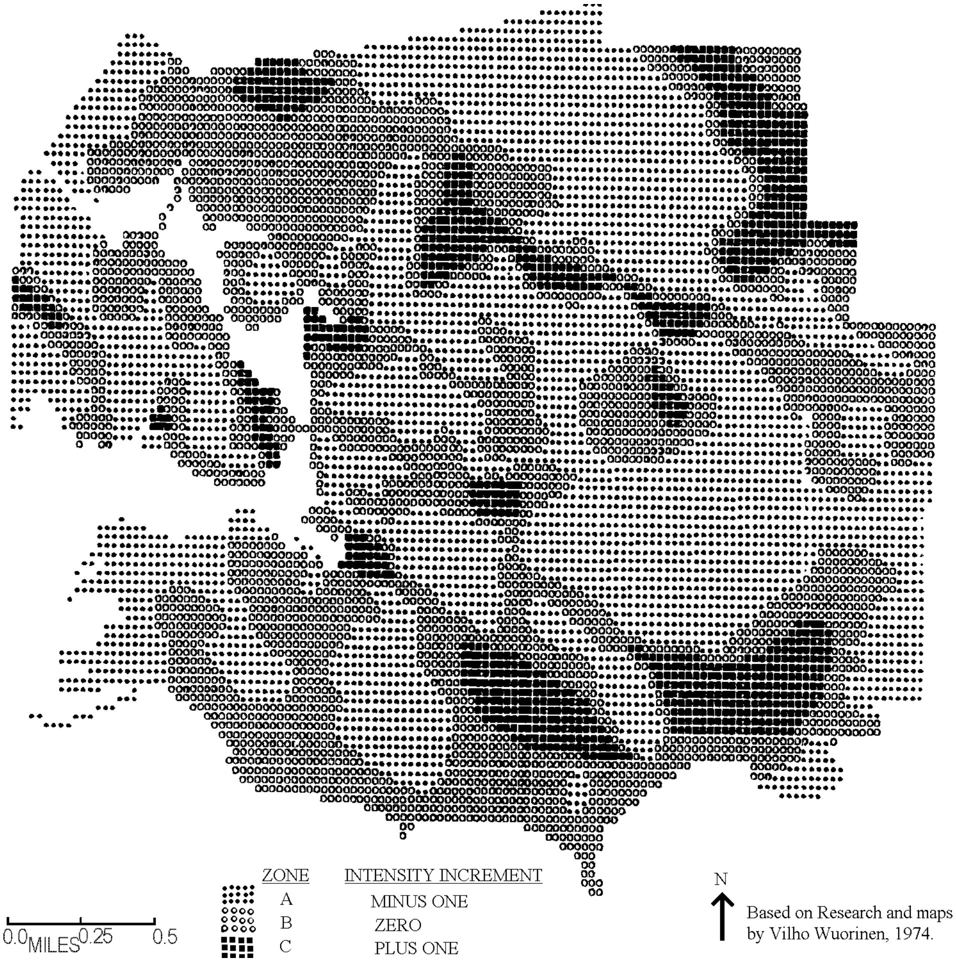

Figure 1. Computerized earthquake hazard map of Victoria

These classes were based on response differences, noted during seismic ground motion experienced elsewhere. The classes identified are illustrated in Table 1.

Because no up-to-date information was available on land-use in Victoria, a building by building survey was undertaken by the authors (Foster and Carey, 1976). The city was gridded and each rectangle so produced represented an area of some 2320 square metres, within which one predominant land-use was identified. Because of the large scale involved, this was commonly a single building. Each structure or land-use was then assigned to the appropriate category as shown in Figure 2. This process was repeated in 1993-94 for Oak Bay, but in this case all individual land uses and building types were identified and placed into one of the 24 categories.

STEP 3

While the accurate prediction of damage to individual buildings is extremely difficult, trends in structural response to seismic events (by particular building types) have been identified elsewhere. These can be used to anticipate general patterns of damage associated with earthquakes of differing magnitudes (Steinbrugge and Bush, 1965; Steinbrugge, 1982).

The cost of repairing a building after an earthquake, expressed as a percentage of its cost of total replacement, is referred to as the damage ratio. A mean of these ratios, for all buildings within a particular category, is known as the mean damage ratio (MDR) and was developed by Foster and Carey (1976) for all 24 structural types used in the land-use classification. This mean value replaces a full set of damage probabilities with a single "average" figure. Table 1 illustrates the resulting matrix.

Table 1. Mean Damage Ratio Matrix.

Structural Classification	Modified Mercalli Intensity VI	VII	VIII	IX	X	XI
No construction; parks, cemeteries	0.0	0.0	0.0	0.0	0.0	0.0
Asphalt; playgrounds, tennis courts, parking lots	1.0	15.0	40.0	66.0	100.0	100.0
One to three story residential; wood-frame; less than 6000 square feet	0.3	1.25	8.25	12.0	20.0	50.0
One to three story residential; masonry; less than 6000 square feet	2.0	4.0	20.0	70.0	98.0	100.0
Single story business and personal service occupancy; wood-frame; less than 6000 square feet	0.5	1.5	9.0	15.0	25.0	60.0
Single story business and personal service occupancy; masonry and hollow brick. Less than 6000 square feet	1.0	3.0	20.0	75.0	99.0	100.0
Two to three story business and personal service occupancy; wood-frame; less than 6000 square feet	1.0	2.5	12.0	22.0	35.0	75.0
Two to three story business and personal service occupancy; masonry and hollow brick; less than 6000 square feet	2.0	5.0	25.0	85.0	100.0	100.0
Medium and low hazard industrial buildings; three stories or less; wood-frame	2.0	4.0	20.0	92.0	100.0	100.0
Medium and low hazard industrial buildings; three stories or less; masonry or hollow brick	2.25	4.5	22.5	99.0	100.0	100.0
Medium and low hazard industrial buildings; three stories or less; steel frame	0.75	1.8	8.5	45.0	85.0	100.0
Buildings with a ductile moment resisting space frame	4.0	8.5	18.0	45.0	65.0	85.0
Buildings with a dual structural system consisting of a ductile moment resisting space frame and ductile flexural walls	4.5	9.5	20.0	50.0	72.0	94.0
Buildings with a dual structural system consisting of a ductile moment resisting space frame and shear walls; also, buildings with ductile flexural walls	5.0	10.5	22.0	54.0	80.0	100.0
Buildings with reinforced masonry and unreinforced concrete frames and walls	2.5	8.0	25.0	98.0	100.0	100.0
Sub-aerial bulk fuel storage tanks	0.0	9.0	40.0	60.0	90.0	100.0
Storage tanks and content other than fuel storage tanks; elevated tanks		0.0	12.0	60.0	99.0	100.0
Smokestacks, sandpipes, and similar structures not supported by a building	20.0	60.0	100.0	100.0	100.0	100.0
Dams, reservoirs	0.0	2.0	30.0	70.0	80.0	96.0
Poured concrete walkways, piers, and retaining walls	0.0	2.0	25.0	65.0	75.0	90.0
Steel frame (through truss) bridges	0.0	3.0	35.0	75.0	100.0	100.0
Reinforced concrete bridges	0.0	0.0	8.0	40.0	80.0	100.0
Wood pile piers; woodpile wharves; wood pile bridges	0.0	0.0	10.0	25.0	35.0	66.0

It consists of a mean damage ratio for each structural classification, for earthquakes generating Modified Mercalli intensities of VI to XI on "normal" ground, that is Zone B. Values one intensity above and one below the range actually simulated for Victoria and Oak Bay were necessary because of the amplification of ground movement in areas of fill and former swamps (Zone C) and its reduction in areas where bedrock is at or near the surface (Zone A). The design of this matrix has been discussed in more detail elsewhere (Foster and Carey, 1976).

STEP 4

Having computerized an earthquake hazard map and the overlying infrastructure, and incorporated a mean damage ratio matrix (identifying expected damage to particular buildings at specific Modified Mercalli intensities), it becomes possible to simulate earthquake damage. This was achieved for Victoria using a computer program designed by Foster and Carey (1976). In the case of Oak Bay, a 1994 simulation was produced using PAMAP, one of the many geographical information systems that have become available for use (PAMAP Technologies Corporation, 1991). Examples of anticipated earthquake damage for Victoria, first published in 1976, are reproduced here as Figures 3 and 4, whilst those for Oak Bay, created in 1994, are presented as Figures 5 to 10. These simulations illustrate damage expected from seismic ground motion and do not include the effects of associated mass movements, tsunamis, fires or other secondary hazards.

Such computer simulations of the earthquake damage potential in Victoria and Oak Bay demonstrate several important factors. The older section of Victoria, including almost all the central business district, is the highest risk area. Here, many nineteenth century brick and lime mortar industrial and business buildings are located on unstable sediments. Pockets of high risk also occur along former stream channels, or where rock basins have been drained and used as construction sites. This situation contrasts with reasonably low risk in many residential areas in both Victoria and Oak Bay, particularly where wooden frame buildings rest on, or nearly on, bedrock.

Damage state of building	***Fraction dead***	***Fraction injured***
None	0	0
Light	0	0
Moderate	0	1/100
Heavy	1/400	1/50
Building condemned	1/100	1/10
Collapse	1/5	4/5

Source: Whitman *et al.* (1973).

Table 2. The Relationship Between Mean Damage Ratios and Casualties

STEP 5

A model developed by Whitman (1973) relates the damage state of a building to the degree of injury to its occupants (Table 2). For example, if a collapsed building had an occupancy of 100, 20 fatalities could be expected while the remainder would be seriously hurt. By applying Whitman's model to the predicted patterns of damage shown in the earthquake simulations, it is possible to forecast the number of fatalities and injuries that might be expected from differing seismic events. This procedure was undertaken for Victoria, based on certain assumptions about probable building occupancy rates. Casualty figures, therefore, can only be viewed as very rough estimates. This approach, for example, predicts that an earthquake occurring during a normal working day, producing Modified Mercalli VIII in Zone C, might cause 41 fatalities and 590 injuries. If intensity reached IX in this zone, the casualty figures for Victoria might be expected to rise to approximately 946 deaths and 4260 injuries (Foster, 1980). No such estimates of casualties, were produced, for Oak Bay.

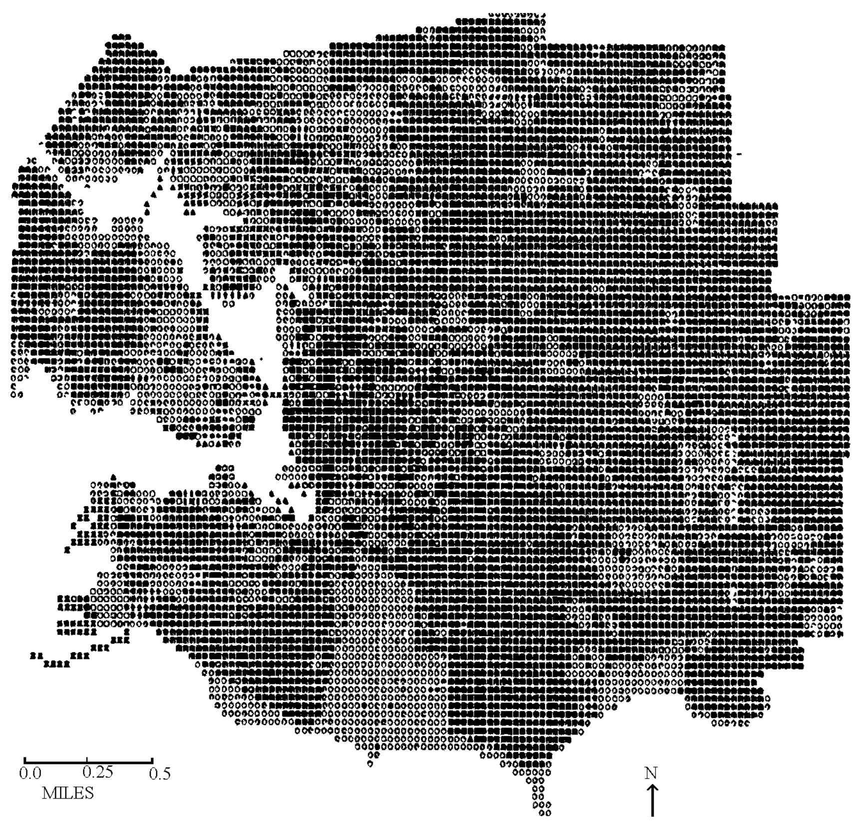

Figure 2. Computerized land use map of Victoria. Landuse categories listed in Table 1. (Open circles are mainly areas with no construction; solid dots are mainly areas with built structures; for a more detailed map legend see Foster and Carey 1976).

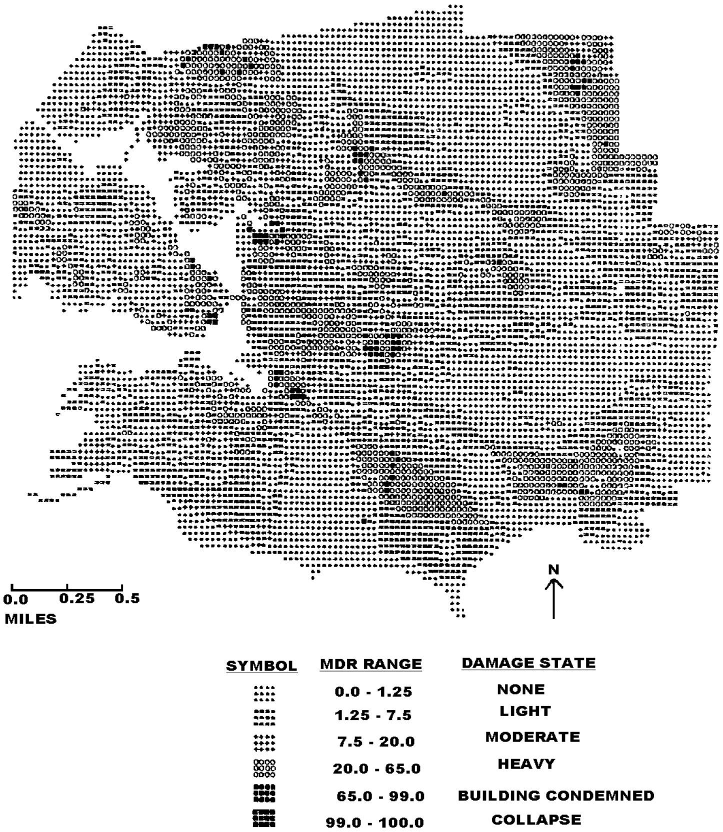

Figure 3. Simulated damage in Victoria caused by an earthquake reaching Modified Mercalli intensity VIII, in Zone B. Structural damage expressed as a mean damage ratio (MDR).

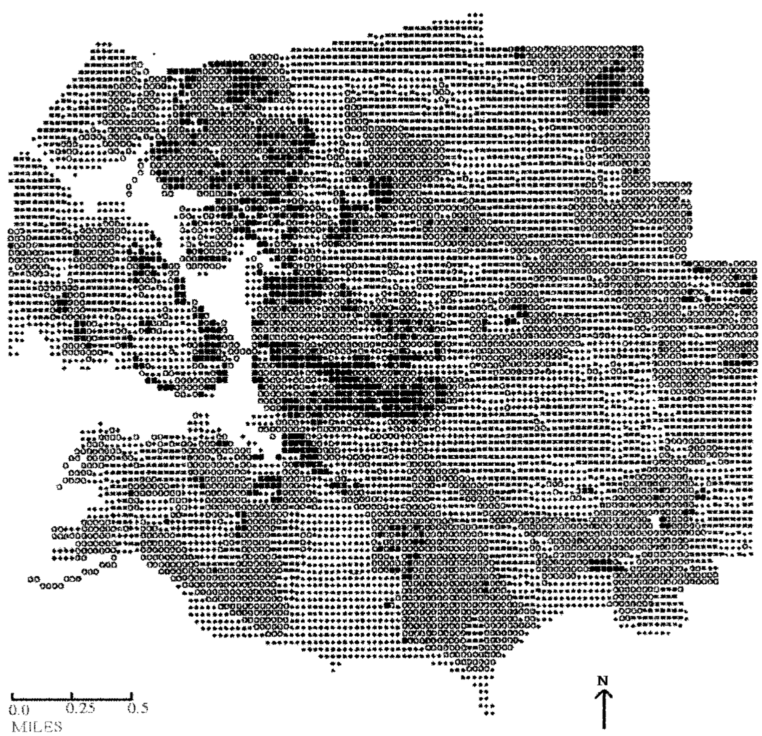

Figure 4. Simulated damage in Victoria caused by an earthquake reaching Modified Mercalli intensity IX, in Zone B. See Figure 3 for legend.

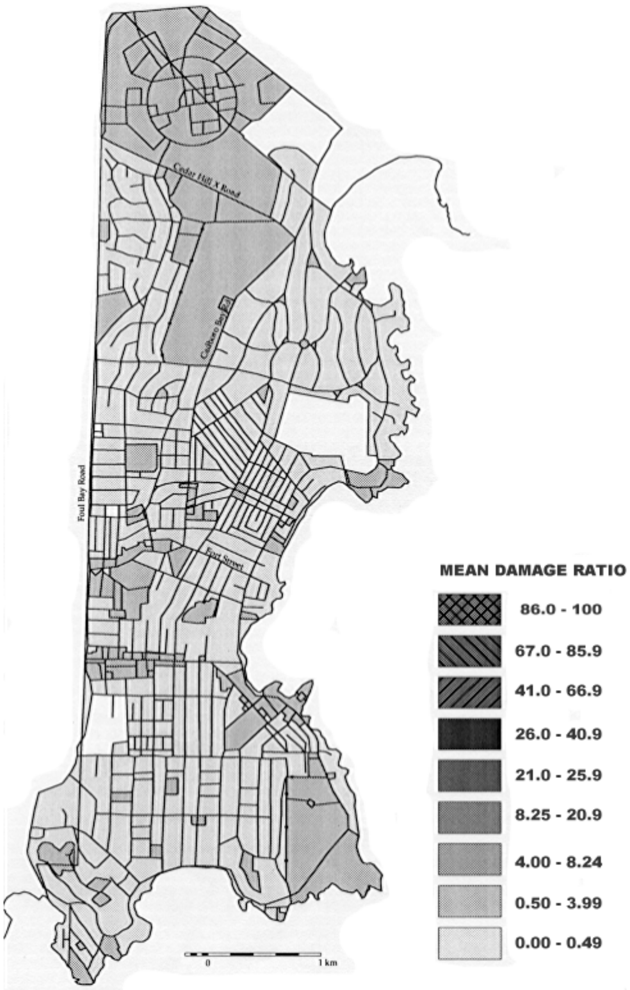

Figure 5. Simulated damage in Oak Bay caused by an earthquake reaching Modified Mercalli Intensity VI, in Zone B (moderate) areas.

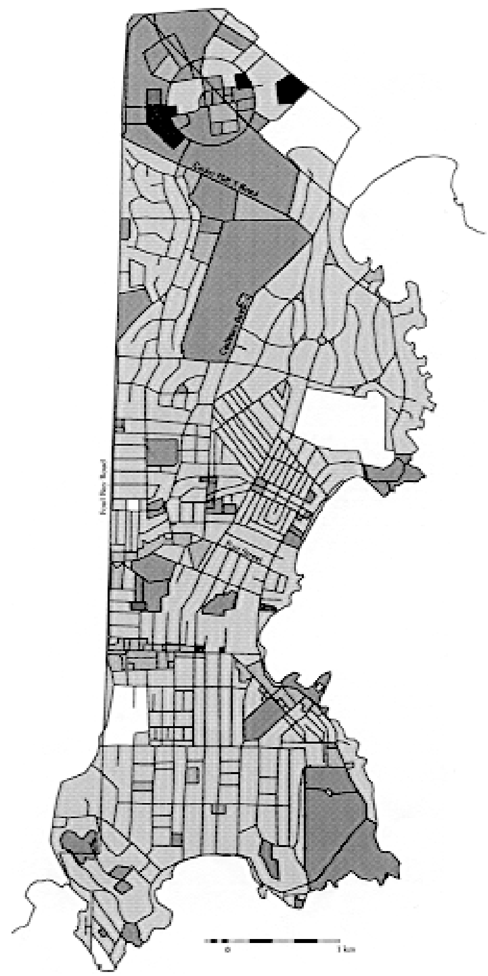

Figure 6. Simulated damage in Oak Bay caused by an earthquake reaching Modified Mercalli Intensity VII, in Zone B (moderate) areas. See Figure 5 for legend.

EXERCISE ORACLE

These models simulating earthquake damage in Victoria and Oak Bay were used in 1994 to increase realism during Exercise Oracle, designed to test the disaster preparedness of the British Columbia Ministry of Health and Ministry Responsible for Seniors. This disaster exercise involved some 70 people, including most of the Ministry's senior decision makers. They were located in an emergency operations centre set up in the Richard Blanshard building in Victoria and in two field response centres, one at the University of Victoria and the other at the Centre for Disease Control in Vancouver.

Exercise Oracle was based on the assumption that British Columbia had been struck at 9 a.m. on February 24, 1994 by an earthquake with a magnitude of 8.25 on the Richter scale. The epicentre of this imaginary seismic event was located 10 kilometres south of Chilliwack. In the Greater Victoria area it resulted in Modified Mercalli intensities of VII in Zone A, VIII in Zone B and IX in Zone C. Anticipated damage in Victoria and Oak Bay was derived from the previously discussed computer earthquake simulations. While considerable new building has occurred in Victoria since 1976, many of the older heritage buildings remain and, therefore, the simulation was still of value. Damage to post-1976 structures was estimated using Table 1. The GIS simulation of damage in Oak Bay had been prepared specifically for use in Exercise Oracle and all information was current.

Figure 7. Simulated damage in Oak Bay caused by an earthquake reaching Modified Mercalli Intensity VIII, in Zone B (moderate) areas. See Figure 5 for legend.

Figure 8. Simulated damage in Oak Bay caused by an earthquake reaching Modified Mercalli Intensity IX, in Zone B (moderate) areas. See Figure 5 for legend.

Information on the structural damage and casualties caused by the 9:00 a.m. earthquake was provided to participants in four ways:

- Written reports of the experiences of survivors during and immediately after the earthquake.
- Telephoned situation reports.
- Photographs of damage.
- Radio news reports.

SURVIVORS' REPORTS

Each member of the ministry's Emergency Operations Centre was given a sealed envelope to be opened when the earthquake struck. This detailed his or her location, injuries (if any) and, if out of the office, a map of the route followed back to the Richard Blanshard building. It also contained a description of the damage seen during the journey and information collected from other survivors. These data, of course, were based on the earthquake computer simulations already described. An example of one of these scenarios is now presented. As can be seen, it governed the time at which the participant could become involved in the decisions being taken at the Ministry's Emergency Operations Centre.

Location

When the 9:00 a.m. February 14, 1994 earthquake occurs you are driving down Fort Street, going to a dental appointment. Your car bounces violently as the road suddenly begins to buckle. It hits another vehicle and overturns. After some difficulty, you crawl out of the badly damaged vehicle.

Figure 9. Simulated damage in Oak Bay caused by an earthquake reaching Modified Mercalli Intensity X, in Zone B (moderate) areas. See Figure 5 for legend

Figure 10. Simulated damage in Oak Bay caused by an earthquake reaching Modified Mercalli Intensity XI, in Zone B (moderate) areas. See Figure 5 for legend.

Health

Your left arm is broken (please wear a sling for the rest of Exercise Oracle). At approximately 15 minute intervals during the exercise you are expected to let out cries of pain.

Decision taken

You decide to walk to 1515 Blanshard Street to help in the disaster response effort. The route you follow is shown on the map.

Observations

Damage clearly is enormous. The air is full of dust and smoke from fires. The injured are crying out for help. Water mains have fractured and power and telephone lines are down; some are sparking dangerously.

TELEPHONE SITUATION REPORTS

Situation reports describing the damage and injuries sustained in British Columbia, as a result of the 9:00 a.m. earthquake, were provided to the members of the Ministry of Health field response centre, located at the University of Victoria. These were generated at approximately one per minute throughout the seven hours of the exercise. Members of this centre then decided which information warranted transmission to the rest of the ministry's disaster response network. As an earthquake of this magnitude would almost certainly have disrupted land-based telephones, only cellular, fax and radio communication was permitted. To add realism to this simulation, many of these situation reports were written with reference to the damage and injuries predicted by the computer simulations previously described. Examples are illustrated below, taken from six minutes of the exercise.

PHOTOGRAPHS OF DAMAGE

Photographs of the destruction supposedly caused by the earthquake were provided to members of the field response centre at regular intervals throughout the exercise. These attempted to illustrate damage predicted by the computer simulations. They were produced in two discrete ways. Most simply, photographs of earthquake damage elsewhere were reproduced and the structures misidentified as being located in British Columbia. Others, however, were electronically manufactured using the software package Photostyler. Once a series of photographs from other earthquake ravaged areas have been entered into memory, this software permits electronic "cut and paste" to occur. In this way various photographs taken in Victoria and Oak Bay were modified to produce "earthquake damage." Figure 11 illustrates the Photostyler-created earthquake damage to the Ministry of Health's Vital Statistics building on Fort Street, while Figure 12 shows electronically manufactured damage to the B.C. Government Employees' Union building on Douglas Street. Despite the "evidence" in these photographs, both structures are still located in Victoria and are as yet undamaged. Photostyler is termed digital darkroom software and it, and similar packages, can add considerable realism to disaster exercises.*

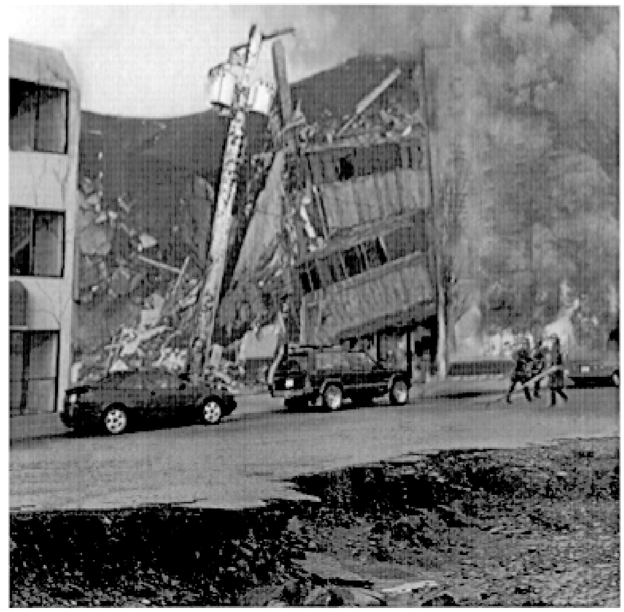

Figure 11.Vital Statistics, Fort Street, Victoria: a) before and b) after the hypothetical "earthquake".

RADIO NEWS REPORTS

To stimulate greater emotional involvement in Exercise Oracle, a radio news report was prepared describing the situation in the late morning of February 24. This script was recorded, with appropriate sound effects, by members of CFUV radio, located in the University of Victoria Student Union building and played at the appropriate time during Exercise Oracle. This news report lasted for 25 minutes and was based, to a large degree, on the damage and injuries predicted by the computer simulations.

CONCLUSIONS

The value of computer simulations of potential and, indeed, actual earthquake damage is already well established (Foster and Carey, 1976; Scawthorn, 1986). However, many such models, including those described here, have reduced utility because of weaknesses in the quality of the data they use. Improvements can only be expected if future research is directed towards increasing the availability of Level III earthquake hazard maps; producing detailed structural data banks that include building occupancy rates at various times of day, and designing more accurate seismic

* Editors note: Details of information provided to participate in the exercise, including "observations" of damaged buildings, details of situation reports and radio broadcasts can be obtained from the authors.

Figure 12. B.C. Government Employees' Union Building, Douglas Street, Victoria: a) before and after b) the hypothetical "earthquake".

vulnerability estimation functions. Beyond this, earthquakes frequently cause a variety of subsequent disasters linked to hazards such as mass movement, fires and gas leaks. The effects of such secondary threats can also best be modelled using computer simulations.

A second weakness lies in the way in which information is used. It is almost pointless collecting high quality information and developing effective simulations if the results are not reasonably easily available in an understandable policy format that can be used by government ministries, municipalities, hospitals and school boards, both for preventive measures (*e.g.* building code enforcement) and training exercises such as Exercise Oracle. Hazard mapping meets this requirement. If agencies and organizations take the initiative to conduct annual exercises using hazard simulation models, the high surprise factor that normally occurs when disaster strikes, and the associated human tragedy, will be reduced.

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A WEST COAST UTILITY'S APPROACH TO MITIGATING EARTHQUAKE HAZARDS

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B.C.Hydro

ABSTRACT

British Columbia (B.C.) Hydro's seismic spending plan focuses on a requirement to obtain the best incremental improvement in seismic preparedness for dollars spent. A Seismic Task Group, with cross-corporate representation, rotating membership, and the ability to form ad hoc teams, recommends the extent and timing of capital investment in proposed seismic strengthening to senior management. This paper describes the stages of development of the spending plan.

INTRODUCTION

British Columbia Hydro

B.C. Hydro is the third largest electric utility in Canada. It serves more than 1.3 million customers in an area which encompasses 92 per cent of the population of the province of British Columbia. Approximately 50,000 gigwatt-hours of electricity are generated annually with over 80 per cent produced by major hydroelectric generating stations on the Columbia and Peace rivers. Electricity is delivered to customers through an interconnected system of over 17,000 kilometres of transmission lines and over 51,000 kilometres of distribution lines. The generating system has 30 hydroelectric plants, one thermal plant, two gas turbine plants and 13 diesel stations. All but the diesel stations and one small hydroelectric plant are tied into the interconnected grid of transmission lines ranging from 60 kilovolts to 500 kilovolts. The B.C. Hydro electric system, with interconnections to Bonneville Power Administration to the south and TransAlta Utilities Corporation to the east, forms part of the Western Systems Coordinating Council network serving western North America. The company's network covers most of the southern two-thirds of British Columbia as shown in Figure 1.

British Columbia includes some of the most seismically active regions in Canada, although the degree of seismicity varies considerably as shown in Figure 2. The highly active Queen Charlotte fault located at the Pacific/North American plate boundary off the west coast has produced earthquakes as large as M8.1 in this century.

The southwest corner of British Columbia, which contains most of the population and electric load centres, has experienced earthquakes larger than M7 and is located adjacent to the Cascadia subduction zone, which may have the potential to generate great subduction earthquakes. The Vancouver and Victoria metropolitan areas, which contain a combined population of more than 2 million and comprise about 55% of B.C. Hydro's customer load, are at risk to earthquakes that occur within the continental North American plate, within the subducting Juan de Fuca plate, and within the Cascadia subduction zone.

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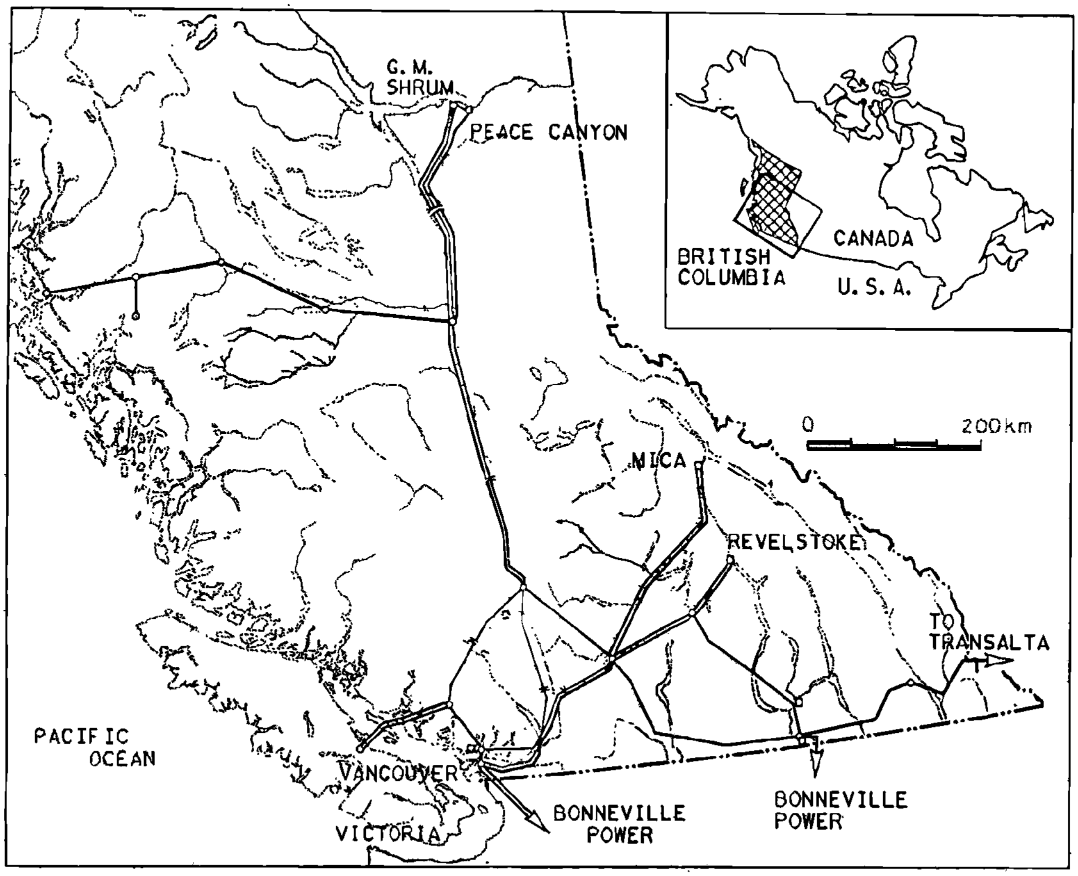

Figure 1. B.C. Hydro major electric system.

Inland from the coast, where seismicity is more diffuse and less frequent than along the plate boundary, earthquakes up to M6 have occurred. In most cases, this inland seismicity has not been conclusively correlated with specific geologic features. There are no known cases of surface ground rupture associated with a seismic event and no active faults have been identified, other than along the plate boundary along the west coast.

British Columbia has not experienced a damaging earthquake near a major populated centre. However, certain areas have had considerable population growth since the last major earthquake.

A significant portion of the greater Vancouver area is underlain by deep, soft soils of the Fraser River delta with potential for liquefaction and ground displacements. Part of greater Victoria is underlain by soft clays which are not a liquefaction hazard, but which apparently can significantly amplify seismic shaking. The west coast of Vancouver Island is also at some risk from tsunamis. Considerable tsunami damage occurred at Port Alberni following the 1964 Alaska earthquake.

British Columbia Emergency Prepardness

The government of British Columbia has a Provincial Emergency Program which developed an "earthquake response plan" in 1989. B.C. Hydro emergency response plans fit into the provincial plan, which coordinates ties with other "life-lines". The company's internal response plans address network operations, interfaces with customers, and engineering support services.

With respect to strengthening of facilities, organizations within British Columbia proceeded independently until 1992 when the Emergency Preparedness for Industry and Commerce Council (EPICC) was formed.

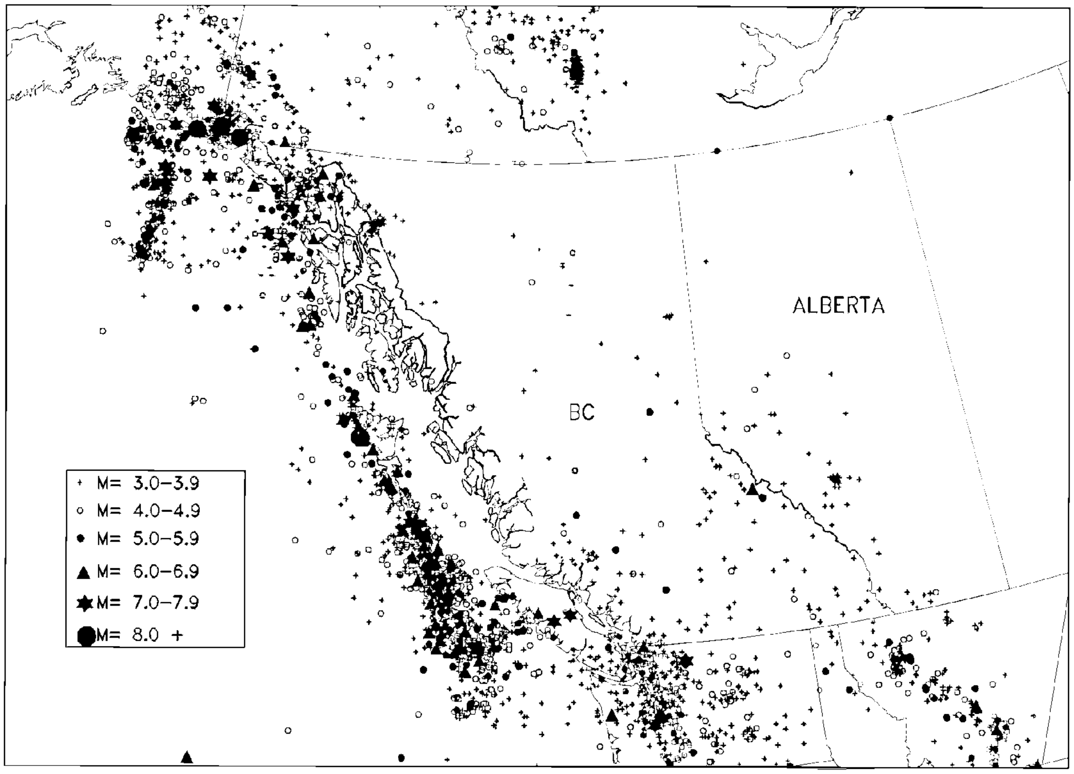

Figure 2. Seismic activity in British Columbia.

Members of EPICC include private corporations, provincial government ministries and crown corporations, utilities, and municipalities. EPICC has a mission to prepare British Columbia business and industry to survive and recover from emergencies. The council promotes the sharing of information on preparedness and engineering study results through regular membership meetings and seminars. Members use the council as a forum for discussing and coordinating response plans, and avoiding duplication in studies and capital investment.

In 1993, B.C. Hydro coordinated a province-wide survey for EPICC, collecting information on past and planned expenditure for earthquake preparedness and strengthening of facilities. The results allowed members to compare their own preparations with the state of preparedness of the community.

The remainder of this paper describes B.C. Hydro's approach to planning expenditure on strengthening of electric system facilities.

Approach

Consensus has been the key to progress in the multi-discipline matter of electric system seismic strengthening. A Seismic Task Group, with cross-corporate representation, rotating membership, and the ability to form ad hoc teams, recommends the extent and timing of capital investment in proposed seismic strengthening to senior management.

Seismic Task Group

Concern about seismic issues has been a major part of B.C. Hydro's dam safety program since the late 1970s. Dams have been strengthened, upgraded or replaced to improve seismic performance. Seismic concerns developed at different rates for other elements of the electric system. By 1986, management had received requests to provide funding for several diverse seismic-related studies or programs. It was clear that different parts of the company had varying levels of concern about seismic issues and were not always aware of related work being done or considered elsewhere. In early 1987, a Seismic Task Group was formed at the direction of corporate management to review the seismic strength of electric system components and to obtain consensus on recommended capital improvements. A four_phase program was initiated as follows:

- rank facilities with respect to seismic hazard and importance to the system;
- determine probable damage and system integrity;
- develop seismic withstand criteria for the electric system taking into account system integrity, economic implications, life safety and seismic hazard levels;
- prioritize and develop upgrades for susceptible system components; and
- implement the upgrades determined in the previous phase.

The Seismic Task Group is made up of B.C. Hydro planning, engineering and operating staff and frequently draws on other expert resources within and outside the corporation, as the need arises.

Seismic concerns include a number of related issues which have vastly different timetables. Recommendations may be based on assumptions which require validation. The Seismic Task Group has generally tried to reduce uncertainty, where practically possible, and has delayed capital strengthening plans to allow reasonable time for further study.

Figure 3 indicates general timing of B.C. Hydro's approach to significant organizational, study and capital expenditure initiatives.

System Studies

Initially, priorities for system elements were set by considering the seismic exposure and the importance to the system of each element. By identifying those facilities considered strategically very important to the electric system, and their relative seismic exposures based on seismic hazard zone maps in the National Building Code of Canada (NBCC, 1990), a relatively short list of "early attention" facilities was developed. Relatively low cost/high benefit measures were identified, including anchoring or bracing of equipment and control panels. System strengthening, to date, has concentrated on these measures.

Early studies at the key facilities involved surveys to identify seismic deficiencies and to assess seismic-withstand capability of generic equipment types. Where deficiencies could be remedied relatively quickly and economically, amounts were included in the capital plan. The evolving studies program includes the following:

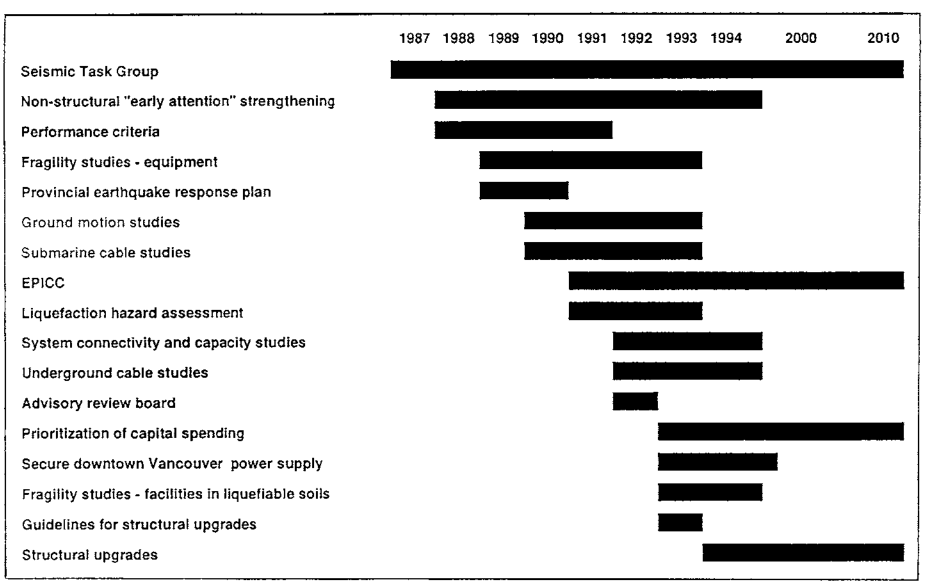

Figure 3. B.C. Hydro's approach to mitigating earthquake hazards.

DAMAGE LEVEL OUTAGE DURATION	1. MINIMUM HOURS	2. MODERATE DAYS	3. EXTREME WEEKS
SYSTEM ELEMENT CATEGORY A 500 kV Transmission; 500 kV Substation; Major Generating Stations; 230 kV Supply to Major Load; Areas (ie Downtown Vanc); Control Centres; Communication Network; 500, 287, 230 kV Interties;	≥ 1/475	≥ 1/1000 (up to 1/475)	< 1/1000
CATEGORY B Area Transmission (230, 138,69 kV); Generating Stations; Distribution System; Distribution System; Non-Integrated System	≥ 1/100	≥ 1/200 (up to 1/100)	< 1/200

Figure 4. Seismic performance for new construction. Annual probability of exceedance.

- prioritization studies to determine the relative likelihood of electric system component failures and the cumulative impacts of such failures on system connectivity;
- planning studies to design seismic withstand capability into new installations;
- ground motion and soil hazard studies to better define ground motion and soil hazards and their potential impacts on the electric system;
- response studies in support of emergency preparedness plans where emergency response is the only economic alternative to seismic strengthening; and
- strengthening and withstand studies of generic and specific B.C. Hydro buildings and facilities.

Studies undertaken to date have enhanced our understanding of the seismic fragility of the electric system. Significant projects are described below.

Performance Criteria

Phase 2 of the Seismic Task Group's program was to develop withstand-criteria for the electric system taking into account system integrity, economic implications, life safety and seismic hazard level. In 1988 a Seismic Criteria Team was formed to address this task.

The first step was to develop corporate level criteria which would serve as a guideline in the development of seismic design criteria for use by the various design departments within B.C. Hydro. The primary purpose was to ensure uniformity and consistency in the development of design criteria.

The performance criteria for new construction are shown in Figure 4. These criteria are directed towards future design and construction and are not intended to initiate upgrading of the existing electrical system. However, the performance criteria are used in any assessment of the present system when modifications or reinforcements are necessary. Since the performance criteria are closely coupled with ground motion parameters they are expressed in probabilistic terms. Together, the seismic performance and the ground motion data provide the basis from which detailed seismic design criteria can be developed.

Category "A" elements are defined as those which, by their loss, could result in the inability to supply 500 megavolt-amps or more of load. Category "B" elements are remaining elements of the system. Three levels of withstand are defined as follows:

- Level 1, a minimum damage level for which normal operation can be restored, on average, within 2 hours:
- Level 2, a moderate damage level for which loss of supply for at least 72 hours can be expected; and

- Level 3, an extreme damage level for which extended damage would result in the loss of supply for long (1 month) periods.

For example, a 500 kilovolt transmission line must meet the Level 1 requirement if subjected to earthquake ground motions with annual probabilities ranging from 1.0 to 1/475. At the same time, it must meet Level 2 withstand requirements for earthquake ground motions with annual probabilities between 1/475 and 1/1000. For ground motions with annual probabilities less than 1/1000, failure of the element would be expected.

Ground Motion and Liquefaction Hazard Assessment Studies

Seismic ground motion parameters are required for design and analysis of a variety of B.C. Hydro facilities and structures, including dams, substations, buildings and transmission, communication and control facilities. To ensure that all future seismic design work within the company is based on consistent fundamental parameters, B.C. Hydro has carried out a complete regional seismic hazard study (Figure 5). The in-house study included selected input from specialist consultants and external review by a technical review panel.

Standard probabilistic methods were applied to develop seismic ground motion parameters, in particular, peak firm ground accelerations and uniform hazard response spectra (Figures 6 to 9) (Little and Meidal, 1994). Ground motion parameters were developed on both a regional and site-specific basis, depending on the needs of the project. The effect of local soil conditions on firm ground motions is considered on a site-specific basis.

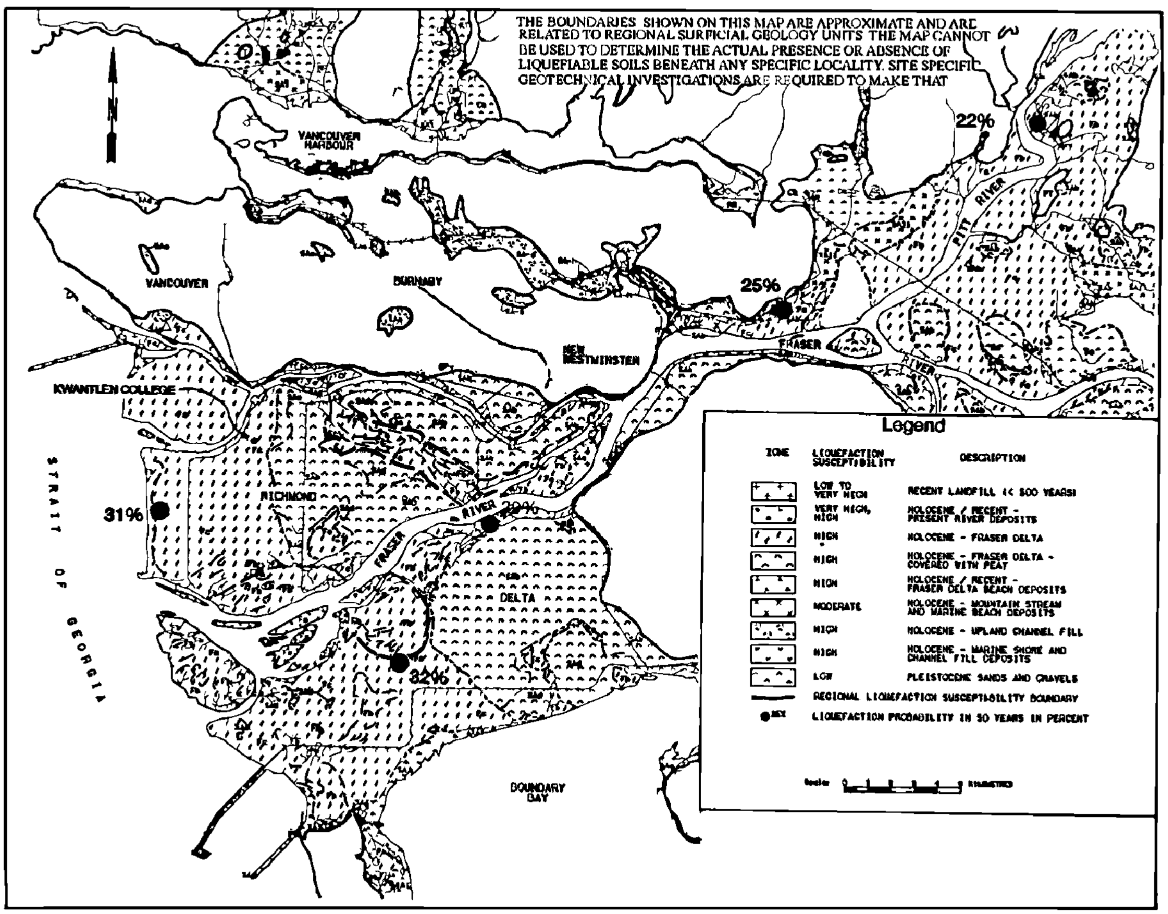

Figure 5. Preliminary Map of Liquefaction Susceptibility Zones (from Watts *et al.,* 1992).

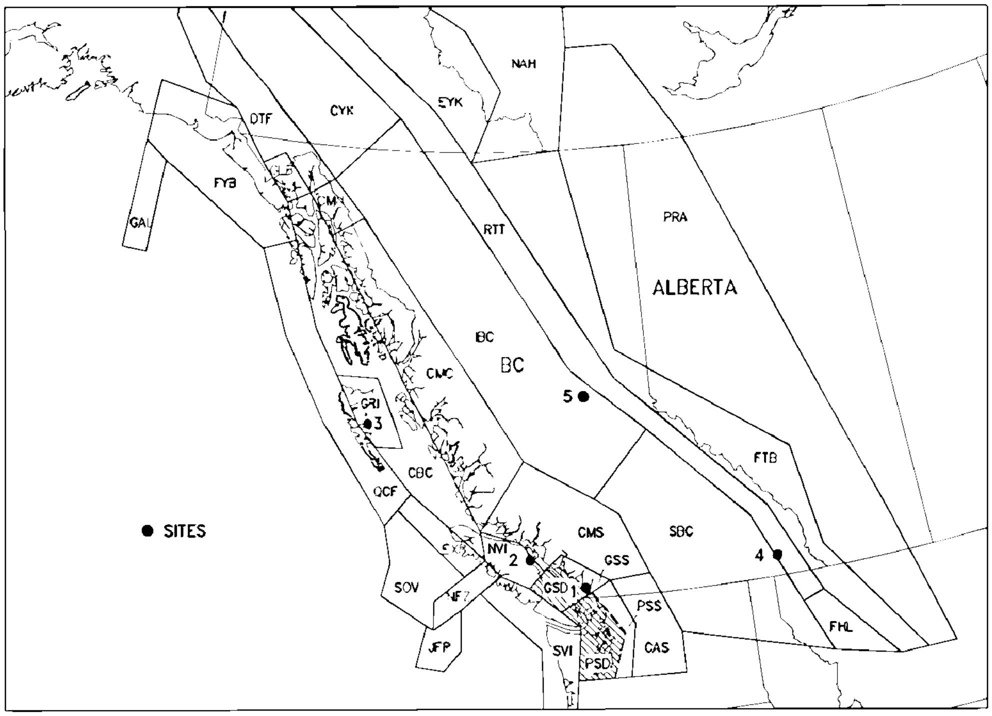

Figure 6. Seismogenic zone model. Shallow zones GSS and PSS are underlain by deep zones GSD and PSD (shaded) (from Little and Meidal, 1994).

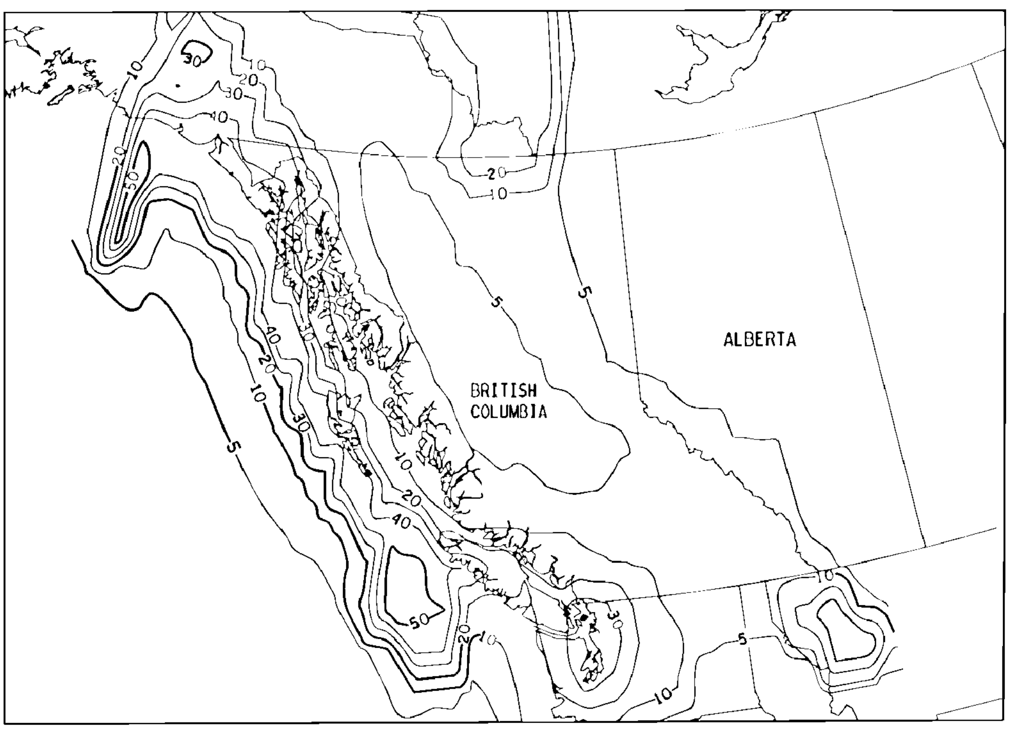

Figure 7. Contours of median plus sigma (84th percentile) peak firm ground accelerations (%g) for an annual probability of exceedance of 1/1000 (from Little and Meidal, 1994).

Many substations in southwestern British Columbia were constructed on land that is flat and saturated. Such land was generally inexpensive and provided good grounding for station equipment, although piling was often required to support foundations on the soft saturated soil. Similarly, many high voltage cables were buried in soft soils. Today, it is known that these soils typically are deltaic or fluvial deposits that are liquefaction-susceptible.

In addition, several older B.C. Hydro dams were constructed using hydraulic fill methods, and other dams were constructed in valleys infilled with deep deposits of glacial and glacial fluvial soils. Since about 1980, a comprehensive dam safety program has included reviews of the potential for liquefaction of these dams or their foundations, and a number of dams have been significantly upgraded or replaced.

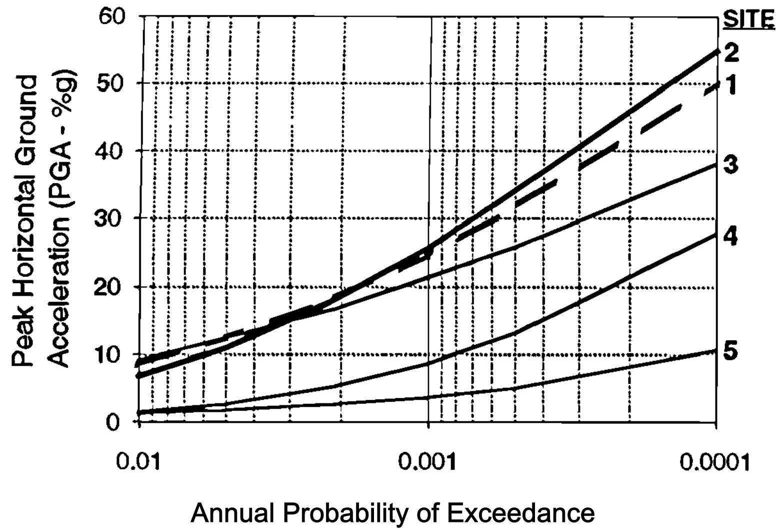

Figure 8. Median plus sigma (84th percentile) peak firm ground accelerations for the five sites shown on Figure 6 (from Little and Meidal, 1994).

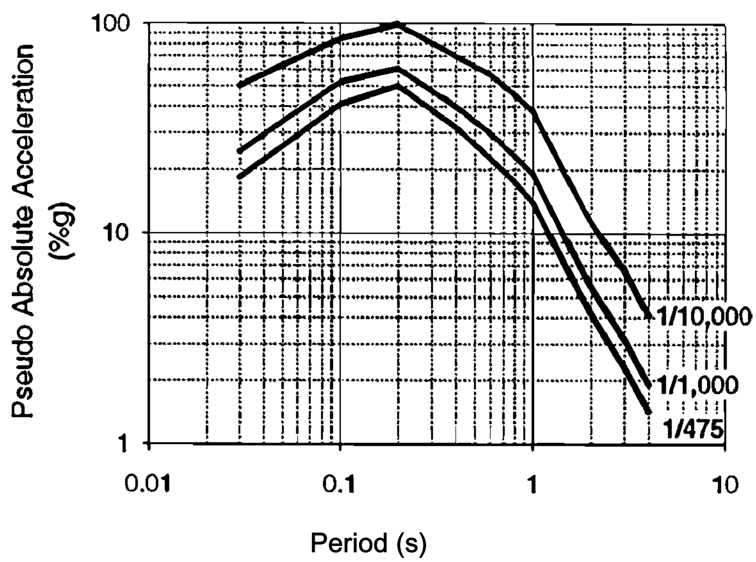

Figure 9. Median plus sigma (84th percentile) firm ground UHRS at Site 1 (Figure 6) for three annual probabilities of exceedance (from Little and Meidal, 1994).

In assessing and remediating these problems, B.C. Hydro has gained considerable experience in characterizing soft soil site conditions and understanding their dynamic performance using state-of-the-art methods. Prediction of the potential for, and the extent of, liquefaction is only the first step in assessing the hazard to the electric system. Liquefaction may result in various forms of ground movement including flow slides, lateral spreading, ground oscillation and vertical settlements. Elements of the electric system are vulnerable to such movements. Sites which have a gentle slope, adjacent to the ocean or river channels, are a particular concern. B.C. Hydro is placing an increasing emphasis on the prediction of the magnitude of ground movements.

Prioritization Studies

Prioritization of effort is a primary issue facing B.C. Hydro because fiscal limitations preclude immediate correction of all identified deficiencies. A seismic capital spending prioritization team was formed in response to a need identified by B.C. Hydro's Vice-Presidents' Steering Committee on Earthquake Preparedness in May 1992 - that need being the prioritization of proposed seismic capital spending on the electric system with proposed seismic capital spending on buildings which are generally occupied by B.C. Hydro personnel (reporting locations). The objective was to provide a total for proposed seismic expenditures which could be compared with proposed spending for other corporate initiatives in setting the annual capital plan. The prioritization team developed a multi-attribute judgmental ranking method to prioritize seismic capital spending (Fan *et al.,* 1994).

In 1992, B.C. Hydro retained EQE Engineering Consultants Inc. to model the backbone of the electrical power network to determine whether, and in what manner, a credible earthquake would significantly affect power supplies to major load centres in the Lower Mainland. The study provided preliminary relative seismic fragility for 93 system nodes (including substations, transmission water-way crossings, and underground cable in liquefiable soils) and direction for future studies. B.C. Hydro is in the process of extending the model to include its major load centre on Vancouver Island. The company has also developed an in-house capability for prioritization of individual components within substations.

Other Studies

In addition to criteria, ground motions, soils and prioritization studies, B.C. Hydro has also undertaken significant initiatives in the following areas:

- submarine cable studies to assess the impact of underwater flow slides or other ground deformation on submarine cables to Vancouver Island;
- underground cable studies to assess the seismic fragility of cables in duct, pipe-type cables, and cross-linked polyethylene cables in poor soils;
- downtown Vancouver power supply studies to minimize the cost of improving withstand-capability of substation buildings and underground cables where power supply is critically dependent on three non-redundant facilities;
- fragility studies of facilities in liquefiable soils to establish the expected failure modes, and related present risks of failure, for substation equipment located in poor soils; and
- guidelines for structural upgrades to provide guidance for evaluating the need for structural upgrades for the "owners" of the more than 400 buildings occupied by B.C. Hydro people and equipment (Fan *et al.,* 1994).

Status

From 1988 - 1994, the Seismic Task Group oversaw the expenditure of approximately $4 million on various seismic studies and research. Capital expenditure, from 1988 through March 31, 1994, for electric system seismic strengthening (excluding Dam safety) amounted to approximately $18 million, compared to annual capital expenditure of approximately $500 million for all of B.C. Hydro. Most of the expenditure was to stabilize substation equipment, crossing towers, and cable oil reservoirs.

The Seismic Task Group has continued to evaluate components of the electric system as well as the structures which shelter them.

Evaluations are limited by the amount of information available regarding seismic-withstand capability of certain unique features of the B.C. Hydro electric system, access to relatively scarce technical expertise, and requirements for fiscal responsibility. By 1994, detailed structural and preliminary soils investigations were completed for 38 of 250 substations. Where studies and investigations identified weaknesses in seismic-withstand capability, funds were budgeted for in proposed future capital programs.

By 1992, B.C. Hydro's seismic program for the electric system was five years old. As the program developed, the company determined that many of the desired improvements are more difficult to define and evaluate. It became increasingly important to focus on the process of identifying and prioritizing capital improvements.

External Review

External review is carried out on certain engineering studies and design, generally by retaining specialist consultants as direct participants or in an advisory or review role.

Specialist input has been obtained for ground motion studies and assessment of the seismic performance of soft-soil sites. This input ensures that difficult problems are addressed by methods that are reasonable and appropriate. In some cases, the methodologies applied have been state-of-the art.

An external review was commissioned by B.C. Hydro's Chief Engineer in late 1992 to determine whether the company was taking all the steps that a prudent utility should take to provide the level of service that its customers would expect following an earthquake. In addition, the review was to determine whether B.C. Hydro had a systematic approach that ensures that large investments in seismic upgrade are appropriate and necessary. The Review Board, while recommending a small number of improvements in program details, commented that "B.C. Hydro's pro-active approach to its own preparations for seismic mitigation and its associated community outreach programs make it a leader in these areas."

CONCLUSIONS

B.C. Hydro's approach to mitigating earthquake hazards could serve as a model for organizations in the initial stages of planning for earthquakes. Key elements are:

- a multi-disciplinary Seismic Task Group;
- a four phase program to rank facilities, develop seismic withstand criteria, and prioritize, develop, and implement upgrades;
- coordination with community emergency preparedness plans; and
- external review.

ACKNOWLEDGMENTS

The authors wish to acknowledge the fourteen members of the Seismic Task Group for their ongoing contribution to B.C. Hydro's seismic preparedness.

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USE OF QUANTITATIVE TECHNIQUES FOR ZONING LANDSLIDE HAZARD✦

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SUMMARY

This paper joins the effort in developing new techniques for zoning landslide hazard. The favourability modeling (FM) approach, a framework for implementing quantitative techniques, is suggested for spatial data integration using certainty factors (CF). The framework solves some of the problems associated with zoning and geographic information systems (GIS), the first being the dilemma of selecting either a qualitative or quantitative approach. Favourability modeling with certainty factors is a good compromise, offering a valid quantitative method, where subjectivity or expert knowledge can be incorporated in the analysis, particularly when data are not sufficient or reliable.

A second problem is associated with the popularity of thematic data which may limit the establishment of quantitative models. With favourability modeling, thematic data are transformed into continuous data, by considering the degree of relationship, using certainty factors in this paper, between the hazard and classes of each map.

Another issue concerns the rigidity of some quantitative techniques. As it may be more effective to use surrogates, simply because of the cost, accessibility, or difficulty of measuring the original property, the FM approach provides the advantage of flexibility as results are generated independently from the input data. The technique is also capable of zoning more than one type of geological hazard.

Landslide hazard maps were generated from a 1960 dataset, and compared with the occurrence of events from 1961 to 1980. The quantitative technique using certainty factors, constructed with seven data layers, successfully predicts 63% of all landslides occurring from 1961 to 1980 in its High and Very High classes, representing only 25% of the total surface of the study area. These results demonstrate clearly the applications of new data integration techniques for the zoning of landslide hazard and in the field of spatial data analysis.

NECESSITY FOR ZONING

Losses resulting from landslides can only be reduced in one of two ways: either by modifying the hazard event itself, or by reducing human vulnerability to it. Both philosophies require the natural hazard to be zoned.

Zonation is defined as the division of the land into homogeneous areas or domains and their ranking according to the degrees of actual or potential hazard (adaptation from Varnes, 1984).

The event modification approach is closely linked with engineering designs. Hayes (1981) believes that these designs improve the capability of the site and structures to withstand the physical effects of a hazard in accordance with a level of acceptable risk. Smith (1992), on the other hand, writes that most natural hazards are insufficiently understood, or manageable, to be physically suppressed at source through some form of environmental control engineering. He believes, however, in hazard-resistant design and emergency measures to safeguard lives and property from selected phenomena in certain high-risk settings. In this framework, the zoning of hazards provides the necessary parameters to the design engineers and the emergency planners.

The vulnerability modification approach implies creating a change in human attitudes and behavior toward hazards that have occurred or will occur in the future. Three management exercises have been identified with regard to vulnerability modification: preparedness, forecasting and warning, and land-use planning.

✦ Portions of this paper also were published as part of the proceedings annual conference of the International Association of Mathematical Geology (Chung and Leclerc, 1994).

Preparedness may involve the promotion of public education and awareness programs, the development of evacuation plans, the supply of medical aid, or the preparation of emergency food and shelter for evacuees (Smith, 1992). All of these measures require the use of hazard maps to accomplish their purpose.

Forecasting and warning systems, based on scientific and technological development, have become an important tool in recent decades. The greatest success has been achieved with atmospheric and hydrologic hazards, notably hurricanes and flood warning systems. China's Flood Risk Forecasting and Countermeasure Information System of the Lower Yellow River demonstrates an example of the value of zoning. The system provides flood risk maps derived from hazard maps (Chen, 1989).

Land-use management seeks to intervene in the complete process whereby hazard-prone land has been identified by hazard zonation. Its main purpose is to guide residential, commercial and industrial development away from identified hazard zones. For example, in Veneto, Italy, a cartographic document, containing a zonation of the suitability of the soil with regard to permanent settlement, was produced to assist planners (Spagna and Schiavon, 1989).

CAPTURING AND PROCESSING DATA

This section introduces some relevant topics in zoning hazards with GIS. They include a short discussion on existing data type and representation, data quality and extensive computer processing involved with spatial datasets.

DATA TYPE

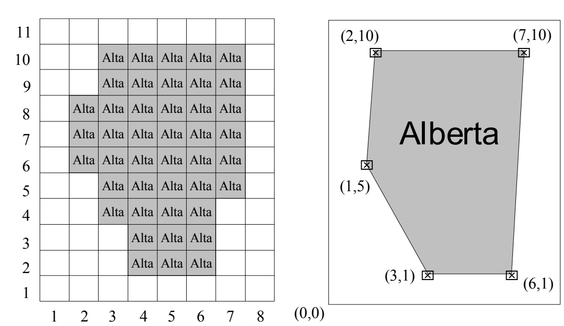
Maps consist of layers of different types of observations overprinted on the same planar surface, where the relationship between spatial features and processes are represented for human perception. Different types of observations depicted in maps are (Chung and Fabbri, 1993):

- Continuous measurements, *e.g.* slope angle.
- Discrete samples, *e.g.* stream-sediment geochemical data.
- Distinct geometric objects (polygons, segments and points), *e.g.* individual landslides, lineaments, mineral occurrences.
- Complete polygonization of map space, *e.g.* bedrock geology.

Such maps can be digitally captured, managed and analyzed by geographic information systems (GISs). Manipulations of the data enable the establishment of models as both spatial attributes (*e.g.* size of a landslide) and nonspatial attributes (*e.g.* type of landslide) can be quantified. Quantification of the spatial attributes is recorded in either one of the two most common formats: raster or vector.

Raster data structures consist of an array of grid cells termed pixels or picture elements. Each grid cell is referenced by a row and column, and contains a number representing the type or value of the attribute being mapped or displayed. For instance, in Figure 1(a), the province of Alberta is mapped on a 11x8 grid with pixels having *Alta* as attributes. The surface is not continuous, but quantified by the dimension of the pixels.

By contrast, the vector representation attempts to portray the object as exactly as possible. The coordinate space is assumed to be continuous, allowing all positions, lengths and dimensions to be defined precisely. Figure 1(b) illustrates the concept in which Alberta is represented with arcs linked by points in a Cartesian space.



(a) Raster (b) Vector

Figure 1. Spatial data representation models.

The choice of either vector-based or raster-based GISs has direct consequences on the design of spatial models. Because the building of a model (data integration) requires that spatial data be reformatted to a common denominator, it is crucial to select either an appropriate raster-based or vector-based GIS. Aronoff (1989) and Fabbri (1991) discuss the advantages and disadvantage of both data representations.

DATA QUALITY

Many sources of errors related to a GIS support analysis have been identified (Aronoff, 1989; van Westen, 1994). Although there are usually no specific numerical values attached to these errors, there is great concern about them. In most cases, data quality is influenced by the areal coverage, the relevance, type, accessibility and costs of data, and by other sources related to age, scale, natural variations and measurements. These errors contained in the data layers are referred to as inherent errors (Burrough, 1986). The uncertainty of some maps is related significantly to the subjectivity induced by the surveyor and consequently, these maps greatly influence the outcome of the models. The degree of uncertainty characterized with some of the layers is well associated by Carrara *et al.* (1992) in the mapping of existing landslides:

> “The tests performed under different conditions on different sample areas proved that landslide identification and mapping is an error-prone operation which is dependent on the skill of the surveyor and the technical tools selected. Overall errors may well be greater than 50 percent.”

Due to this type of error, the overlaying process may result in very low accuracy (Burrough provides an overview of errors in overlaying). Furthermore, the combination will generate operational or data processing errors. An example is the overlay on several layers of information. Such an overlay generates thousands of different combinations of classes, some caused by positional and attribute errors (van Westen, 1993), especially in combinations with small areas. These small classes can either be very rare combinations of variable classes, or they can be considered as errors, as it is unlikely that a certain combination will occur in such a small area. The exercise of validating these small areas is somewhat difficult. Although their role in accuracy and precision is known, little can be done about it apart from being aware of their contribution to computer processing errors. As irrelevant variables create unnecessary unique conditions, the best solution is to promote only useful combinations of variables.

Some errors are also introduced by the violation of the assumptions required for the integration of spatial data. Although these errors are impossible to calculate, users should understand their meaning in order to avoid mistreatment of the assumptions and of the utilization of the integration techniques.

EXTENSIVE COMPUTER PROCESSING

Even though today's personal computers provide numerous capabilities for manipulating spatial data, such manipulations are often impeded by the large number of sample units, especially in raster data where each pixel may be considered as a single sample. In the case of a multivariate approach, Chung *et al.* (1994) have suggested some ways to alleviate computer processing problems.

The choice of using intensive computer processing techniques for hazard zonation should be carefully examined (with special attention given to the size of the spatial and nonspatial database) as the user is often unaware of its computer and software limitations.

ISSUES IN SELECTING APPROPRIATE ZONING TECHNIQUES FOR GIS

Some issues concerning the selection of appropriate zoning techniques are reviewed next. They are the dilemma between the quantitative versus qualitative techniques, the popularity of thematic data, and the flexibility of the zoning technique.

QUANTITATIVE TECHNIQUES VERSUS QUALITATIVE TECHNIQUES

In geoscience applications such as natural hazard assessment, many layers of data such as lithology, structural features, geophysics, hydrology, slope, and remotely sensed data are available for building models that delineate areas for further investigation. Such models are founded on the notion that their behavior is controlled by natural, physical or logical laws, and once these laws are understood, the models can be adopted for representing the phenomena of interest (*e.g.* landslide hazard). Models can be classified as: quantitative and qualitative. The issue involving the selection of either a quantitative or qualitative technique for zoning is important.

Quantitative models involve the use of mathematics, and statistics, to express relationships between variables. Examples in the zoning of landslide hazard include bivariate and multivariate models (Carrara, 1983; Wang and Unwin, 1992; van Westen, 1993) and regression techniques and models based on uncertainty (Chung and Fabbri, 1993; Chung *et al.,* 1994).

On the other hand, qualitative models rely on expert knowledge which dictates the selection, the weighting and the combination function of the variables. An example is the qualitative map combination in geomorphological mapping (Stevenson, 1977).

Most scientists recognize the superiority of quantitative techniques due to their rigorous scientific framework which promotes objectivity. Nevertheless, a quantitative model is superior only if the following two conditions, namely validity and accuracy, are met (Matthews, 1981).

For any model to be valid, it must express the true meaning of what it is attempting to represent and must respect assumptions appropriate to its quantitative technique. An example is the formulation of the standard of living index by the United Nations for 1993. The index is not based on a single quantitative measure, such as the income per capita, but on additional environmental, social and economic criteria, as people attach more than a monetary value to the concept of a worthy standard. Validity is also determined by the degree to which the model assumptions are met. Consequently, qualitative models have sometimes been suggested as an alternative by, among others, Nijkamp *et al.* (1985).

Accuracy or correctness is another criterion for accepting a quantitative over a qualitative approach. Inaccurate models not approximating the theory disprove the fundamental concept of the quantitative approach. Consequently, geoscientists have the responsibility of deciding upon the acceptable level of accuracy of a model. Some relatively inaccurate models may be suitable for some purposes and not for others. For example, a map depicting flood hazards with 60% accuracy may be appropriate as it represents the best possible approximation of the event that can be generated from a limited data set.

The problems of validity and accuracy in quantitative models have raised issues about the rigid scientific framework. Some have suggested incorporating subjectivity into the process. For example, Haining (1990) encourages sensitivity tests in areas of “uncomfortable science”, where observational data are not obtained by means of any formal experimental design and where data are not always very accurate or precisely measured. Haining describes sensitivity analysis as a subjective process embedded in an objective framework concerned with assessing model fragility to data attributes. This may be used to help construct a better model. An interactive procedure, aimed at modifying some estimators influenced by a small number of extreme values, is an example that may prove valuable. The concept is attractive providing that the degree of subjectivity is proportional to the model validity and to the data properties. For example, a valid and accurate model accompanied by quality data would require little subjectivity and would, thus, respect a fully objective path. Using valid quantitative methods, which maximize accuracy while they incorporate subjectivity or expert knowledge when data is not sufficient, proves to be the best compromise in the selection of either a qualitative or a quantitative approach.

POPULARITY OF THEMATIC DATA

As spatial attributes are taken care of by the computer data representation (*e.g.* vector, raster, quadtree) of the GIS, the quantification of non-spatial attributes is recorded in either one of the four available scales: categorical and ordinal or thematic data, interval and ratio or continuous data. The adopted scale has significant implications for the chosen modeling technique. For instance, the popularity of thematic data may limit the establishment of some quantitative models that are based on continuous data.

FLEXIBILITY OF ZONING APPROACH

Not all data are directly relevant to the purpose for which they are used. It may be more practical to use surrogates, simply because of the cost, accessibility, or difficulty of measuring the original property. In other cases, one information layer may be unavailable for security reasons. With some zoning techniques, an exact set of variables may be required to generate outputs and consequently, they may be less desirable for zoning as the results may be adversely affected by lack of data, or lack of specificity.

Flexibility in the selection of input layers is an important feature in the selection of zoning techniques. Although flexible, such techniques must be used carefully as the outputs are generated independently from the input data. In such a situation, it is up to the user to judge the appropriateness of the results and the loss of information that results from a simplistic model which should be accounted for by assigning less certainty to the results.

FAVOURABILITY MODELING (FM)

The proposed quantitative techniques are based on the favourability modeling (FM) approach aimed at data integration as defined by Chung and Fabbri (1993):

> "Given several layers of spatial geoscience information in a study area, by combining them for a specific purpose according to a model, generate one map showing target areas for further investigation for that specified purpose in the study area."

The approach provides advantages in resolving some of the problems associated with zoning and GIS for the integration of multiple sources of data. These are discussed below.

In favourability modeling the purpose specified for Data Integration is called the Proposition**.** For example, in the modeling of landslide hazards, the proposition is finding areas containing a specific type of landslide. The proposition is defined by the user. Thus it permits an approach directed at a wide range of geoscientific applications and the user's task is simplified.

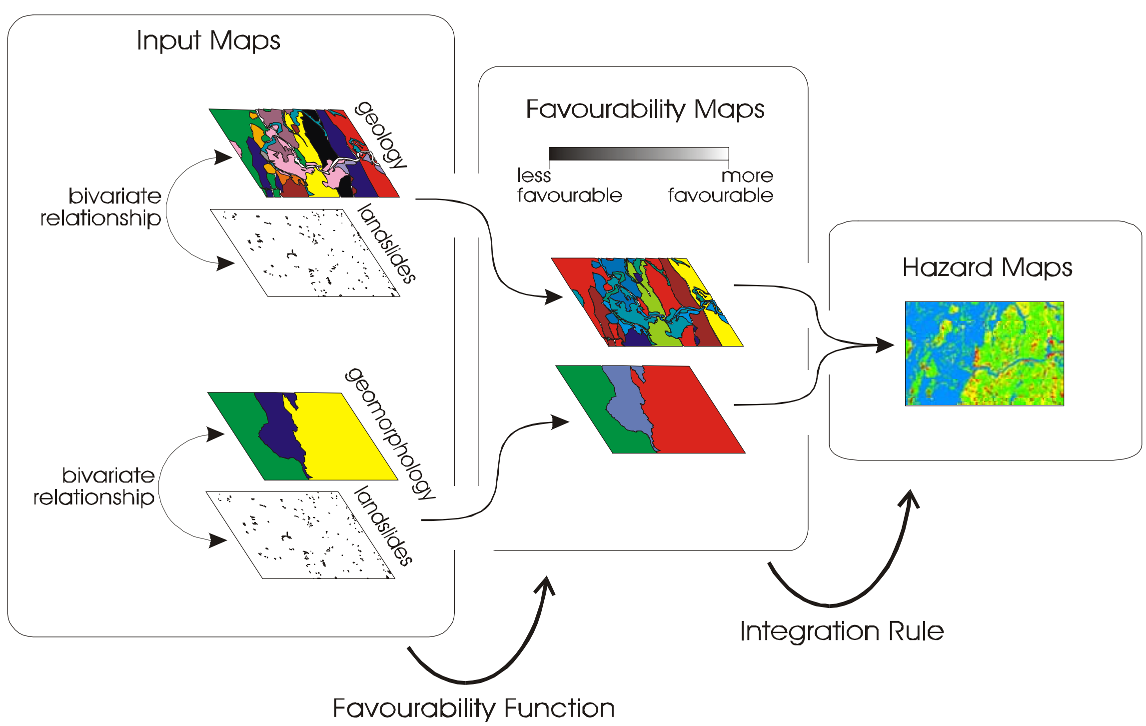


Figure 2. Favourability modeling.

The methodology for solving the proposition is represented in Figure 2. In each data layer or map, each continuous or noncontinuous class is transformed into a value, called the 'Favourability Value', ranging between two known constants such as -1 and 1 for a certainty factor. Its scale will be discussed later. The transformation is performed by a 'Favourability Function' from a point or area in the study area to the specific interval, based on a bivariate relationship between the distribution of the geological hazard and each map class. The map layer with the transformed numbers containing the favourability values is called a favourability map or 'Evidence'. The favourability value is a measurement of the sureness that the proposition is true given the evidence from the map layer. A low favourability value indicates that the certainty that the proposition is true is very low, as compared with a high favourability value meaning that the evidence strongly supports the proposition. In the zoning of landslide hazards for instance, the value could describe the degree of certainty that an evidence, such as the slope, is contributing to the mass movement.

Favourability modeling has advantages over other quantitative techniques in some situations as the favourability value or the bivariate relationship is calculated from either a common data type such as thematic data, or from non-thematic data. Another advantage of FM is that it allows for subjective assessment of the favourability value if the user chooses. This marriage between subjectivity and objectivity is useful when decision makers are forced to make decisions on issues for which the scientific foundations are unclear and fundamental data are lacking. Decisions made in this context with considerable ignorance have important consequences; delaying such decisions is also potentially costly.

In the last stage of FM methodology, the evidence is combined with a specific integration rule respecting the proper interpretation of the favourability function. The favourability modeling approach is explained using a flow chart (Figure 3).

The flowchart is divided in three sectors, two of which show tasks that can be performed with today's GISs [Data Preprocessing (a) and

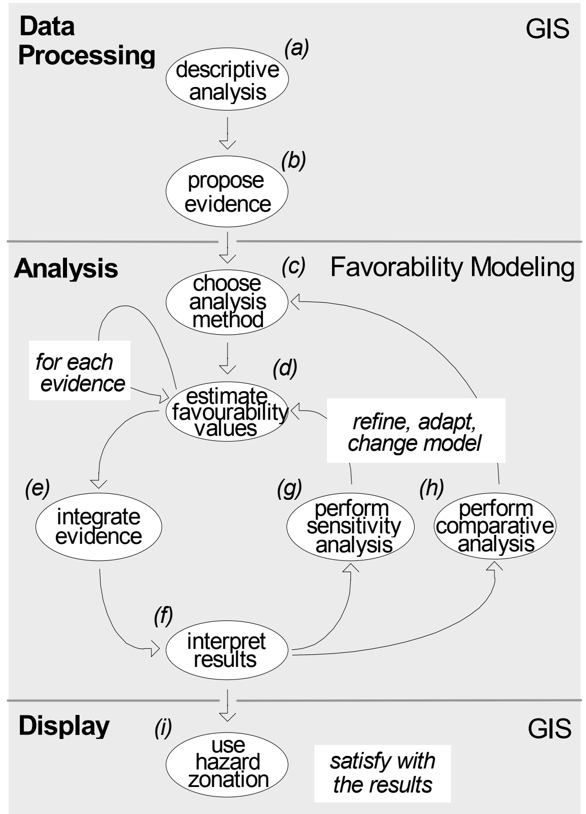


Figure 3. Data Analysis Approach.

Display (i)] and one depicting the capability of modeling with the favourability approach [Analysis (c-h)]. After deciding upon the model's variables (b) by performing some descriptive analysis on the data (a), the favourability values are calculated from the data (d) and then edited by the user if necessary. The layers are then integrated using the integration rule respecting the interpretation of the favourability functions (e) to derive the final model(s) (f). At this stage of the analysis, sensitivity analyses (g) are possible by modifying the favourability values. Moreover, comparative analyses (h) can be performed by the selection of another integration rule or by attempting a different combination of variables, until complete satisfaction with the model (i) is obtained.

The data analysis framework presented here promotes both analytic and comparative methodologies. It also recognizes that a variety of combinations of variables and favourability values may in fact be complementary, as the outputs generated may not all be similar. Different resulting models may also advocate the predominant view that there can be no fully objective, value-free approaches to acceptable-risk decisions and that, as comparatively little is known about the management of many controlling factors present in models, expert analysis is best viewed as a relative, rather than an absolute function.

Computer programs (Leclerc, 1994; Leclerc and Chung, 1993) were developed to implement three quantitative techniques using the FM theory: Bayesian probability, certainty factors (CF) and a multivariate regression technique. Chung and Fabbri (1993) have also suggested the use of fuzzy logic theory and of Dempster-Shafer belief functions for FAVOURABILITY FUNCTIONS. Chung *et al.* (1994), Chung and Fabbri (1994) provide descriptions of some of these approaches. Only the result from CF approach in Chung *et al.* (1994) is discussed here.

CASE STUDY: ZONING LANDSLIDE HAZARD WITH CERTAINTY FACTORS (CF)

Certainty factor (CF), a method that has seen widespread use in rule-based expert systems, is based on probabilistic reasoning. The expert system MYCIN, for diagnosing and treating infectious blood diseases, was the first one to reason with certainty factors. It is one of the most widely studied expert systems because of its great success (Frenzel, 1987).

The CF approach transforms each class or area to a specific interval varying between -1 and +1, referred to as certainty factors. A CF near the low end of -1 indicates that the certainty of the proposition being true is very low, as compared with a high CF near to +1 meaning that the evidence strongly supports the proposition as true. On the other hand, a CF near 0 means that the evidence does not provide enough information for the proposition. The CFs are based upon experience and when statistical data appear to be sufficient, as in this paper, some functions to calculate the value can be proposed (see Chung and Leclerc, 1994; Chung *et al.,* 1994).

Although the conditional probabilistic scale is one of the best known for most measurements, the chances for the occurrences of geological disasters, given evidence, are generally extremely low and, consequently, it is difficult to interpret such small numbers directly. For this reason, we favour the CF approach for its scale varying between -1 and +1, where CF values are determined by comparing the conditional probability value to the prior probability value.

As an example of the utilization of CF for zoning geological hazards, results from Bayesian approaches to landslide hazard zonation by Chung *et al* (1994) are now discussed.

STUDY AREA

The study area, situated in Colombia, South America, is part of the Rio Chinchina catchment basin located on the western slope of the central Andean mountain range (Cordillera Central-Figure 4).

The area of 68 square kilometres is located southeast of the city of Manizales and encompasses the city of Chinchina, one of the major coffee-producing towns in Colombia. The Rio Chinchina basin is susceptible to mass movements, earthquakes and volcanic hazards, and is experiencing intensive industrial and agricultural activities, thus increasing its vulnerability to hazards. The dataset for this study constitutes part of GISSIZ (van Westen, 1993), a training package for GIS in slope instability zonation.

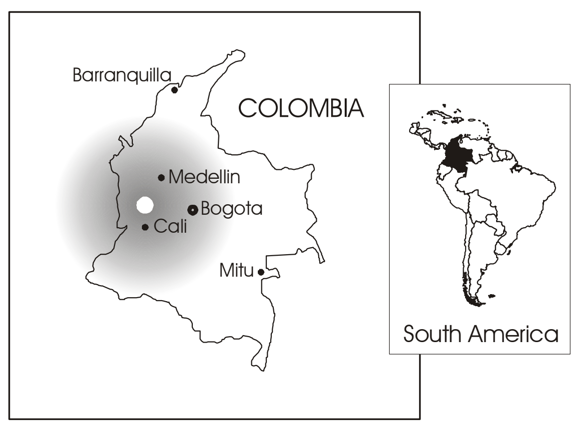


Figure 4. Location of study area.

SPECIFYING THE PROPOSITION

In zoning landslide hazard, certain causes are dynamic and transient while others are static. It is the latter that this paper explores or simply, the assumption that hazards can be zoned in part by establishing relationships between static causal factors. Moreover, it is assumed that future landslides can be predicted by the statistical relationships calculated between the past landslides and the spatial dataset. Carrara (1983), Wang and Unwin (1992), Chung *et al.* (1994)

and Chung and Leclerc (1994) have modeled landslide distribution based on similar principles.

To empirically evaluate the quantitative data integration technique, it was pretended that the time of the study was the year 1960 and that all the spatial data listed in Table 1 - the following seven layers: lithology, geomorphology, slope, land use, the distance to valley heads, distance to roads and distance to geological faults - were compiled in 1960. The distribution of the landslides which occurred prior to the year 1960 was also compiled. The prediction, using the CF model and based on a dataset prior to 1960, was then compared with the distribution of the landslides which occurred during the period 1961-1980.

As each type of landslide possesses important distinct characteristics, only one landslide type, that is the *derrumbe*, was selected. Derrumbes, the local Spanish word for soil avalanches, is a fast and shallow mass movement occurring mostly as a translational failure, during which the material is transported to the nearest stream or blocking object. The material involved is mostly volcanic ash, but it may also be residual soil or terrace deposits.

GENERATING FAVOURABILITY VALUES

After initializing the program's parameters, the conversion of scales, accomplished by the certainty factor function or by the bivariate relationship between the distribution of geological hazard and the classes of each map, holds various benefits in terms of model building:

- Modification of the favourability values.
- Measure of the contribution of each class to the occurrence of the geological hazard.
- Acquired knowledge.

The principal reason for using favourability modeling is the possibility of incorporating expert knowledge in the favourability values prior to the integration of the data layers.

While testing the software, no editing was performed on these values due to the complete mapping of landslides in 1960. Consequently, the model is considered data-driven compared to knowledge-driven modeling that would have been an exercise with some editing of the favourability values. However, Table 2 demonstrates the necessity for modifying the favourability values, especially for the slope classes *80-89°*, *60-69°* and *70-79°*. The CF value for the class *80-89°* is -1.0 meaning that it is unlikely that such slopes contribute to the occurrence of landslides.

Table 1. Data Layers Used for Modeling

MAP	CLASSES
Geology	· gneissic intrusive · schists · volcanic and metasedimentary rocks · gabbro and diorite · alluvial sediments · flow materials and alluvium and ashes · weathered debris-flow materials · lake deposits · lahar deposits · pyroclastic flow deposits · mix of pyroclastic and debris flow · andesitic intrusive · tertiary sediments
Geomorphology Complexes	· Western hills · terrace · Romeral fault zone
Slope Intervals	· 0-9° · 10-19° · 20-29° · 30-39° · 40-49° · 50-59° · 60-69° · 70-79° · 80-90°
Landuse	· traditional farming system · mechanized farming system · modern intermediate farming system · other crops · construction · bare · grass · shrubs · forest
Distance to Roads	· < 25 metres · 25-50 m · > 50 m
Distance to Valley Heads	· < 25 metres · 25-50 m · > 50 m
Distance to Faults	· <50 metres · 50-99 m · 100-149 m · 150-199 m · 200-249 m · > 250 m

Nevertheless, it is common sense to repudiate such a statement, and to recognize that such a steep slope contributes to landslides by incrementing the CF. In spite of this, the -1.0 was not modified in this exercise as it is comprised of only 552 pixels and consequently has little influence on the outcome of the analysis.

The second advantage is the descriptive information the favourability values provide about the contribution of each class to the geological hazard. For example, in the zoning of landslide hazards and in Table 2, the slope demonstrates the minor contribution of gentle and steep gradient to the occurrence of landslides.

A third advantage is that the bivariate relationships can also be viewed as acquired knowledge portable to other study areas. The knowledge acquired from the favourability values could be used in the modeling of landslide hazards for areas with similar environmental characteristics. They should not be considered absolute, but rather an indication of the relationship between the hazard and one controlling factor.

Table 2. Favourability Values of Slope Classes.

Slope Class *degrees*	# Pixels	# Landslide Occurrences	Certainty Factor
0-9	168691	768	-0.644901
10-19	110363	1121	-0.205522
20-29	90429	1789	0.356865
30-39	44987	1125	0.492544
40-49	16122	381	0.462661
50-59	4424	391	0.860952
60-69	857	4	-0.635718
70-79	594	1	-0.868769
80-89	552	0	-1.000000

INTEGRATING THE EVIDENCE

Integrating the evidence, or generating the final results, involved using a valid mathematical formula to combine the CFs of all layers. The original CF formula used in expert systems was used to perform this task (Chung *et al.*, 1994). The landslide hazard map is shown in Figure 5 while Figure 6 depicts the same image in three- dimensional space. Both use an arbitrary classification described in Table 3.

A relief map and an intensity-hue-saturation process were used to generate the 3-D image by using the software PCI (version 5.2). The four colours, red, yellow, green and blue, represent high, medium, or low landslide hazard based on the 1960 dataset. The additional black color on the 3-D image represents landslides that occurred between 1961 and 1980.

Such a classification exercise may be required in hazard planning and assessment. For example, the path of a disaster evacuation route could be based on the *low hazard* class, as only 11% of all the landslides occurring after 1960 fall into that category representing 50% of the total surface.

The CF hazard map was evaluated for its prediction capability, with respect to the landslides occurring from 1961-80. The percentage of mapped 1961-80 landslides in relation to the models' classes was graphed (Figure 7).

The graph represents the potential capability of the CF model. For example, the classes covering 25% of the highest hazard values manage to map 63% of all landslides that occurred in the period between 1961 and 1980. Similar results were obtained with the Bayesian and multivariate approach (see Chung *et al.*, 1994; Chung and Leclerc, 1994).

Table 3. Arbitrary Classification.

Hazard Class	Colour	Surface (%)	Number of Mapped Landslides from 1961-80 (%)
very high	red	5	19
high	yellow	20	44
medium	green	25	25
low	blue	50	11

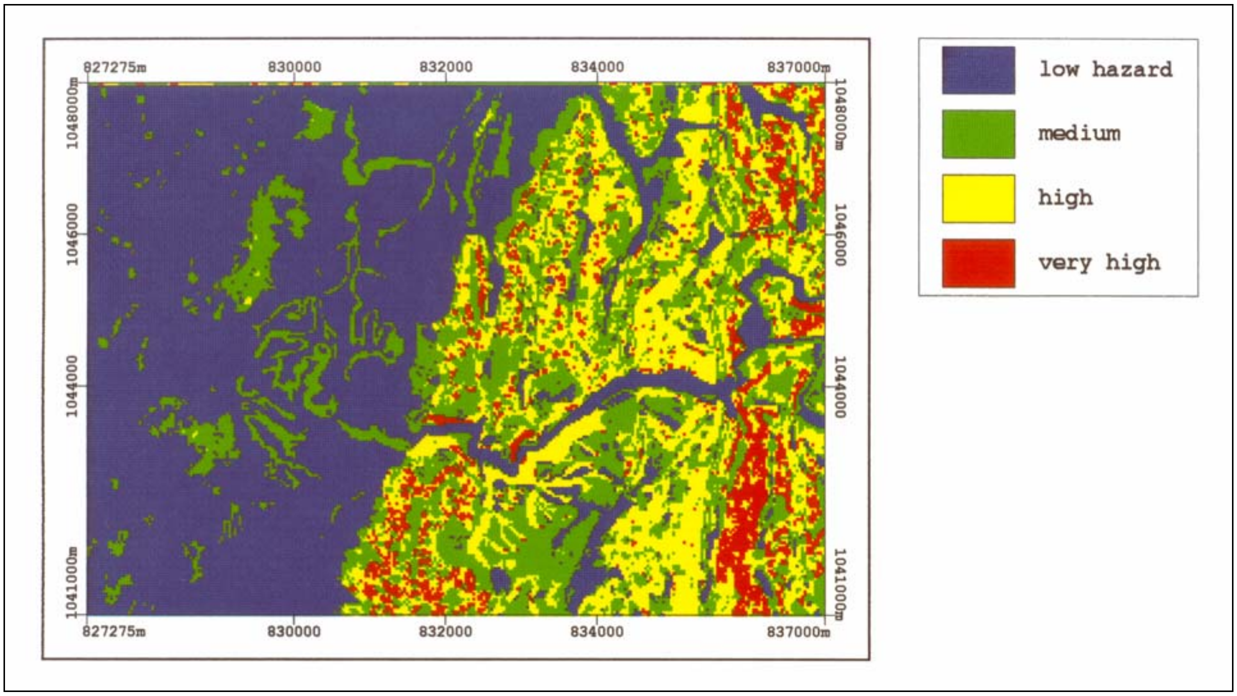


Figure 5. Certainty Factor Landslide Hazard Map.

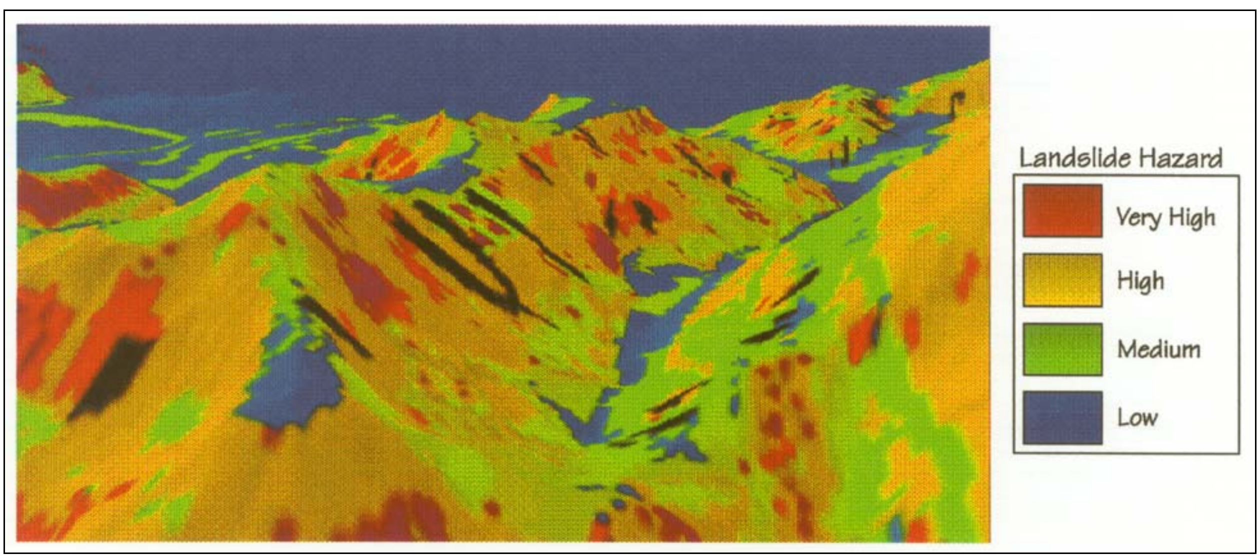


Figure 6. 3D Visualization Representation of CF Map.

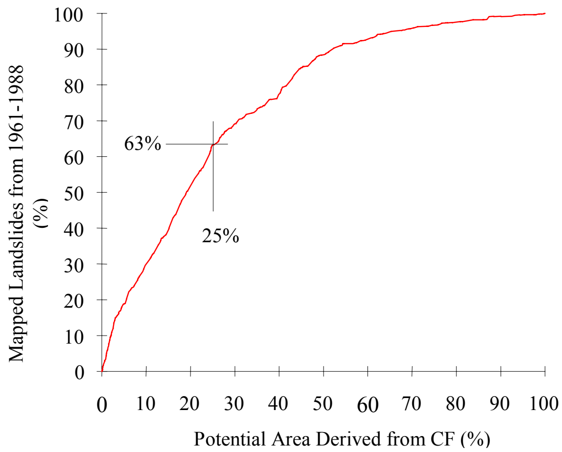


Figure 7. Prediction performance of the CF model.

CONCLUDING REMARKS

This study was based on the idea that the field of geological hazard assessment can benefit by providing scientists with new tools and analytical methods. The favourability modeling approach validates this by clearly demonstrating its ability to predict landslides, in a process involving uncertainty associated with the nature of the information, and with the exercise itself.

The success of a model not only depends on the degree of subjectivity included in the process, but on the building of the model, on the respect of statistical assumptions, and on the quality of the data. In the zoning of landslides, the seven layers resulted in close to 5000 different combinations of classes. The more complex the model is, the more complex are the comparative and sensitivity tests needed for achieving acceptable results; also the greater are the processing errors generated by the computer and the more elaborate are the interpretations of the final maps. Simplicity may well be sufficient for the zoning, as a compromise is reached between the uncertainty of less information and the uncertainty generated by too much information.

The presentation of the integration techniques establishes a base for the development of future GISs for three principal reasons. First, some new data integrating techniques currently lacking in today's GISs were successfully implemented in a software package. Secondly, favourability modeling encourages a robust data analysis and some homogeneity in the combination of different themes. Lastly, the integration techniques used in this study are versatile and could be used in a wide range of applications in the fields of environmental impact assessment, mineral exploration and habitat suitability, to name a few.

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