# EARTHQUAKE RISK ANALYSIS

# FINAL REPORT

## VOLUME ONE

Submitted To

The City of Portland, Oregon

by
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## ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY

## Focus of This Study

This study is designed to help the City of Portland make decisions about life safety seismic retrofits of existing buildings. We evaluate life safety seismic retrofits for those classes, locations and uses of buildings which may constitute a significant life safety risk in Portland. In evaluating these life safety retrofits, we also examine the full economic benefits of the retrofits, including reduced damages and reduced loss of functionality, to provide the information necessary for the City and building owners to make better informed decisions - about possible retrofit alternatives.

This study includes information on four main topics:

1) a review of Portland's earthquake hazard from known faults or fault zones,

2) an assessment of the life safety risks associated with some classes of buildings when subjected to the range of future earthquakes that can affect Portland,

3) an analysis of the benefits associated with life safety seismic retrofits of vulnerable existing buildings compared to the typical costs of such retrofits, and

4) conclusions regarding the types, locations and uses of buildings that would be good candidates for seismic retrofit.

## Life Safety Risk

This study focuses on the ten building classes which pose the highest life safety risk based on their average probability of causing deaths and injuries in future earthquakes. Within this group, the extent of life safety risk varies by a factor of more than 4,000 between the lowest risk class (steel frame buildings with concrete shear walls) located on rock sites and the highest risk class (unreinforced masonry buildings) located on soft soil sites.

Site characteristics (rock, firm soil, or soft soil) profoundly affect life safety risk because they strongly affect earthquake ground motions and building damages. Thus, evaluation of the life safety risk posed by existing buildings must consider not only building class, but also site characteristics.

## Life Safety Retrofits

Life safety retrofits are designed to reduce earthquake deaths and injuries by preventing the full or partial collapse of a building and by ensuring access and egress to/from the building after earthquakes for occupants and/or emergency responders. Life safety retrofits also typically have economic benefits (i.e., reduced damage, less loss of functionality) in addition to substantial reductions in deaths and injuries.

**Seismic retrofit does not make a building earthquake proof!** Depending on the severity of an earthquake, a building which has been seismically retrofitted may have minor damage or even major unrepairable damage which results in demolition of the building.

Typical costs for life safety retrofits vary with building class, building size and use and may range from $10 to $50 per square foot. However, for many building classes, typical retrofit costs are in the range of $30 to $40 per square foot, with retrofits of industrial-use buildings commonly in the range of $20 to $30 per square foot. These cost estimates include the full costs of seismic retrofit, not just the cost of the structural strengthening measures.

## Benefits of Life Safety Retrofits

We consider two main kinds of benefits: life safety benefits which are the dollar value of avoided casualties and non-life safety benefits which are the value of avoided economic damages and losses. Total benefits are the sum of these two kinds of benefits.

> For rock sites, life safety benefits will be a small fraction of retrofit costs for typical buildings in all 10 building classes.
>
> For firm soil sites, life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for unreinforced masonry (URM) buildings for typical uses of 1 to 5 occupants per 1,000 square feet. Life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for precast concrete frame, precast concrete tiltups, concrete frame with URM infill and steel frame with URM infill buildings only for high occupancies (5 to 10 per 1,000 square feet).
>
> For soft soil sites, life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for unreinforced masonry, precast concrete frame, precast concrete tiltups, concrete frame with URM infill and steel frame with URM infill buildings for typical occupancies of 1 to 5 per 1,000 square feet. Life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for reinforced masonry buildings and for concrete frame buildings only for high occupancies (5 to 10 per 1,000 square feet).

The pattern of non-life safety economic benefits for building classes and soil types is very similar to that presented above for life safety benefits. The conclusions drawn above, based only on life safety benefits, are amplified by the inclusion of the non-life safety economic benefits of retrofit. Thus, when total benefits are considered, retrofit benefits will exceed retrofit costs for a broader range of combinations of building classes, soil types and occupancy levels.

Tables 7.2, 8.1a and 8.1b, in the main body of this report, provide the results necessary to evaluate the life safety benefits and the non-life safety benefits for any typical building in Portland, for any of the 10 building classes considered, for any combination of building class, location, use and occupancy.

## Caveats

There are several important caveats which apply to consideration of the seismic vulnerability of buildings. Understanding these caveats is fundamental to a proper understanding of this study and the conclusions reached.

> Seismic life safety is not and cannot be absolute. All buildings, even those designed to or beyond the seismic design levels of the current building code, may fail if ground motions substantially exceed the design basis or due to design errors or insufficient quality of construction. In earthquakes with ground motions at or below the design basis, casualties will generally be reduced, but not completely eliminated, in current code buildings or in well-designed and well-constructed retrofitted buildings.
>
> Conclusions about the seismic vulnerability and extent of life safety risk of buildings are expected to be generally applicable, on average, to "typical" buildings of a defined class (structural system). The seismic performance of any individual building may differ substantially from the "typical" performance of the class depending on the design, construction and condition details of each individual building. **Our analysis considered ONLY typical buildings within defined classes of buildings and did not consider any specific individual buildings.** Depending on the details of a building's design, construction and condition and on site characteristics, any individual building, even those in classes generally deemed not to constitute a significant life safety risk, may constitute a substantial life safety risk.
>
> Throughout this report, we consider the effects of ground shaking on buildings and the resulting damages and casualties. We do NOT consider liquefaction, landslides, or other ground movements because such effects are highly site-specific and thus require evaluation of site and building characteristics for each individual building.
>
> Estimates of the extent of seismic risk in Portland, the seismic vulnerability of building classes, the relationship between building seismic damage and casualty rates, the effectiveness of retrofits in avoiding damages and casualties, and the costs and benefits of retrofits are subject to substantial uncertainty. Interpretation of results and conclusions must consider this uncertainty.

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# 1.0 INTRODUCTION

The purpose of this study is to assist the City of Portland in making important policy decisions regarding the seismic safety of its existing private and public building stock. **The City's paramount earthquake issue is life safety.** Our charge is not to determine what level of life safety is acceptable nor to proscribe seismic retrofit ordinances for the City. Rather, our charge is to assist the decision-making process by providing quantitative assessments of the extent of the seismic hazards faced by Portland, the degree of life safety risk posed by existing buildings, and the costs and benefits of retrofit alternatives.

Existing buildings in Portland generally pose a greater threat to life safety in earthquakes than do new buildings because most existing buildings were designed and built to lower seismic standards than are currently required for new construction or were built without any consideration of seismic forces. New buildings pose a much lower threat to life safety because the seismic design requirements for new buildings were increased in 1993 to reflect current understanding of the degree of earthquake hazards in Portland.

This study is designed to help the City of Portland make decisions about **life safety** seismic retrofits of existing buildings. The objective of life safety retrofits is to reduce earthquake deaths and injuries by preventing the full or partial collapse of a building and by ensuring access and egress to/from the building after earthquakes for occupants and/or emergency responders. However, seismic retrofit does not make a building earthquake proof: damages, even substantial damages, may still occur in large earthquakes.

In this study, we evaluate life safety seismic retrofits for those classes, locations and uses of buildings which may constitute a significant life safety risk in Portland. The focus of this evaluation is on life safety, rather than on the economic aspects of earthquake damage to buildings. However, in evaluating these life safety seismic retrofits we also examine the full economic benefits of the retrofits, including reduced damages and reduced loss of functionality, to provide the information necessary for the City and building owners to make better informed decisions about possible retrofit alternatives.

This study includes information on four main topics:

1) a summary of Portland's earthquake hazard from known faults or fault zones,

2) an assessment of the life safety risks associated with certain types of buildings in Portland when subjected to the range of future earthquakes that can affect Portland,

3) an analysis of the benefits associated with life safety seismic retrofits of vulnerable existing buildings compared to the typical costs of such retrofits, and

4) conclusions regarding the types, locations and uses of buildings that would be good candidates for seismic retrofit.

The information provided in this report provides an objective basis to help the City make its policy decisions about the earthquake safety of existing buildings in Portland.

# 2.0 SEISMIC HAZARDS IN PORTLAND

## 2.1 Earthquakes in the Pacific Northwest

Historically, seismic activity in the Pacific Northwest region as a whole and in Western Oregon in particular has been relatively low, compared to more active areas such as California. However, earthquakes are an inevitable fact of life throughout this region. The same geologic processes which have produced Mt. Hood, Mt. St. Helens and the other beautiful (but dangerous) chain of active volcanoes which run from Northern California through Oregon and Washington into British Columbia also produce earthquakes.

Geologically, the phenomenon responsible for both volcanoes and earthquakes in the Pacific Northwest is known as "subduction." Subduction is the process by which portions of the Pacific ocean floor slowly move under the North American continent at the rate of an inch or two per year. Over many years, this subduction process builds up strain in the rocks under the Pacific Northwest and this strain is eventually released as earthquakes. Geologists cannot predict exactly when or where future earthquakes will occur or exactly how big a particular earthquake will be. However, future earthquakes, including very large earthquakes, are almost certain to occur.

The subduction process is the big picture for geologic processes in the Pacific Northwest. However, in addition to this big picture, local geologic processes may also produce earthquakes. There are many crustal fault systems throughout the Pacific Northwest and in the Portland area which can produce locally damaging - even devastating - earthquakes. For example, the Portland Hills fault (see below) could produce a devastating earthquake for Portland, with roughly similar impacts as the recent Kobe earthquake in Japan.

## 2.2 Earthquakes Affecting Portland

In discussing the potential impact of earthquakes on the Portland area it is helpful to consider two separate, but related concepts: seismic "hazard" and seismic "risk". Seismic "hazard" is defined as the probabilities of earthquake ground motions at a given location. Seismic "risk" is defined as the potential for damages and casualties to the built environment.

A region may have high seismic hazards, but very little seismic risk if the area is sparsely populated. On the other hand, a highly populated area with moderate seismic hazards may have high seismic risk if the built environment is highly vulnerable to earthquake damages.

The City of Portland falls into the latter category. The degree of seismic hazard in Portland is moderate; that is, the probability of damaging earthquakes is substantial, but lower than in more active areas such as California. However, despite this moderate degree of seismic hazard, seismic risk in Portland is rather high, because many of the existing buildings in Portland are quite vulnerable to damage and casualties in earthquakes.

The seismic hazards affecting Portland include the cumulative effects of all possible earthquakes affecting Portland. There are three main sources of earthquakes which may affect the Portland area. Two of these are directly related to the subduction of part of the Pacific ocean floor underneath the North American continent: 1) Cascadia subduction zone (interplate) earthquakes which can occur on the interface (boundary) between the Juan de Fuca plate and the North American plate, and 2) deep intraplate earthquakes which can occur within the subducting Juan de Fuca Plate. The third major source of earthquakes occurs on shallow crustal faults within the North American plate.

A map showing the significant numbers of earthquakes caused by subduction-related geologic processes along plate boundaries is shown in Figure 2.1.. A more local cross section, showing the spatial relationship between Portland, the subducting plate and the three main sources of earthquakes, is shown in Figure 2.2. In Figure 2.2, the Cascadia subduction zone earthquakes would occur in the area marked "locked zone of interface"; the deep intraplate earthquakes could occur anywhere within the subducting plate; and the shallow crustal earthquakes are shown in the upper right hand portion of the lower figure.

The Cascadia subduction zone earthquakes and the deep intraplate earthquakes tend to be large earthquakes, which produce long durations of strong ground shaking. Fortunately, these earthquake fault zones are located quite far from Portland (about 50 to 75 miles west) so that the levels of ground shaking expected in Portland are only moderately high.

The shallow crustal earthquakes tend to be smaller earthquakes, which produce shorter durations of strong ground shaking. Unfortunately, some of these earthquake fault zones are located much closer to Portland (only 2 to 12 miles away from the center of Portland); in fact, one, the Portland Hills Fault, passes through the west side of downtown. As a result, the levels of ground shaking expected in Portland may be very high for some of these earthquake events. In particular, a major earthquake on the Portland Hills fault would probably be the worst earthquake which could affect Portland.

For the purposes of estimating the risks that these seismic hazards pose to the existing building inventory of Portland, we combine the probabilities of these three types of earthquakes in a cumulative probability estimate. In addition, we adjust the hazard estimates for the effects of the long and short duration earthquakes. In simple terms, the seismic hazards in Portland may be characterized as follows:

1) Numerous micro-earthquakes are expected to occur every year in Western Oregon. In the Pacific Northwest as a whole, approximately 1,000 detectable earthquakes occur every year. These earthquakes, which are too small to be felt by humans, are only detectable by sensitive seismic instruments,

2) Frequent very small earthquakes are expected in Western Oregon. These earthquakes, which are felt by humans over a small area, are too small to cause any significant damage. Such very small earthquakes may occur anywhere from a few times per year to once every several years.

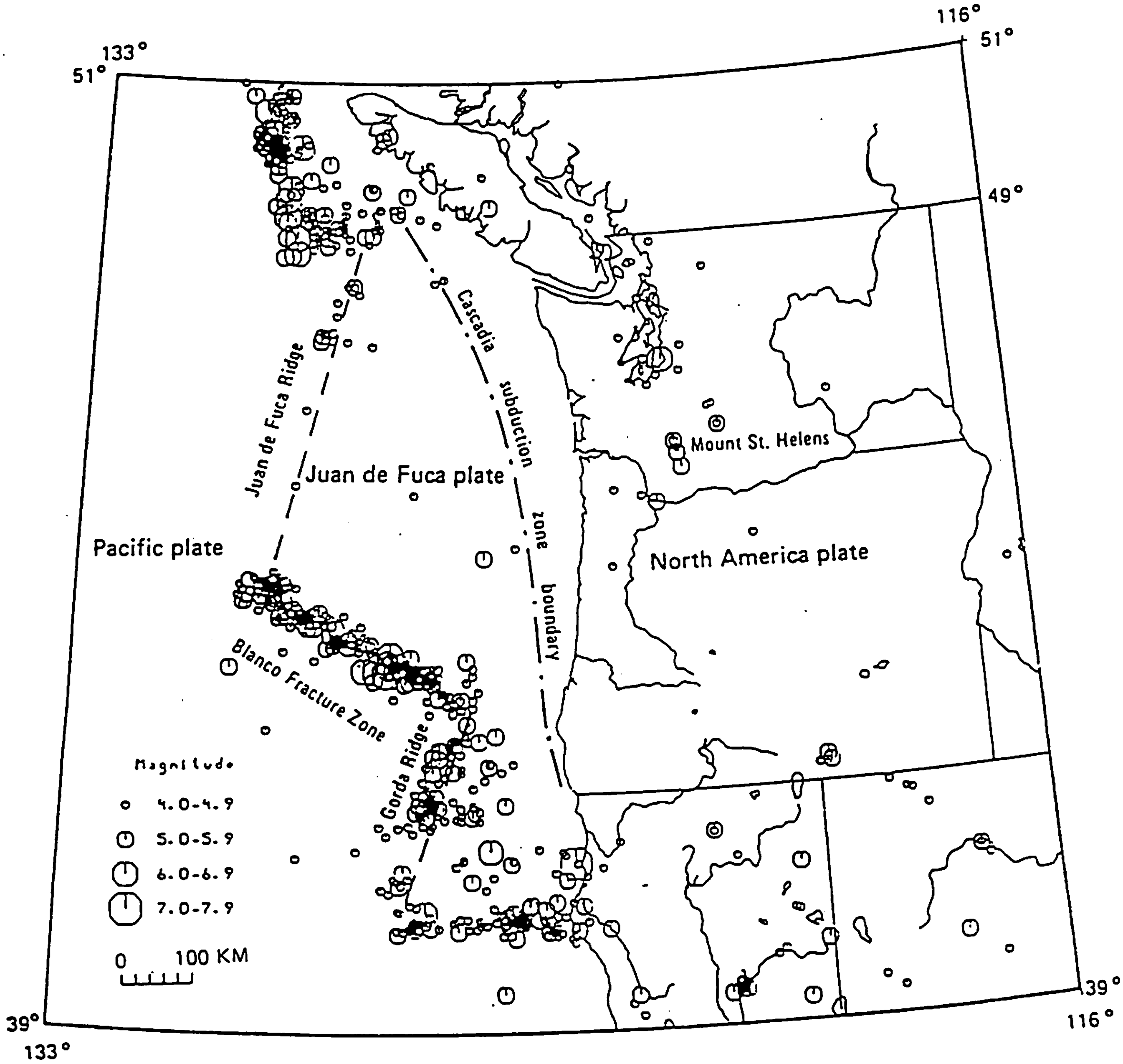


Figure 2.1. Epicenters of Earthquakes in the Pacific Northwest Since 1960

Only the largest earthquakes near Mount St. Helens are indicated. (Data from the National Oceanic and Atmospheric Administration and the University of Washington. Adapted from Washington State Earthquakle Hazards, November 1988.)

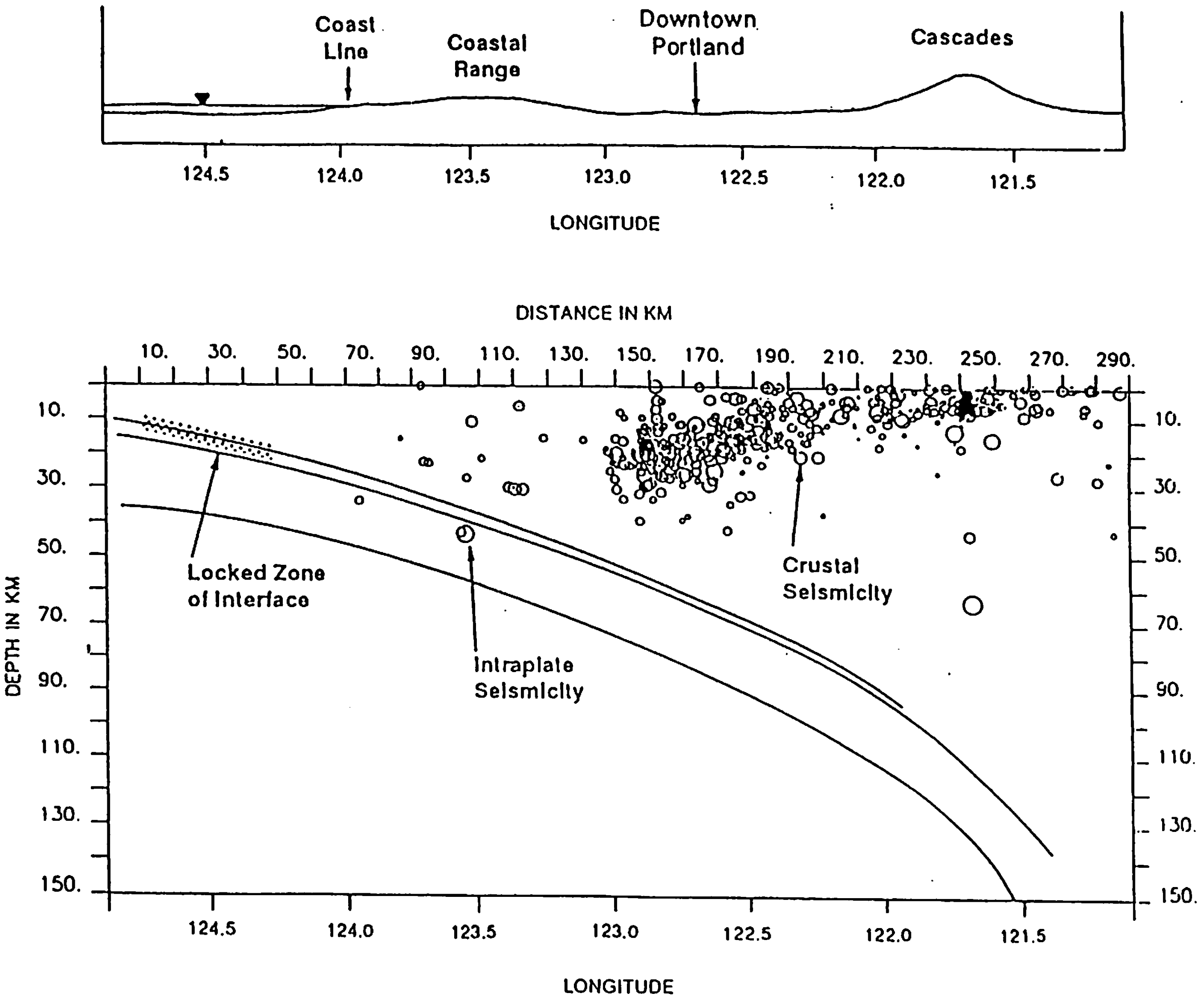


Figure 2.2 Cross Section of Seismicity Centered on Latitude 45.5 with Inferred Location of Subduction Portion of Juan de Fuca Plate

3) Small to moderate earthquakes, which cause some damage to buildings and may cause some casualties, are expected approximately every few decades on average.

4) Large earthquakes, which cause widespread significant damage to many buildings and significant casualties may be expected roughly every few hundred years. A large earthquake on the Cascadia subduction zone, which probably occurred last in the year 1700, is the best example of this class of earthquake.

5) Catastrophic earthquakes, which cause massive damage to many of the buildings in Portland and very high casualties may be expected only once in a thousand years or longer. A large earthquake on the Portland Hills fault is the best example of this class of earthquake. Such catastrophic earthquakes have not yet been observed in the relatively short written-history time period of Western Oregon.

In considering the full range of damaging earthquakes which could affect Portland, it is important to remember that geologists cannot yet predict when specific earthquakes will occur. For example, a major Cascadia subduction zone earthquake, which occurs on average once every several hundred years or so, might not occur for several hundred years or it could occur next year, next week, or tomorrow.

Our detailed assessment of the seismic hazard in Portland, including quantitative estimates of the probabilities of damaging ground motions for rock, firm soil and soft soil sites, is given in Technical Appendix 1 in Volume 2.

# 3.0 SEISMIC RISK IN PORTLAND: BUILDING SEISMIC VULNERABILITIES

## 3.1 Building Classes

Seismic "risk" (i.e., the potential for earthquake casualties and damages) results from the combination of seismic "hazard" (i.e., the probabilities of damaging ground motions) and the vulnerability of the existing building inventory to earthquake damage. Thus, building seismic vulnerability is a major determinant of the degree of seismic risk which Portland faces.

A building's seismic vulnerability depends on the ability of its structural systems (i.e., walls, columns, beams, floors and roofs) to withstand seismic forces. Therefore, an individual building's seismic vulnerability depends on the materials used in its construction, on its age and condition and on the construction details connecting parts of the building together.

To compare seismic vulnerabilities, buildings are commonly grouped into "classes" of buildings with common construction materials, details and seismic performance. Seismic vulnerability varies markedly from building class to building class. We have evaluated the seismic vulnerability of existing buildings in Portland using the 16 building class list used by the National Institute of Building Sciences (NIBS). Definitions for these building classes are given in Table 3.1 on the following page.

There are several published compilations of building seismic vulnerability vs. building class. For the reasons discussed in Technical Appendix 2, we have adjusted these existing compilations in order to account for the Portland-specific building stock. We have made Portland-specific estimates of the vulnerability of these building classes to seismic damage. **In evaluating the seismic vulnerability of buildings in Portland, we have <u>not</u> made assessments of any individual buildings. Rather, all of our estimates apply to typical buildings in each building class** (see Table 3.1). The details of these estimates and descriptions of each building class are given in Technical Appendix 2.

The building seismic vulnerability estimates indicate the fraction of the total inventory of buildings in each building class that will reach each of five damage states when exposed to a specific range of ground motion severity. These five damage states (none, slight, moderate, extensive and complete) are summarized in Table 3.2.

The following example illustrates the principles of the damage state estimates shown in Table 3.2. For a given level of ground shaking, a population of buildings in a single class will have some buildings in several damage states. This variation occurs because of the variations from building to building, variations in site conditions and because of the variation in ground motions with location. For example, at a given level of ground shaking, a large population of unreinforced masonry buildings might have a damage distribution as follows: no damage (3%), slight damage (11%), moderate damage (32%), extensive damage (34%) and complete damage (20%). At higher levels of ground shaking, the fraction of buildings in the higher damage states would increase. At lower levels of ground shaking, the fraction of buildings in the higher damage states would decrease.

## Table 3.1
## Building Classification

| LABEL | STRUCTURAL SYSTEM DESCRIPTION |
|---|---|
| W1 | Wood, Light Frame |
| W2 | Wood, Commercial and Industrial |
| S1 | Steel Moment Frame |
| S2 | Steel Braced Frame |
| S3 | Steel Light Frame |
| S4 | Steel Frame with Cast-In-Place Concrete Shear Walls |
| S5 | Steel Frame with Unreinforced Masonry Infill Walls |
| C1 | Concrete Moment Resisting Frame |
| C2 | Concrete Shear Walls |
| C3 | Concrete Frame with Unreinforced Masonry Infill Walls |
| PC1 | Precast Concrete Tilt-Up Walls |
| PC2 | Precast Concrete Frame with Concrete Shear Walls |
| RM1 | Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms |
| RM2 | Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms |
| URM | Unreinforced Masonry Bearing Walls |
| MH | Mobile Homes |

Buildings' seismic vulnerability - that is, their potential for damage and casualties in earthquakes - varies significantly with building class.

Buildings' seismic vulnerability also depends on the design of individual buildings within a class. Buildings with configurational irregularities, soft stories and other less than optimum design characteristics may be more vulnerable than the typical building in a given class. "Configurational irregularities" means buildings with irregular shapes in plan (e.g., U-shaped instead of square) or changes in size between stories. "Soft stories", which are common in buildings with retail space on the ground floor, are weaker than the other stories in a building because they have nonstructural storefronts or other structurally weak elements instead of solid walls that typically occur in the floors above the ground floor.

All building classes located on rock or firm soil sites are generally much less vulnerable to seismic damage than are similar buildings located on soft soil sites. Soft soil sites are prone to amplification of ground motions, longer duration shaking and other effects that substantially increase building damages and thus the potential for injuries and deaths.

## Table 3.2
## Building Damage States

| Damage State | Damage Range (percent of building replacement value) | Average Damage (percent of building replacement value) |
|---|---|---|
| none | 0 | 0% |
| slight | 1% to 10% | 5% |
| moderate | 10% to 30% | 20% |
| extensive | 30% to 70% | 50% |
| complete[1] | 100% | 100% |

[1] "complete" damage indicates that a building cannot be economically repaired and does not necessarily indicate that collapse occurs or that damage is "total."

Average damage percentages relate to the costs of damage repair as a fraction of building replacement value. Replacement value is the current cost to construct a new building of the same size and use with similar materials as the existing building.

For the "complete" damage state, collapse does not always occur. Rather, this damage state indicates that the building cannot be economically repaired and will probably be demolished.

Descriptions of the specific types of damage expected for each building class at each damage state are given in Technical Appendix 3 in Volume 2.

At any given level of ground shaking, the distribution of a population of buildings between these damage states will vary depending on building class. More vulnerable classes will have higher fractions of their populations in the higher damage states. Less vulnerable classes will have lower fractions of their populations in the higher damage states.

For a given building class, the fraction of a population in the higher damage states will increase as the intensity and duration of ground shaking increases.

## 3.2 Building Classes: Relative Life Safety Risk

All building types present some degree of life safety hazard in the "complete" damage state. However, wood framed, steel moment and braced frame, steel light frame buildings and mobile homes have seldom resulted in significant deaths in historical earthquakes in the United States. Furthermore, the levels of ground motion where a significant fraction of these buildings would be in the "complete" damage state are generally higher than the ground motions which are expected in Portland in all but extremely rare and unlikely (but not impossible) earthquakes. Therefore, we do not believe that typical buildings in these six classes of buildings - wood light frame (residential), wood frame (commercial), steel moment and braced frame, steel light frame and mobile homes - pose a significant life safety risk for Portland and we have excluded them from further consideration in our study.

The remaining 10 classes of major building types <u>do</u> pose varying degrees of life safety risk and we consider these 10 classes in more detail. These 10 building classes have significantly different materials (concrete, steel, masonry, wood) and structural systems. Therefore, the types of seismic damage differ significantly between building classes. At any given damage state (expressed as a percentage of a building's replacement value), some building classes pose a greater life safety risk than others. However, for all building classes, deaths result predominantly from the "complete" damage state because the death rates in lower damage states are much lower than in the "complete" damage state.

The relative extent of life safety risk posed by these 10 building classes in Portland is summarized in Table 3.3. These life safety risk rankings are based on the estimated probabilities of death due to earthquake damages. Quantitative estimates of life safety risk for these 10 building classes for three types of sites (rock, firm soil and soft soil) are given in Chapter 6.

### Table 3.3
### Relative Life Safety Risk by Building Class

| LIFE SAFETY RISK | BUILDING CLASS |
|---|---|
| HIGHEST RISK | Unreinforced Masonry Bearing Walls (URM) |
| | Precast Concrete Frame with Concrete Shear Walls (PC2) |
| | Concrete Frame with Unreinforced Masonry Infill Walls (C3) |
| | Steel Frame with Unreinforced Masonry Infill Walls (S5) |
| | Reinforced Masonry Bearing Wall with Precast Concrete Diaphragms (RM2) |
| | Concrete Moment Resisting Frame (C1) |
| | Precast Concrete Tilt-Up Walls (PC1) |
| | Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1) |
| | Steel Frame with Cast-In-Place Concrete Shear Walls (S4) |
| LOWEST RISK | Concrete Shear Walls (C2) |

These relative life safety risk rankings are based on the estimated probabilities of death due to earthquake damages. Quantitative estimates of life safety risk for these 10 building classes for three types of sites (rock, firm soil, and soft soil) are given in Chapter 6.

# 4.0 SCENARIO EARTHQUAKE DAMAGES

There are many possible earthquakes which can affect Portland, ranging from those that cause little or no damage to the worst case earthquake which would cause massive damage and high casualties. To help readers better understand the potential impacts of earthquakes on the City of Portland, we consider three earthquake "scenarios" which describe approximately the types of damages expected in these earthquakes. These earthquake scenarios include summaries of the locations and magnitudes of the earthquakes, a description of the areas of the City which would be most strongly affected and descriptions of the approximate levels of damages and casualties, with particular emphasis on some of the most vulnerable building classes.

The size of earthquakes is commonly classified on the Richter magnitude scale which is a measure of the total amount of energy released by an earthquake. Great earthquakes which cause damage over wide geographic areas have magnitudes of 8 to 9. Large earthquakes which may cause extensive damages tens of miles from the earthquake have magnitudes in the 7 range. Small to moderate earthquakes which will be locally damaging have magnitudes in the 5 to 6 range. Earthquakes below magnitude 5 may be felt but generally cause little or no damage.

A common misconception is that earthquakes of a higher magnitude are worse for a particular city. This is not necessarily true because the impacts of an earthquake on the built environment of a city depend on three main factors: 1) the magnitude of the earthquake, 2) the distance between the earthquake and the city, and 3) the site characteristics of buildings in the city (i.e., whether buildings are on rock, firm soil or soft soil). Thus, a very large earthquake may cause little or no damage at a given site if the earthquake is quite far away. On the other hand, a moderate earthquake may cause immense damage if it is located directly within the heavily populated areas. Two examples of moderate earthquakes causing immense damages are the Northridge earthquake (magnitude 6.7) and the Kobe earthquake (magnitude 6.9).

For Portland, we consider three scenario earthquakes: 1) a magnitude 6.9 on the Portland Hills fault, 2) a magnitude 8.5 on the Cascadia subduction zone, and 3) a magnitude 6.5 on the Lackamas Creek fault. The magnitude 6.9 on the Portland Hills fault is the most devastating earthquake for Portland because of the proximity of the fault to the city. The magnitude 8.5 on the Cascadia subduction zone would cause widespread damage throughout Western Oregon and the Pacific Northwest, including Portland, but the effects on Portland would be less devastating than the magnitude 6.9 on the Portland Hills fault, because the magnitude 8.5 earthquake is located much further away. A magnitude 6.5 on the Lackamas Creek fault would cause locally heavy damage, but only moderate damages for most of the city.

The life safety seismic retrofits, which are discussed beginning in Chapter 5, would substantially reduce the casualties expected in future earthquakes, if such retrofits were applied to the building classes most vulnerable to seismic damages. Such retrofits would also reduce, but not eliminate, some of the economic damages to buildings and contents.

## Table 4.1
## Scenario Earthquakes Affecting Portland

| Earthquake Scenario Description | Portland Hills Fault | Cascadia Subduction Zone | Lackamas Creek Fault |
|---|---|---|---|
| **magnitude** | 6.9 | 8.5 | 6.5 |
| **location** | 2 miles SW of downtown | about 75 miles west | 12 miles NE |
| **frequency of earthquake** | every 1,000+ years | every few hundred years | every 1,000+ years, but total frequency of similar or slightly smaller events may be every 100 to 200 years |
| **last occurrence** | unknown | 1700 | unknown |
| **geographic extent of damages** | very heavy damages widespread in Portland, extreme damages in SW | throughout Western Oregon and the Pacific Northwest, widespread damages in Portland | concentrated near the fault, light/moderate damage widespread in Portland |
| **unreinforced masonry buildings (high life safety risk)** | city-wide, at least 50% may have extensive or complete damage; on soft soil sites, nearly all will have extensive or complete damage | city-wide, most have moderate damage or higher; on soft soil sites, 50% or more may have extensive or complete damage | city-wide, most have slight/moderate damage; much higher damages in NE, especially on soft soils near Columbia River |
| **concrete moment frame buildings (moderate life safety risk)** | city-wide, 80% have moderate damage or higher; on soft soil sites, 50% may have extensive or complete damage | city-wide, most have slight/moderate damage; on soft soil sites 20% may have extensive or complete damage | city-wide, most have none/slight damage; on soft soils in NE near Columbia river, many with moderate to extensive damage and a few with complete damage |
| **steel frame with concrete shear walls buildings (lower life safety risk)** | city-wide most have slight/ moderate damage; on soft soil sites 30% may have extensive damage and a few percent may have complete damage | city-wide, many have slight/ moderate damage; on soft soil sites 10% may have extensive damage | city-wide, most with none or slight damage; on soft soils in NE near Columbia river, many with slight/moderate damage and 10% with extensive damage |
| **deaths** | high: perhaps 1,000 to 5,000 | moderate: perhaps several hundred | low: a few to perhaps 100 to 200 |

These scenario damage estimates are based on the seismic hazard modeling and on the building seismic vulnerability estimates which are presented in Volume 2.

All of these estimates are very approximate because regional earthquake damages and losses vary markedly depending on the precise characteristics of each earthquake.

In particular, the death estimates are very uncertain. Death rates vary markedly depending on the time of day of earthquakes. For example, collapses of a few large buildings could kill hundreds of people if the buildings were fully occupied but only a few people if the earthquake occurred at a time of minimum occupancy.

# 5.0 LIFE SAFETY RETROFITS

## 5.1 Objectives of Life Safety Retrofits

There are many seismic retrofit techniques for improving the seismic performance of existing buildings. The specific details of the retrofit techniques vary depending on a building's construction type, configuration and condition and thus will differ from building to building. Generally, these techniques involve strengthening the structural elements of the building (i.e., the walls, columns, beams, floors and roofs) which provide strength and resistance to earthquake forces. Common techniques include adding bracing, adding heavily-reinforced concrete walls (known as shear walls), and strengthening floors and roofs. Such measures are known as structural retrofits because they improve the seismic resistance of the structural elements of a building.

In addition to the structural retrofits discussed above, seismic retrofits also commonly involve non-structural elements of buildings. Non-structural elements include ceilings, light fixtures, electrical and mechanical systems and other building elements which do not contribute to the structural integrity of the building (i.e., they do not provide strength to resist either vertical or horizontal forces on a building). In earthquakes, many injuries, some deaths and much of the loss of functionality may result from the failure (falling) of non-structural elements. Thus, for life safety and for reducing damages and loss of functionality, non-structural elements (especially ceilings and light fixtures) are often retrofitted at the same time as structural retrofits are undertaken. In some cases, some non-structural measures may be code-mandated.

The objective of life safety retrofits is to reduce earthquake deaths and injuries by preventing the full or partial collapse of a building and by ensuring access and egress to/from the building after earthquakes for occupants and/or emergency responders. **Seismic retrofit does not make a building earthquake proof!** Depending on the severity of an earthquake, a building which has been seismically retrofitted may have minor damage or even major unrepairable damage which results in demolition of the building. **In considering life safety retrofits it is essential to remember that the objective is to minimize deaths and injuries, not to preserve the functionality of the building nor to eliminate building damage.** Despite these limitations, buildings which have undergone life safety retrofits often have less damage than unretrofitted buildings, especially in small to moderate earthquakes. Thus, life safety retrofits will have some economic benefits (i.e., reduced damage, less loss of functionality) in addition to substantial reductions in deaths and injuries. Life safety benefits are presented and discussed in Chapter 7. Other economic benefits are presented and discussed in Chapter 8.

Life safety retrofits of existing buildings are generally quite effective in avoiding deaths in earthquakes because full or partial collapse is generally prevented. However, there may still be occasional deaths from falling objects and significant numbers of injuries, especially in larger earthquakes. In addition, just as for newly-designed buildings (even those in full compliance with current building codes), full or partial collapse of a retrofitted building may happen in the unlikely, but not impossible scenario, where earthquake ground motions occur which are much larger than the retrofit design basis.

## 5.2 Typical Retrofit Costs

The Federal Emergency Management Agency (FEMA) has recently updated and revised its publication on "Typical Costs of Seismic Rehabilitation of Buildings." Because such a high percentage of seismic retrofits (rehabilitations) to date have been designed for life safety, "typical" seismic retrofits are life safety driven and therefore the costs of "typical" retrofits are a good estimate for the costs of life safety retrofits.

Seismic retrofits are commonly undertaken in conjunction with repairs, remodeling, or refurbishing of existing buildings. Therefore, proper care must be taken to separate the seismic costs from total costs. Similarly, some costs which may be associated with seismic retrofits are properly excluded from the present estimates, because these costs are not related to improving the seismic life safety of the buildings.

Some compilations of seismic retrofit costs include only "structural costs" which are the costs necessary only for the strengthening of structural elements of buildings such as walls, floors, beams, columns and roofs. "Structural cost" estimates considerably underestimate total seismic costs because there are several other costs that are usually a necessary and integral part of a seismic retrofit. These other costs include:

1) restoration of architectural finishes after structural work,
2) non-structural mitigation work such as bracing of ceilings and lights,
3) other project costs such as architectural and engineering fees, permits, management, insurance, and
4) relocation costs if a building must be vacated during construction.

The following table is a compilation of the FEMA "Typical Costs" of retrofits for various building classes, expressed in dollars/square foot of building area. These cost estimates are for "medium" sized buildings between 10,000 and 50,000 square feet. Because of economies of scale, costs per square foot are typically slightly higher for smaller buildings and slightly lower for larger buildings. For each building class, costs estimates are given for "average" or typical commercial buildings, for "institutional buildings" and for "industrial" buildings. The retrofit costs vary between these three categories of use because of significant differences in the amount of restoration of architectural finishes, differences in non-structural costs and differences in relocation costs.

The typical costs for life safety retrofits are summarized in Table 5.1. These costs include: structural costs, restoration of architectural finishes, "light" non-structural retrofit, other project costs (estimated at 30% of total construction costs) and relocation costs (estimated at $9.00/sf for most buildings, but only $1.50 for industrial use buildings and for all precast tilt-up (PC1) and reinforced masonry with wood or metal diaphragm buildings (RM1), regardless of use). Full tables of costs, including subcosts for each of the cost categories above, along with more detailed discussions are given in Technical Appendix 4

As with any compilation of "typical" costs, the actual costs for a specific building may vary - being either higher or lower than these "typical" values.

## Table 5.1

### TOTAL LIFE SAFETY RETROFIT COSTS $/sf
### (Medium Size Buildings, 10,000 to 50,000 square feet)

| Building Classes | Institutional Buildings cost/sf | Average Buildings cost/sf | Industrial Buildings cost/sf |
|---|---|---|---|
| **URM** | $37.09 | $34.49 | $23.09 |
| **W1, W2** | $33.91 | $31.31 | $19.91 |
| **PC1, RM1** | $17.43 | $14.83 | $10.93 |
| **C1, C3** | $43.96 | $41.36 | $29.96 |
| **S1** | $44.28 | $41.68 | $30.28 |
| **S2, S3** | $28.77 | $26.17 | $14.77 |
| **S5** | $48.01 | $45.41 | $34.01 |
| **C2, PC2, RM2, S4** | $43.73 | $41.13 | $29.73 |

See Table 3.1 on page 8 for names and descriptions of the building classes.

These typical costs include: structural retrofit costs, restoration of architectural finishes, "light" non-structural retrofit, other costs (architectural and engineering fees, permits, management, insurance) and relocation costs during retrofit construction.

All of these cost estimates are based on data in FEMA's "Typical Costs of Seismic Rehabilitation of Buildings," except for the relocation costs which were estimated by the authors of the present report.

These typical costs exclude: costs associated with refurbishing/remodeling/upgrading of buildings, abatement of hazardous materials, any non-seismic safety measures (e.g., fire sprinklers) and enhanced access for disabled persons.

Actual costs for a specific building may be higher or lower than these typical costs depending on the retrofit design, the architectural finishes in the building, the building's configuration and condition, actual relocation costs and many other considerations.

The typical costs shown in the Table 5.1 exclude costs associated with refurbishing/ remodeling/upgrading of buildings, abatement of hazardous materials, any non-seismic safety measures (e.g., fire sprinklers) and enhanced access for disabled persons. These exclusions are made because such costs are not part of the seismic retrofit (even if code-mandated) and do not improve seismic performance. These costs are inappropriate to consider because they do not relate to earthquake life safety benefits. See Technical Appendix 4 for a fuller discussion of costs which are included and excluded from the "typical" costs of life safety retrofits.

# 6.0 LIFE SAFETY RISK: EXISTING BUILDINGS IN PORTLAND

## 6.1 Introduction

Earthquake life safety risk in existing buildings can be defined quantitatively for each building class by estimating the annual probability of deaths per 100,000 occupants. Each building class has its own unique earthquake vulnerability. Therefore, there is a substantial variation in the probable death rates between building classes. For example, the probable death rate in the most vulnerable building class (unreinforced masonry) is 20 to 50 times higher than the least vulnerable building classes in our study (steel frame with concrete shear walls and concrete shear walls). Without question, unreinforced masonry buildings, on average, pose the greatest life safety risk.

The location of a building with respect to the soil type (rock, firm soil or soft soil) on which it is built also creates major variations in a building's earthquake vulnerability and consequently substantially affects the extent of life safety risk. Within each building class, the life safety risks posed by those buildings located on soft soils are 3 to 4 times higher than those of similar buildings located on firm soil sites. Similarly, the life safety risk posed by those buildings on firm soils are 20 to 50 times higher than those of similar buildings located on rock sites. Thus, buildings on soft soil sites pose a much higher life safety risk than similar buildings on firm soil or rock sites. For a more detailed discussion of soil conditions and their effects on buildings' seismic vulnerability see Technical Appendices 2 and 3 in Volume 2.

## 6.2 Soil Variations in Portland

In Portland, rock sites are generally found only in the hilly areas. Much of the city is on sites which would be classified as firm soils. Firm soils are dense, well compacted soils with good bearing strengths. Soft soils are loose, poorly compacted soils or poorly engineered fills with low bearing strengths and higher potential for liquefaction and other types of soil failures. Soft soils, which are much more dangerous in earthquakes, are located primarily in the areas near the Willamette and Columbia Rivers. The soft soil areas in Portland are shown in yellow, red and purple on the generalized geologic map of surface geology in Portland, Figure 6.1. It is important to note that boundaries between "firm" and "soft" soils are not as sharply defined as, for example, the boundary between an asphalt parking lot and a grassy field. Rather the soil boundaries are more gradational and vary with soil depth, soil characteristics and the water table elevation.

In considering the impact of soil conditions on the life safety risks posed by buildings on Portland it is important to note that the surface soil type may not always be representative of the soils on which buildings are founded. For example, especially for larger buildings, some buildings in areas shown as "soft soil" on the maps, may actually have foundations on deeper layers which are firm soil or rock.

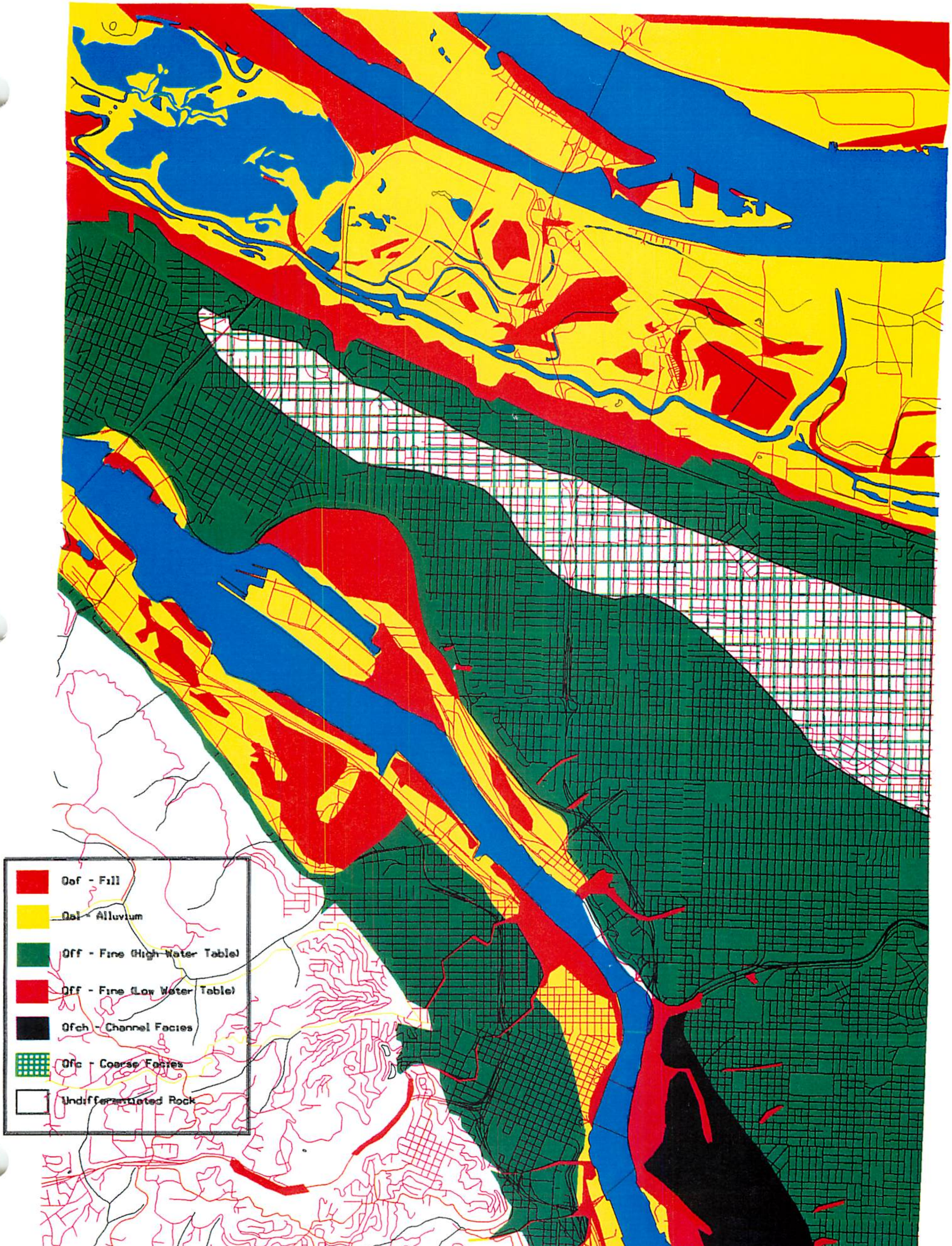


Figure 6.1 Portland Quad Geologic Map G&E Engineering Systems, R27.02, 1995

## Guide to Interpretation of Figure 6.1 (Portland Quadrangle Geologic Map)

### Soft soils

Soft soils are generally found along the Columbia and Willamette Rivers and along smaller stream channels. Areas shown in red are man-made fill. Areas in yellow are unconsolidated alluvium (loose river deposits). Areas shown in purple are coarser channel facies (river deposits).

### Firm Soils

Firm soils, which are shown in green on the map, are found on higher ground, further from the Columbia and Willamette Rivers. In addition, there is a small strip of reddish purple between the yellow and green areas south of the Columbia river which indicates soils which may be intermediate between the soft soil areas (yellow on the map) and the firm soil areas (green on the map).

### Rock sites

Rock sites, which are shown in white on the map, are found in the Portland hills west of downtown and in the higher elevations northeast of downtown.

## Ground Shaking vs. Other Seismic Hazards

Throughout this report, we consider the effects of ground shaking on buildings and the resulting damages and casualties. Some soft soil areas may be subject to liquefaction and ground displacements (lateral spreads) during earthquakes. Such effects would increase the expected damages at a given level of ground shaking. Similarly, some hilly areas may be subject to earthquake-induced landslides, which could greatly increase building damages. **We do NOT consider liquefaction, landslides, or other ground movements because such effects are highly site-specific and thus require evaluation of site and building characteristics for each individual building.**

In addition, the "typical costs" for seismic retrofits are based on ground shaking only. In some cases, liquefaction potential, lateral spread potential and landslide potential can be mitigated by appropriate remedial work to soils and foundations. Such work is generally very expensive and varies markedly depending on the characteristics of each site and each building. Therefore, all of our analyses in this report consider only ground shaking hazards and the typical retrofits evaluated are those designed to mitigate the adverse effects of ground shaking only.

## 6.3 Earthquake Life Safety Risk Estimates

This study focuses on the ten building classes which pose highest life safety risk based on their average probability of causing life loss. Within this group, the extent of life safety risk varies by a factor of more than 4,000 between the lowest risk class (steel frame buildings with concrete shear walls, S4) located on rock sites and the highest risk class (unreinforced masonry, URM) located on soft soil sites.

Estimates of the average annual death rate per 100,000 occupants in each of the 10 building classes across the three soil types is shown in Table 6.1. The earthquake death risk estimates in this table will NOT occur every year. Rather, the estimates represent the long term average death risk accumulated from all possible earthquakes affecting Portland. **The death risk estimates are the weighted average from all of the possible earthquakes, considering the death rate and the probability of each earthquake.** Over a long time of several hundred years or more, Portland is likely to experience several small to moderate earthquakes with a few casualties and one or more larger earthquakes with much higher casualties. These annual death rate estimates average the expected deaths from all earthquakes and present the results on an annualized statistical basis.

These earthquake death rate estimates depend on 1) the earthquake probabilities for Portland, 2) the effects of the three types of sites (rock, firm soil and soft soil), and 3) on the relationships between building damage and casualties. The absolute death rates per 100,000 occupants are subject to the uncertainties in all of the factors which affect these estimates. However, the relative death rates and the distinctions between the high risk classes and the lower risk classes are much more robust. Thus, the general trends between building classes and between site types are reliable.

To put these estimated death rates per 100,000 occupants in context, we note that in the United States about 15 people per 100,000 die every year in automobile accidents. We compare the earthquake death risk for the 10 building classes to the automobile death risk as follows.

> On rock sites, the earthquake death risk ranges from 20 to 700 times lower than the automobile death risk. Thus, the earthquake death risk appears very low for all of these building classes, relative to another common source of accidental deaths.
>
> On firm soil sites, the earthquake death risk is about 1.5 to 2.5 times higher for unreinforced masonry (URM) and precast concrete frame (PC2) buildings than the automobile death risk. For concrete frame with URM infill (C3), steel frame with URM infill (S5) and reinforced masonry buildings with precast concrete diaphragms (RM2), the earthquake death risk is about 40 to 70% as high as the automobile death risk. For the other five building classes, the earthquake death risk is a factor of 5 to 25 lower than the automobile death risk.
>
> On soft soil sites, the earthquake death risk for the five most vulnerable building classes is about 2 to 6 times higher than the automobile death risk. The earthquake death risk for concrete frame (C1), precast concrete tilt-up (PC1) and reinforced

## Table 6.1

## Estimated Long-Term Average Deaths per Year per 100,000 Occupants by Building Class and Site Characteristics

| Building Class | Rock Sites | Firm Soil Sites | Soft Soil Sites |
|---|---|---|---|
| Unreinforced Masonry Bearing Walls (URM) | 0.82 | 36.5 | 91.0 |
| Precast Concrete Frame with Concrete Shear Walls (PC2) | 0.80 | 18.4 | 51.0 |
| Concrete Frame with Unreinforced Masonry Infill Walls (C3) | 0.17 | 10.1 | 37.3 |
| Steel Frame with Unreinforced Masonry Infill Walls (S5) | 0.16 | 10.1 | 36.0 |
| Reinforced Masonry Bearing Wall with Precast Concrete Diaphragms (RM2) | 0.12 | 6.7 | 24.5 |
| Concrete Moment Resisting Frame (C1) | 0.04 | 3.3 | 13.5 |
| Precast Concrete Tilt-Up Walls (PC1) | 0.07 | 3.7 | 11.1 |
| Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1) | 0.04 | 1.7 | 7.4 |
| Steel Frame with Cast-In-Place Concrete Shear Walls (S4) | 0.02 | 0.66 | 3.6 |
| Concrete Shear Walls (C2) | 0.04 | 0.74 | 3.4 |

These estimated earthquake death rates are the average rates per year per 100,000 occupants in each building class over a long time period.

These earthquake death rates depend on the earthquake probabilities for Portland, the effects of the three site types (rock, firm soil, soft soil), on the vulnerability of each building class to seismic damage and on the relationships between building damage and casualties.

The absolute death rates per 100,000 occupants are subject to all of the uncertainties in all of the factors which affect these estimates. However, the relative death rates and the distinctions between the high risk classes and the lower risk classes are much more reliable.

masonry with wood diaphragms (RM1) buildings is about 50 to 90% as high as the automobile death risk. The earthquake death risk for steel frame with concrete shear walls (S4) and concrete shear wall buildings (C2) are factors of 5 to 8 lower than the automobile death risk.

Based on these estimated earthquake death rates and the comparisons between earthquake and automobile death risks, we reach the following preliminary life safety conclusions:

1) on rock sites, none of the building classes appear to constitute a significant life safety risk,

2) on firm soil sites, the five most vulnerable building classes may constitute a significant life safety risk. These classes include, in decreasing order of life safety risk: unreinforced masonry (URM), precast concrete frame (PC2), concrete frame with URM infill (C3), steel frame with URM infill (S5) and reinforced masonry bearing wall with precast concrete diaphragms (RM2).

3) on soft soil sites, the five building classes which constitute a significant life safety risk on firm soils constitute a much more substantial life safety risk on soft soil sites because these soft soils increase building damages and thus increase casualties. Furthermore, three additional classes may also constitute a significant life safety risk: concrete frame (C1), precast concrete tilt-ups (PC1) and reinforced masonry with wood diaphragms (RM1).

4) two building classes, steel frame with concrete shear walls (S4) and concrete shear walls (C2) do not appear to constitute a significant life safety risk for any site conditions.

It is very important to note that all of these conclusions apply to typical buildings in each class. **Any specific single building may pose a much lower or a much greater life safety risk than posed by the typical building in a class because of its individual characteristics and specific earthquake vulnerability.** In addition, these conclusions do not take into account the variations in occupant density (number of persons per 1,000 square feet, based on use and hours of operation) that will affect the relative life safety risk, especially for unusually low or usually high occupancy buildings.

The conclusions discussed above are based on life safety risk from the entire building. An exception to this generalization is necessary for unreinforced masonry building parapets. Unreinforced masonry (URM) building parapets present a life safety hazard at levels of ground motion as low as 0.10 g, with widespread failures at 0.25 g or higher Thus, they constitute a life safety hazard even on rock sites, because such low levels of ground motion are to be expected on all sites in Portland.

Typical costs for parapet bracing range from $25 to $30 per linear foot of parapet; higher costs are possible if roofs must be strengthened to support the braces.

The extent of life safety risk posed by parapet failures cannot be evaluated by the same methods as used for buildings as a whole, because the persons at risk are primarily not the occupants of the building itself but rather persons on the sidewalk or street outside of the buildings and/or occupants in lower adjacent buildings which may be subject to falling parapets.

Parapet bracing is very inexpensive compared to whole-building retrofits and a significant fraction of the life safety risk posed by unreinforced masonry buildings is posed by parapets. Therefore, we conclude, qualitatively, that bracing of unreinforced masonry parapets is highly recommended as a low-cost life safety enhancing measure.

These preliminary life safety conclusions are discussed in more detail in the following two chapters in which benefit-cost analysis is used to make more quantitative determinations of the extent of life safety hazard and to explore whether or not retrofitting some classes of buildings to enhance life safety is economically justified. Chapter 7 considers life safety benefits; Chapter 8 considers non-life safety economic benefits. Determining whether or not a retrofit is economically justified requires considering the total benefits of retrofit, including both life safety and non-life safety benefits.

# 7.0 LIFE SAFETY BENEFITS

## 7.1 Benefit-Cost Analysis: Assumptions

The benefit-cost methodology used for these Portland analyses is very closely based on methodologies developed for and adopted by the Federal Emergency Management Agency (FEMA). The first FEMA methodology, **A Benefit-Cost Model for Seismic Rehabilitation of Buildings** (FEMA 227 & 228, 1992), is applicable to private-sector buildings. The second FEMA methodology, **Seismic Rehabilitation of Federal Buildings: A Benefit-Cost Model** (FEMA 255 & 256, 1994) is applicable to public-sector buildings.

The justification for the procedures and the selection of variables to be included in our benefit-cost analyses are those of the FEMA methodologies which are based on widely-accepted economic principles, with the concurrence of economists on the project teams which developed the FEMA methodologies and with the concurrence of three nationally-recognized economists on each of the projects' technical advisory panels.

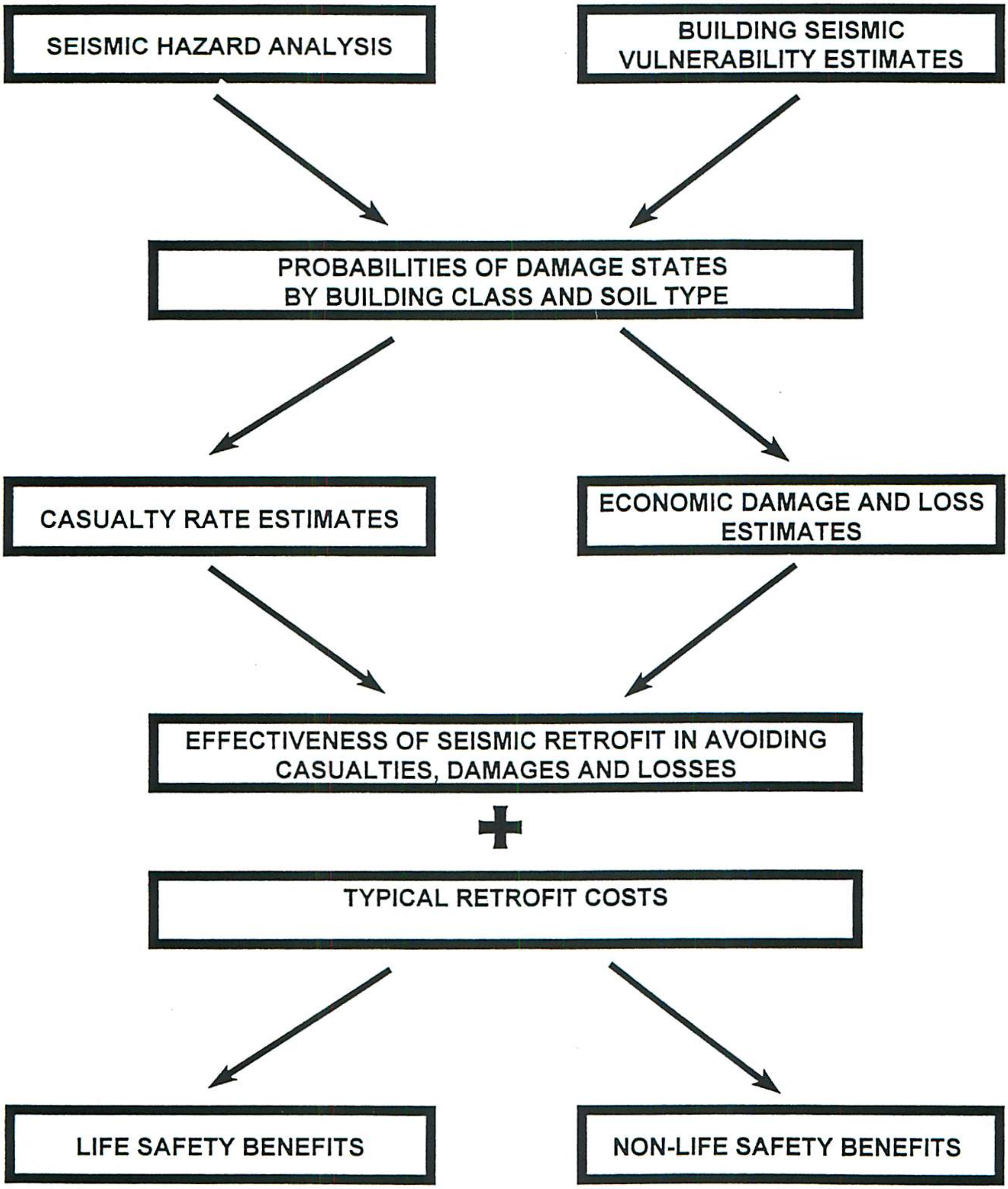
The benefits of a seismic retrofit of a building are the reduction in expected future damages and losses, compared before and after retrofit. In other words, benefits are the present value of avoided future damages and losses. The avoided damages and losses considered in this benefit cost methodology include: casualties, building damages, contents damages, displacement costs due to seismic damage, rental and business income losses and loss of public/nonprofit services. See Technical Appendix 5 in Volume 2 for details of the underlying assumptions and data used in the benefit-cost analysis.

The logical path leading from seismic hazard estimates, to building vulnerability estimates, to casualty and economic loss estimates and to benefits estimates is shown in Figure 7.1, a conceptual flow chart of the benefit-cost methodology.

This chapter is limited to a discussion of ONLY the life safety benefits (avoided casualties) that may accrue as a results of seismic retrofits of buildings. This emphasis on life safety benefits is taken because of the City's paramount interest in life safety. However, it is important to note that seismic retrofits also have significant non-life safety economic benefits, which include the reduction of building and contents damages, the reduction of economic losses and costs associated with displacement of occupants due to damages, rental and business income losses and, for public buildings, the loss of governmental or quasi-governmental (non-profit) services. These non-life safety benefits, which are generally dominated by avoided damages to buildings and contents, are discussed in Chapter 8.

The analyses discussed below ONLY consider life safety benefits and ignore the non-life safety benefits. In some cases, the life safety benefits alone may exceed retrofit costs. In other cases, the non-life safety benefits may be comparable to or exceed the life safety benefits. In any case, decisions about the economic viability of prospective seismic retrofits MUST consider the total benefits of retrofit by summing the life safety benefits and the non-life safety benefits.

Figure 7.1
Flow Chart of Benefit-Cost Methodology



## 7.2 Benefit-Cost Analysis: Results, Life Safety Only

The primary focus of this study is life safety. Therefore, we first address only the life safety benefits (i.e., the avoided casualties) which may accrue as a result of seismic retrofits, without including the other economic benefits. Later, in Chapter 8, we address the non-life safety economic benefits of seismic retrofits.

Life safety retrofits are, by design, focused primarily on enhancing life safety by greatly reducing the risk of full or partial collapse of buildings. We assume that life safety retrofits are highly effective in avoiding casualties because this is their intended purpose. Based on the assumptions in the FEMA benefit-cost methodology, we assume that such retrofits reduce the deaths rates by a factor of 1,000, reduce major injuries by a factor of 100 and reduce minor injuries by a factor of 10, in every building class.

In evaluating the life safety benefits (avoided casualties) of seismic retrofits we focus primarily on deaths avoided because public policy decisions on earthquake life safety risk are typically based primarily on deaths rather than injuries. The life safety benefits (avoided deaths) are expressed numerically (numbers of deaths expected before and after retrofit) and in economic terms (i.e., the economic value, in dollars, of a statistical human life). Placing a dollar value on human life is necessary to determine whether or not additional safety measures are justified economically. For example, the Environmental Protection Agency, the Department of Transportation and other federal and state agencies always place an economic value on life when determining whether or not safety standards are justifiable when compared to the costs.

For the benefit-cost analysis of seismic retrofits, we consider the economic values of deaths and injuries as follows: deaths ($2,200,000); major injures which require hospitalization ($12,500), minor injuries which do not require hospitalization ($1,250). These values have also been adopted by FEMA for valuing casualties avoided by FEMA-funded hazard mitigation projects for earthquakes and other natural hazards.

The life safety benefits of retrofitting any particular typical building will depend on the building class, on the site characteristics (rock, firm soil, soft soil) and on the specific occupancy of each building. The occupancies of individual buildings, usually expressed per 1,000 sf so that comparisons can be made, vary widely depending on use and function.

**For the purposes of life safety risk assessment and benefit-cost analysis, average occupancies on a 24 hours per day, 7 days per week basis are used to represent the statistical average life safety risk.** If individual earthquakes occur at times of above average occupancy or at times of below average occupancy then the expected casualty rates for that earthquake will be higher or lower than average. However, it is the average occupancy which determines the long-term life safety risk, averaged over many earthquakes and thus it is the average occupancy which is used for all of our calculations.

For most buildings, occupancies average between 1 and 5 people per 1,000 square feet. Facilities which are in use 24 hours per day have much higher average occupancies than do facilities which are heavily occupied only 40 or 50 hours per week. For example, an office building may have 5 people per 1,000 square feet during normal office hours, about 50 hours per week, but very low occupancy during non-office hours. Thus, the average occupancy for this example is about 1.5 people per 1,000 square foot. This is based on the weighted average of 5 occupants per 1,000 square feet for 50 hours per week and about 0.1 occupants per 1,000 square feet for the remaining 118 hours of a week.

Occupancies vary markedly depending on building use. Typical occupancies for major building uses are shown in Table 7.1. It is important to note that actual occupancies for specific buildings may be higher or lower than these typical values.

To examine the life safety benefits of retrofits we consider the occupancy rates per 1,000 square feet that would be necessary in order for the typical costs of seismic retrofits to be equalled by the benefits of avoided deaths. Typically, the economic value of all injuries avoided due to seismic retrofit is a small percentage (often only 1 or 2 percent) of the economic value of deaths avoided. Therefore, considering only deaths counts nearly all of the life safety economic benefits of retrofits.

Table 7.2 shows the occupancy rates per 1,000 square feet, for each building class and each soil type, at which life safety benefits alone would equal total retrofit costs for institutional buildings, average (or commercial buildings) and industrial buildings. The occupancies of institutional buildings must be higher than for average buildings in order for life safety benefits alone to equal total retrofit costs, and the occupancies of industrial buildings can be lower than for average buildings, because the costs of seismic retrofits are different for the these three building use classifications (see Table 5.1).

The occupancy figures in Table 7.2 assume costs for medium-sized (10,000 to 50,000 square feet) buildings. Typical retrofit cost are slightly higher for smaller buildings and slightly lower for larger buildings (see Technical Appendix 4 in Volume 2). However, these cost differences are small, only a few percent and thus do not significantly affect our conclusions.

**Table 7.2 provides a powerful framework to evaluate the life safety benefits of any typical building in Portland in any of the 10 building classes considered. The life safety benefits and the benefit-cost ratio for any occupancy level in any building class can be determined by ratio from these results.** For example, if a building has 3 occupants per 1,000 square feet and the breakeven occupancy (life safety benefits equal to typical retrofit costs) is 30 occupants per 1,000 square feet, then the life safety benefits for this case will be only 10% of typical retrofit costs.

### Table 7.1

### Typical Occupancies Based On Building Uses

| Use Description | Average Square Feet per occupant[1] | Occupied Hours/Day | Occupied Days/Week | Weighted Average Occupants per 1,000 square feet |
|---|---|---|---|---|
| Offices | 200 | 9 | 5 | 1.33 |
| Multi-family residential | 350 | 14 | 7 | 1.67 |
| high-tech industry | 300 | 16 | 6 | 1.90 |
| heavy industry | 500 | 24 | 7 | 2.00 |
| churches | 25 | 6 | 2 | 2.86 |
| schools | 50 | 7 | 3.75 | 3.13 |
| hospitals | 225 | 24 | 7 | 4.44 |
| retail | 100 | 12 | 7 | 5.00 |
| restaurants | 50 | 7 | 7 | 5.83 |
| movie theaters | 25 | 12 | 7 | 20.00 |

[1] These square footages are based on the expected occupant density during business hours and may be higher or lower in specific buildings

[2] The number of days per week for schools is adjusted to less than five, based on a school year of nine months duration.

A typical calculation of the weighted average number of occupants per 1,000 square feet is performed as follows:

The values of square feet per occupant are converted to a number of occupants per 1,000 square feet by dividing that number into 1,000. For office uses, the occupants per 1,000 square feet is therefore 1000/200 = 5.0. This value is then weighted according to the fraction of hours per week that the building is occupied. For offices, 9 hours per day times 5 days gives 45 hours per week of occupancy. Dividing this number by the number of hours per week (168) gives the fraction of a week for which the building is occupied (e.g., 45/168 = 0.268). Finally, multiplying this value times the occupants per 1,000 square feet during occupied hours (5 x 0.268) yields the value of 1.33 for the weighted average occupants per 1,000 square feet. If desired, differing occupancy levels at different times of the day and/or on different days of the week could be averaged in a similar manner.

## Table 7.2
## Occupancies per 1,000 square feet such that Life Safety Benefits Equal Retrofit Costs by Building Class and Site Characteristics

### ROCK SITES

| Building Use | URM | PC2 | C3 | S5 | RM2 | C1 | PC1 | RM1 | S4 | C2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Institutional | 147 | 180 | 834 | 984 | 1211 | 3367 | 822 | 1554 | 7009 | 3781 |
| Average | 137 | 170 | 785 | 930 | 1139 | 3168 | 700 | 1322 | 6592 | 3559 |
| Industrial | 92 | 123 | 568 | 696 | 823 | 2295 | 516 | 974 | 4765 | 2571 |

### FIRM SOIL SITES

| Building Use | URM | PC2 | C3 | S5 | RM2 | C1 | PC1 | RM1 | S4 | C2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Institutional | 3.35 | 7.82 | 14.37 | 15.68 | 21.53 | 44.05 | 15.38 | 33.05 | 219 | 196 |
| Average | 3.11 | 7.35 | 13.52 | 14.83 | 20.25 | 41.44 | 13.08 | 28.12 | 219 | 184 |
| Industrial | 2.08 | 5.31 | 9.79 | 11.11 | 14.64 | 30.02 | 9.64 | 20.73 | 149 | 133 |

### SOFT SOIL SITES

| Building Use | URM | PC2 | C3 | S5 | RM2 | C1 | PC1 | RM1 | S4 | C2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Institutional | 1.34 | 2.82 | 3.85 | 4.40 | 5.88 | 10.76 | 5.16 | 7.76 | 39.80 | 42.41 |
| Average | 1.25 | 2.66 | 3.65 | 4.16 | 5.53 | 10.13 | 4.39 | 6.60 | 37.44 | 39.89 |
| Industrial | 0.84 | 1.92 | 2.64 | 3.11 | 4.00 | 7.34 | 3.24 | 4.87 | 27.06 | 28.83 |

**Table 7.2 provides a powerful framework to evaluate the life safety benefits of any typical building in Portland in any of the 10 building classes considered. The life safety benefits and the benefit-cost ratio for any occupancy level in any building class can be determined by ratio from these results.** Remember that typical average occupancies for many buildings are in the range of 1 to 5 people per 1,000 square feet.

There are several ranges of values to consider in these tables:

1) Combinations of building class and site where the occupancy figure in the above tables is close to 1: life safety benefits exceed retrofit costs for most buildings.

2) Combinations of building class and site where the occupancy figure is between about 2 and 5: life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs, depending on the occupancy per 1,000 square feet for the specific buildings under consideration.

3) Combinations of building class and site where the occupancy figure is between 5 and 10: life safety benefits will be less than retrofit costs unless occupancy is unusually high; life safety benefits may be a significant fraction of retrofit costs, depending on the specific occupancy.

4) Combinations of building class and site where the occupancy figure is well above 10 to well above 100: life safety benefits will generally be a small fraction of retrofit costs.

## 7.3 Life Safety Benefits as a Function of Occupancy Levels

The results presented in Table 7.2 provide the framework to evaluate life safety benefits compared to typical retrofit costs for all of the building classes and soil types considered. These results are interpreted in the following sections.

### Rock Sites

For rock sites, all of the combinations of building classes and building uses would require from approximately 100 to well above 1,000 occupants per 1,000 square feet in order for the life safety benefits to equal typical retrofit costs. These occupancies are 20 to 1,000 or more times higher than typical occupancies. Consequently, life safety benefits will be a small to tiny fraction of typical retrofit costs. Thus, for the level of seismic hazard in Portland, life safety seismic retrofits are not economically justified for typical buildings on rock sites. The life safety benefits of retrofitting buildings on rock sites will generally be less than 5% to less than 1% of typical retrofit costs.

This conclusion does not mean that buildings on rock sites pose no life safety risk or that no one will ever die in such buildings in a large earthquake. Rather, this conclusion means that the probability of these buildings being damaged badly enough to cause significant casualties is so low that the estimated future benefits of avoiding casualties are very small relative to typical retrofit costs.

It is also important to note that these conclusions, and all of the conclusions which follow, apply to "typical" buildings in a class. Buildings which by virtue of their materials, condition or specific design features are much more vulnerable than "typical" buildings in a class may well pose substantial life safety risks and thus may potentially accrue significant benefits from retrofit.

### Firm Soil Sites

For firm soil sites, the life safety benefits of building classes and uses fall into three groups:

1) S4 (steel frame with concrete shear walls) and C2 (concrete shear wall) buildings would require well above 100 occupants per 1,000 square feet in order for life safety benefits to equal typical retrofit costs. Thus, as for all of the building classes on rock sites, life safety benefits for these building classes will be a small to tiny fraction of typical retrofit costs.

2) most of the combinations of building class and uses would require 10 to 40 occupants per 1,000 square feet in order for life safety benefits to equal typical retrofit costs. For most typical occupancy levels, the life safety benefits will range from a few percent of typical retrofit costs to perhaps 50% of retrofit costs, depending on building classification and occupancy. For example, if a building has 3 occupants per 1,000 square feet and the breakeven occupancy (life safety benefits equal to typical retrofit costs) is 30, then the life safety benefits for this case will be 10% of typical retrofit costs.

3) URM (unreinforced masonry) and PC2 (precast concrete frame) buildings have breakeven occupancy levels from 2 to 8 occupants per 1,000 square feet. For URMs, life safety benefits will exceed typical retrofit costs if specific occupancies are above 2 to 3 per 1,000 square feet. Many common occupancies fall into this range (or come close to this level of occupancy), including office and retail space, restaurants, movie theaters and others. For PC2 buildings, life safety benefits will not equal typical retrofit costs unless occupancies are very high, about 5 to 8 occupants per 1,000 square feet. However, life safety benefits may be a significant fraction of typical retrofit costs, depending on the specific occupancy. Having life safety benefits a significant fraction of total retrofit costs is important when the non-life safety economic benefits (see Chapter 8) are also considered: the combination of life safety and other economic benefits may equal or exceed typical retrofit costs.

### Soft Soil Sites

For soft soil sites, the life safety benefits of building classes and uses fall into four groups:

1) S4 (steel frame with concrete shear walls) and C2 (concrete shear wall) buildings would require nearly 30 to more than 40 occupants per 1,000 square feet in order for life safety benefits to equal typical retrofit costs. These occupancies are a factor of about 10 or more above typical occupancies and thus life safety benefits are likely to approximately 10% or less of typical retrofit costs. Thus, life safety benefits for these two building classes appear to be much lower than typical retrofit costs even which such buildings are located on soft soil sites.

2) Several combinations of building classes and uses would require occupancies in the range of 5 to 10 per 1,000 square feet in order for life safety benefits to equal typical retrofit costs. This buildings include all uses of C1 (concrete frame) buildngs, non-industrial RM1 and RM2 (reinforced masonry) buildings and institutional PC1 (tilt-up) buildings. For most such buildings. life safety retrofits will be a significant fraction of typical retrofit costs, but will not equal typical retrofit costs unless the specific building occupancies are unusually high.

3) Quite a few combinations of building classes and uses would require approximately 2 to 4 occupants per 1,000 square feet in order for life safety benefits to equal typical retrofit costs. These buildings include all PC2 (precast concrete frame), C3 (concrete frame with URM infill) and S5 (steel frame with URM infill) buildings, average and industrial PC1 (tilt-up) buildings and industrial RM1 and RM2 (reinforced masonry) buildings. In many such cases, life safety benefits will equal or exceed typical retrofit costs or be a substantial fraction of typical retrofit costs, depending on the specific building occupancies.

4) URM (unreinforced masonry) buildings require only about 1 occupant per 1,000 square feet in order for life safety benefits to equal typical retrofit costs. This occupancy level is equal to or lower than most occupancies and thus URM buildings of nearly any use which are located on soft soils will generally have life safety benefits which equal or exceed typical retrofit costs.

## 7.4 Life Safety Benefits Expressed In Dollar Terms

Another useful way to examine life safety benefits relative to typical retrofit costs is to compare the dollar value of life safety benefits per occupant per 1,000 square feet with the typical retrofit costs per 1,000 square feet. Table 7.3a shows typical retrofit costs per 1,000 square feet, for institutional, average (commercial) and industrial buildings. Table 7.3b shows the life safety benefits in dollar terms per occupant per 1,000 square feet. The conversion of avoided deaths to dollar benefits assumes a value of $2,200,000 per statistical life.

For combinations of building class and site characteristics where life safety benefits per occupant per 1,000 square feet are very small (i.e., $1,000 or less) compared to typical retrofit costs, life safety benefits will be much less than typical retrofit costs.

For combinations of building class and site characteristics where life safety benefits per occupant per 1,000 square feet are a significant fraction of typical retrofit costs (i.e., several thousand dollars), life safety benefits are likely to be a significant fraction of typical retrofit costs, but life safety benefits in this range will not exceed the typical costs unless occupancies are unusually high. This result arises because typical costs are tens of thousands of dollars per 1,000 square feet and such cases would require approximately 10 people per 1,000 square feet in order for life safety benefits to equal total retrofit costs.

For combinations of building class and site characteristics where life safety benefits per occupant are high ($10,000 or more), then typical occupancies of 1 to 5 people per 1,000 square feet will result in life safety benefits which exceed typical retrofit costs or are at least a significant fraction of typical retrofit costs, depending on the specific occupancies of the buildings under consideration.

## Table 7.3a
## Typical Retrofit Costs per 1,000 square feet

| Building Use | URM | PC2 | C3 | S5 | RM2 | C1 | PC1 | RM1 | S4 | C2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Institutional | $37,090 | $43,730 | $43,960 | $48,010 | $43,730 | $43,960 | $17,430 | $17,430 | $43,730 | $43,730 |
| Average | $34,490 | $41,130 | $41,360 | $45,410 | $41,130 | $41,360 | $14,830 | $14,830 | $41,130 | $41,130 |
| Industrial | $23,090 | $29,730 | $29,960 | $34,010 | $29,730 | $29,960 | $10,930 | $10,930 | $29,730 | $29,730 |

## Table 7.3b
## Life Safety Benefits for One Occupant per 1,000 square feet

| Site Type | URM | PC2 | C3 | S5 | RM2 | C1 | PC1 | RM1 | S4 | C2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Rock | $252 | $242 | $53 | $49 | $36 | $13 | $21 | $11 | $6 | $12 |
| Firm Soil | $11,086 | $5,595 | $3,059 | $3,062 | $2,031 | $998 | $1,133 | $527 | $200 | $223 |
| Soft Soil | $27,641 | $15,483 | $11,335 | $10,919 | $7,433 | $4,084 | $3,378 | $2,246 | $1,099 | $1,031 |

These two tables show the relationship between life safety benefits per occupant and typical retrofit costs. When life safety benefits in dollar terms are a substantial fraction of typical retrofit costs, then occupancy levels of a few occupants per 1,000 square feet will suffice to have life safety benefits exceed typical costs.

For example, an industrial precast concrete frame building (PC2) on soft soil has life safety benefits of $15,483 for one occupant per 1,000 square feet and typical retrofit costs of $29,730 per 1,000 square feet. The life safety benefits will exceed retrofit costs if occupancy for this building is 2 or more per 1,000 square feet.

The general patterns and trends between life safety benefits and typical retrofit costs are evident in the table.

On rock sites, life safety benefits per occupant are very small compared to typical retrofit costs for all building classes.

On firm soil sites, life safety benefits are generally small compared to typical retrofit costs, but the more vulnerable building classes have fairly high life safety benefits. For the more vulnerable building classes, towards the left hand side of the tables, life safety benefits may exceed typical costs or be a significant fraction of typical costs, depending on the specific occupancies of buildings under consideration.

On soft soil sites, life safety benefits are quite large. For typical occupancies, several of the more vulnerable building classes may have life safety benefits which exceed typical retrofit costs. Some of the moderately vulnerable building classes may have life safety benefits which may exceed typical costs if occupancies are unusually high or be a significant fraction of typical retrofit costs, with more typical occupancies.

## 7.5 Life Safety Benefits: Conclusions

### Ordinary Buildings

The life safety benefits of the life safety retrofits of ordinary (institutional, commercial, industrial) buildings are clearly outlined in Tables 7.2 and 7.3. **Whether or not life safety benefits exceed typical retrofit costs depends strongly on building class, on soil type and on occupancy levels.**

For rock sites, life safety benefits will be a small fraction of retrofit costs for typical buildings in all 10 building classes.

For firm soil sites, life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for unreinforced masonry (URM) buildings for typical occupancies of 1 to 5 per 1,000 square feet. Life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for precast concrete frame (PC2), precast concrete tilt-ups (PC1), concrete frame with URM infill (C3) and steel frame with URM infill (S5) buildings only for high occupancies of 5 to 10 per 1,000 square feet.

For soft soil sites, life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for unreinforced masonry (URM), precast concrete frame (PC2), precast concrete tilt-ups (PC1), concrete frame with URM infill (C3) and steel frame with URM infill (S5) buildings for typical occupancies of 1 to 5 per 1,000 square feet. Life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for reinforced masonry buildings (RM1 and RM2) and for concrete frame (C1) buildings only for high occupancies of 5 to 10 per 1,000 square feet.

### Special Buildings

Special buildings such as hospitals, schools and emergency response facilities (fire, police, emergency medical) are often of special concern with regard to earthquake life safety. In general, the life safety benefits of retrofits for such special buildings are exactly the same as for ordinary buildings. That is, the depend directly on building class, on soil type and on occupancy level per 1,000 square feet. Thus, all of the previous conclusions for ordinary buildings also generally apply to "special" buildings.

There are, however, two cases where special buildings may have different life safety benefits than ordinary buildings. The first case is school buildings. Society commonly values children highly and extra safety measures to protect children are often undertaken. This high value for children can be expressed economically as a higher statistical value of life for children than for the population at large. We suggest that a statistical value of life of about $4.4 million (twice the typical statistical value of life, $2.2 million) approximately reflects the higher value placed on children's lives. This differential is also supported on other economic grounds. For example, the expected lifetime earnings of a child would be much higher than for a middle-aged or elderly adult, which provides additional justification for higher economic values for children. Placing this higher statistical value on children has the effect of lowering, by a factor of two, the occupancy rate per 1,000 feet where life safety benefits equal typical retrofit costs. Thus, life safety benefits for retrofitting school buildings will more easily exceed typical costs for combinations of building class and soil type.

The second exception for life safety benefits of "special" buildings is cases where earthquake damage to a facility not only affects the life safety of occupants but also others in the community. For example, failure of a hospital may result in additional deaths in a community because medical care is delayed. Likewise, loss of police or fire services may have a life safety component not simply related to the buildings' occupants. In such cases, the other benefits of avoiding loss of essential services to the community must be evaluated individually on a case by case basis.

# 8.0 LIFE SAFETY RETROFITS: AVOIDED ECONOMIC DAMAGES AND LOSSES

## 8.1 Non-life safety Economic Benefits

Life safety retrofits are designed to enhance life safety and thus life safety benefits are generally a large fraction of the total benefits of such retrofits. However, life safety retrofits also have ancillary benefits which may, in some cases, be economically significant in decision-making about retrofits. In some cases, the non-life safety economic benefits of retrofit may exceed the economic value of life safety benefits. Such examples occur whenever the occupancy level is low and/or the extent of life safety risk is low, but the economic costs of seismic damage are high due to high building values, high contents values, or high costs associated with loss of building function.

An economically correct benefit-cost analysis of a seismic retrofit should count both life safety and non-life safety benefits. Life safety benefits were discussed in Chapter 7; this chapter discusses non-life safety benefits. In the benefit-cost methodology, non-life safety benefits are the reduction in expected damages and losses in six categories:

building damages
contents damages
displacement costs due to seismic damages
business income losses
rental income losses
loss of public/non-profit services.

Building damages are the cost to repair structural and non-structural seismic damage. Similarly, contents damages are the physical damages to contents. Displacement costs are incurred when temporary space must be rented because buildings must be vacated to repair seismic damage. Business income losses and rental income losses occur when loss of functionality occurs due to seismic damages. Finally, for government or other public/non-profit agencies, the community may lose the value of such services when loss of functionality occurs. This is the public-sector equivalent of loss of business income. The ways in which these non-life safety economic losses are estimated are given in Technical Appendix 5 and the references therein.

The distribution of non-life safety damages and losses (and thus of the benefits of avoiding such damages and losses) can vary markedly from building to building, depending on use and function. However, generally, building damages are the largest component. Contents damages are generally a fraction of building damages, but may exceed building damages when contents are unusually valuable, such as with a computer center, some high-tech manufacturing operations, a hospital or an art museum.

Displacement costs, rental income losses and business income losses (which are counted at net rather than gross), are generally quite a bit smaller than building damages. Likewise, the value of public/nonprofit services lost due to seismic damages is generally small relative to building damages, in part because such services are usually reestablished quickly, in temporary quarters if need be. In some cases, however, such as hospitals or emergency response facilities the cost to the community may be very high if such services are lost, even for a brief period of time. In such cases, avoiding or reducing the loss of such services may be an important component of the total benefits achieved via retrofit.

Given the very wide range of combinations of building uses and the corresponding wide range of economic values for buildings, contents and functions, there is an extremely large number of possible combinations of these non-life safety economic benefits of retrofit. One way of evaluating and comparing these benefits is to use the concept of "unit values" which are the benefits per square feet of building area based on round-number values.

For example, the benefits of avoiding building damages may be presented at a basis of a building value of $100.00 per square foot. Then, the benefits of avoiding building damages for other values per square foot (e.g., $75.00/sf or $150.00/sf) can be determined by simple ratio.

For the purposes of evaluating the non-life safety benefits of life safety-driven seismic retrofits we consider the following "unit values":

| | |
|---|---|
| building value: | $100.00 per square foot |
| contents value | $10.00 per square foot |
| displacement costs: | $1.00 per square foot per month |
| rental income losses: | $1.00 per square foot per month |
| net business income losses: | $1.00 per square foot per month |
| value of public/nonprofit services | $100 per square foot per year. |

Table 8.1, parts a and b, contains unit benefits (per unit values) for the above six categories on non-life safety economic factors. In Table 8.1a, the typical retrofit costs per 1,000 square feet shown for the 10 building classes and the three site characteristics (rock, firm soil, soft soil). In Table 8.1b, for comparison, unit benefits are calculated per 1,000 square feet of building.

In the same manner as illustrated above for building values, the benefits corresponding to avoided damages and losses for any specific building can be computed from the ratios of the specific building's values to the unit values above. Thus, if a specific building has contents valued at $50.00 per square foot, then the benefits of avoiding contents damages will be 5 times the unit benefits shown in Table 8.1, for every combination of building class and soil type. Round-number unit values were chosen for all categories, so that such ratios can be easily computed, if desired.

The interpretation of this unit benefits table is very similar to the interpretation of the life safety benefits presented earlier.

> When the unit benefits for an individual non-life safety economic category, or in total for all such categories, are very small compared to typical retrofit costs, then for virtually any building in that group, the non-life safety benefits will be very small compared to typical retrofit costs.

## Table 8.1a
## Typical Retrofit Cost per 1,000 square feet

| Building Use | URM | PC2 | C3 | S5 | RM2 | C1 | PC1 | RM1 | S4 | C2 |
|---|---|---|---|---|---|---|---|---|---|---|
| Institutional | $37,090 | $43,730 | $43,960 | $48,010 | $43,730 | $43,960 | $17,430 | $17,430 | $43,730 | $43,730 |
| Average | $34,490 | $41,130 | $42,360 | $45,410 | $41,130 | $41,360 | $14,830 | $14,830 | $41,130 | $41,130 |
| Industrial | $23,090 | $29,730 | $29,960 | $34,010 | $29,730 | $29,960 | $10,930 | $10,930 | $29,730 | $29,730 |

## Table 8.1b
## Unit Benefits Corresponding to Unit Values per 1,000 square feet

| | | URM | PC2 | C3 | S5 | RM2 | CI | PC1 | RM1 | S4 | C2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| ROCK | building | $1,381 | $1,424 | $607 | $640 | $526 | $249 | $611 | $238 | $133 | $370 |
| | contents | $137 | $142 | $61 | $64 | $53 | $25 | $61 | $24 | $13 | $37 |
| | displacement | $103 | $147 | $37 | $41 | $27 | $5 | $9 | $1 | $1 | $6 |
| | business inc. | $45 | $47 | $20 | $21 | $18 | $8 | $20 | $8 | $4 | $12 |
| | rent | $103 | $147 | $37 | $41 | $27 | $5 | $9 | $1 | $1 | $6 |
| | public/nonprofit | $373 | $387 | $166 | $175 | $144 | $68 | $167 | $65 | $37 | $101 |
| | TOTAL | $2,142 | $2,294 | $928 | $982 | $795 | $361 | $878 | $337 | $189 | $532 |
| | | | | | | | | | | | |
| FIRM | building | $7,636 | $3,044 | $1,757 | $1,806 | $1,126 | $1,067 | $1,454 | $840 | $618 | $948 |
| SOIL | contents | $372 | $298 | $168 | $173 | $112 | $106 | $145 | $84 | $62 | $95 |
| | displacement | $539 | $403 | $210 | $213 | $114 | $124 | $145 | $86 | $67 | $105 |
| | business inc. | $98 | $85 | $52 | $54 | $37 | $35 | $48 | $28 | $21 | $32 |
| | rent | $539 | $403 | $210 | $213 | $114 | $124 | $145 | $86 | $67 | $105 |
| | public/nonprofit | $807 | $699 | $429 | $440 | $307 | $290 | $397 | $230 | $169 | $260 |
| | TOTAL | $9,990 | $4,931 | $2,826 | $2,898 | $1,810 | $1,747 | $2,335 | $1,354 | $1,004 | $1,544 |
| | | | | | | | | | | | |
| SOFT | building | $12,693 | $11,323 | $7,927 | $8,019 | $3,714 | $3,764 | $4,652 | $2,782 | $2,090 | $3,100 |
| SOIL | contents | $1,128 | $920 | $558 | $565 | $366 | $370 | $458 | $270 | $209 | $310 |
| | displacement | $1,624 | $1,648 | $818 | $829 | $470 | $483 | $438 | $270 | $212 | $317 |
| | business inc. | $310 | $268 | $173 | $176 | $117 | $119 | $151 | $90 | $70 | $103 |
| | rent | $1,624 | $1,648 | $818 | $829 | $470 | $483 | $438 | $270 | $212 | $317 |
| | public/nonprofit | $2,544 | $2,199 | $1,425 | $1,447 | $960 | $979 | $1,238 | $736 | $571 | $847 |
| | TOTAL | $19,924 | $18,004 | $11,720 | $11,864 | $6,097 | $6,198 | $7,374 | $4,418 | $3,364 | $4,994 |

> When unit benefits are a significant fraction of typical retrofit costs, then the non-life safety benefits for buildings in that group will be a significant fraction of typical retrofit costs, with the actual fraction depending on the specific values of building, contents and the other economic factors.
>
> When unit benefits are relatively large compared to typical retrofit costs, then the non-life safety benefits may equal or exceed typical retrofit costs.

As stated earlier, specific buildings may have an almost infinite combination of values with respect to non-life safety economic benefits. However, because building damages generally constitute the lion's share of total non-economic benefits, the values in other categories would have to be extraordinarily large before they substantially affected total non-life safety benefits. For example, if specific buildings had contents values, displacement costs, rental income losses, or net business income losses which were 2 or 3 or 4 times the "unit" values assumed in calculating the unit benefits table, these changes would only affect the total non-life safety benefits by relatively small fractions.

Both non-life safety benefits and life safety benefits are dependent on building class seismic vulnerability because this is what drives casualties and all of the non-life safety damages and losses. Therefore, the patterns in the non-life safety benefits are very similar to those observed earlier for life safety benefits. These patterns are briefly described below.

> For rock sites, the individual "unit" benefits per 1,000 square feet and the total non-life safety unit benefits are all very small compared to typical retrofit costs. The total "unit" benefits are all less than 10% of typical retrofit costs and most are much less than 5% of typical retrofit costs. These "unit" costs may not be representative of specific buildings, but these figures indicate that for most buildings on rock sites the non-life safety benefits are likely to total only a small percentage of typical retrofit costs.
>
> For firm soil sites, the individual "unit" benefits and the total non-life safety unit benefits are several times larger than for rock sites, but still quite small compared to typical retrofit costs. Thus, we conclude that for buildings on firm soil sites, non-life safety benefits may total a significant fraction of typical retrofit costs, but are unlikely to approach or exceed typical retrofit costs. As with the life safety benefits, the non-life safety benefits are much higher for the more vulnerable building classes towards the left hand side of the tables. For these building classes, again depending on the combinations of values for specific buildings, non-life safety benefits may be a large fraction of typical retrofit costs.
>
> For soft soil sites, the individual "unit" benefits and the total non-life safety unit benefits are several times larger than for firm soil sites. Thus, especially for the more vulnerable building classes towards the left hand side of the tables, non-life safety benefits may be a large fraction of typical retrofit costs, or in some cases exceed typical retrofit costs.

## 8.2 Total Benefits of Seismic Retrofits

The total benefits of seismic retrofits are the sum of the life safety benefits and the non-life safety economic benefits. As seen above, the patterns of these two groups of benefits are very similar. The conclusions drawn in Chapter 7, based only on life safety benefits are amplified by the inclusion of the non-life safety economic benefits of retrofit. Thus, when total benefits are considered, retrofit benefits will exceed retrofit costs for a broader range of combinations of building classes, soil types and occupancy levels.

For rock sites, life safety benefits will be a small fraction of retrofit costs for typical buildings in all 10 building classes. Similarly, for typical uses, the non-life safety benefits will be a small fraction of retrofit costs for typical buildings in all 10 building classes. Thus, there will be few, if any, typical buildings on rock sites for which total benefits exceed typical retrofit costs.

For firm soil sites, life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for unreinforced masonry (URM) buildings for typical occupancies of 1 to 5 per 1,000 square feet. Life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for precast concrete frame (PC2), precast concrete tilt-ups (PC1), concrete frame with URM infill (C3) and steel frame with URM infill (S5) buildings only for high occupancies (5 to 10 per 1,000 square feet). When non-life safety benefits are added to life safety benefits, total benefits will exceed costs for some PC2, PC1, C3 and S5 buildings as well as for URM buildings.

For soft soil sites, life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for unreinforced masonry (URM), precast concrete frame (PC2), precast concrete tilt-ups (PC1), concrete frame with URM infill (C3) and steel frame with URM infill (S5) buildings for typical occupancies of 1 to 5 per 1,000 square feet. Life safety benefits will exceed retrofit costs or be a significant fraction of retrofit costs for reinforced masonry buildings (RM1 and RM2) and for concrete frame (C1) buildings only for high occupancies (5 to 10 per 1,000 square feet). When non-life safety benefits are added to life safety benefits, total benefits will exceed costs for some RM1, RM2 and C1 buildings, as well as for URM, PC2, PC1, C3 and S5 buildings.

For special buildings, such as hospitals, schools and emergency response facilities (fire, police, emergency medical), which are often of special concern with regard to earthquake life safety, more buildings may have benefits exceeding costs. In general, the life safety benefits of retrofits for such special buildings are exactly the same as for ordinary buildings. There are, however, two cases where special buildings may have different life safety benefits than ordinary buildings. The first case is school buildings. Placing a higher statistical value of life on children has the effect of lowering, by a factor of two, the occupancy rate per 1,000 feet where life safety benefits equal typical retrofit costs. Thus, life safety benefits for retrofitting school buildings will more easily exceed typical costs for combinations of building class and soil type. The second exception for life safety benefits of "special" buildings is cases, such as hospital, fire and police services, where earthquake damage to a facility not only affects the life safety of occupants but also others in the community.

For special buildings, the higher life safety benefits and the non-life safety benefits will combine to result in more combinations of building class and site type for which total benefits exceed costs.

Finally, in interpreting these results, it is very important to remember that all of these results are for "typical" buildings. Individual buildings which are substantially more vulnerable than typical buildings may have much higher benefits than typical buildings. Thus, even on rock sites, some buildings which are particularly vulnerable or have particularly high occupancies could have benefits exceeding costs.

## 9.0 CAVEATS

1) Seismic life safety is not and cannot be absolute. All buildings, even those designed to or beyond the seismic design levels of the current building code, may fail if ground motions substantially exceed the design basis or due to design errors or insufficient quality of construction. In earthquakes with ground motions at or below the design basis, casualties will generally be reduced, but not completely eliminated, in current code buildings or in well-designed and well-constructed retrofitted buildings.

2) Conclusions about the seismic vulnerability and extent of life safety risk of buildings are expected to be generally applicable, on average, to "typical" buildings of a defined class (structural system). The seismic performance of any individual building may differ substantially from the "typical" performance of the class depending on the design, construction and condition details of each individual building. Our analysis considered ONLY typical buildings within defined classes of buildings and did not consider individual buildings. Depending on the details of a building's design, construction and condition and on site characteristics, any individual building, even those in classes generally deemed not to constitute a significant life safety risk, may constitute a substantial life safety risk.

3) Throughout this report, we consider the effects of ground shaking on buildings and the resulting damages and casualties. We do NOT consider liquefaction, landslides, or other ground movements because such effects are highly site-specific and thus require evaluation of site and building characteristics for each individual building

4) Estimates of the extent of seismic hazard in Portland, the seismic vulnerability of building classes, the relationship between building seismic damage and casualty rates, the effectiveness of retrofits in avoiding damages and casualties, and the costs and benefits of retrofits are subject to substantial uncertainty. Interpretation of results and conclusions must consider this uncertainty.