# TECHNICAL APPENDIX 2

# BUILDING SEISMIC RISK

Seismic "risk" is defined as the potential for seismic damages and casualties from the built environment. In this appendix, we consider seismic risk for the existing building inventory in Portland in two steps. First, we consider the vulnerability of existing buildings to seismic damages. Second, we consider the potential for casualties arising from seismic damage to existing buildings.

## 2.1 Building Classification

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 building classification used by the National Institute of Building Sciences (NIBS). The NIBS classification has 16 major classes of buildings; with subclasses based on building height, there are 36 classes in all. Definitions for these 16 main building classes are given in Table 2.1 on the following page. A more detailed description of the structural systems of these building classes is given in Technical Appendix 3.

**In evaluating the seismic vulnerability of buildings in Portland, we have not made assessments of any individual buildings. Rather, all of our estimates apply to typical buildings in each building class.**

## 2.2 Seismic Vulnerability of Existing Buildings: Approaches

### 2.2.1 Damage Function Format

One of the essential elements of this project is to estimate the vulnerability of existing buildings in Portland to earthquake damage. Furthermore, casualty estimates are based on building damage estimates and thus estimating building vulnerability is central to the quantification of the extent of life safety hazard posed by existing buildings.

Building seismic vulnerability is generally expressed in either a "damage function" format or a "fragility curve" format. In the damage function format, estimates of damage percentages or distributions of damage states are given for discrete steps of earthquake intensity (e.g.,

**Table 2.1**
**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

Modified Mercalli Intensity, MMI) or of some quantitative measure of ground motion such as peak ground acceleration (PGA) or peak velocity or displacement or spectral motion parameters. There are two major peer-reviewed compilations of damage function data for buildings: ATC-13[1] and ATC-36[2], both of which express damage percentages vs. MMI.

ATC-13 is based on expert opinion using California data. Because of the high frequency of earthquakes in California, a higher fraction of the existing building inventory in California has been constructed with some (albeit variable) degree of seismic resistance than elsewhere in the United States. Therefore, for any given building type, the average or typical percentage damage for a given MMI is expected to be lower in California than elsewhere (including Portland).

ATC-36 is based on expert opinion using Utah data. Because of the lower frequency of earthquakes in Utah, seismic provisions of the building code were introduced later in Utah than in California and the seismic design levels are lower than in California. Therefore, for any given building type, the average or typical percentage of damage for a given MMI is expected to be higher in ATC-36 than in ATC-13. ATC-13 damage functions were tabulated for "typical" buildings. Recognizing the wide variation in buildings' seismic capacity, ATC-36 contains three separate compilations of damage function estimates for: "Typical," "Poor," and "Seismically-Designed" buildings.

In general, the relationships between ATC-13 and ATC-36 damage estimates follow the expected pattern. For any given building type, the percentages of damage at a given MMI generally increase in the order: ATC-36 "Seismic Design," ATC-13 "Typical California," ATC-36 "Typical Utah," and ATC-36 "Poor". However, empirical data, engineering knowledge and judgement have evolved over the ten years between these two projects. Therefore, there are some differences and inconsistencies between these two damage function compilations.

For Portland, given the very limited historical seismicity and the history of the building code's seismic provisions, the damage percentages would be expected to be closer to ATC-36 "Typical Utah" than to ATC-13 "Typical California". Generally, the Portland damage functions would be expected to be between ATC-36 "Typical Utah" and ATC-36 "Poor," but closer to ATC-36 "Typical Utah".

### 2.2.2 Fragility Curve Format

The second major format for estimating the vulnerability of existing buildings to seismic damage is the fragility curve format. Fragility curves use log-normal distributions to estimate the fraction of a building class expected to be in a given damage state for a given level of ground motion (e.g., PGA or peak ground acceleration). For example, in the NIBS report[3] five damage states are defined: none, slight, moderate, extensive and complete. Detailed descriptions of these damage states for each building type are given in Technical Appendix 3. The percentages of damages for each damage state are shown in Table 2.2.

In the fragility curve format, median values define the PGA where 50% of the building class is expected to have the given damage state or a higher damage state. For each damage

**Table 2.2**
**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.

*state*, lower median values indicate greater vulnerability -- at any given PGA a higher fraction of buildings will be in the damage state than for building types with higher median fragilities. Betas (log-normal standard deviations) determine the shape of the damage fraction vs. ground motion curve and thus also affect the fraction in the damage state for PGAs above or below than the median value.

The following example illustrates the principles of the damage state estimates shown in Table 2.2. 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 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.

The NIBS report[3] contains fragility curve data for all 36 building subclasses discussed previously. NIBS tabulates fragility curve data primarily with reference to spectral displacement (rather than PGA) but also presents data in PGA format. The NIBS fragility curve data are compiled for 3 ranges of National Earthquake Hazards Reduction Program (NEHRP) seismic areas: Area 7 (high seismicity), Areas 5-6 (moderate seismicity) and Areas 1-4 (low seismicity). Approximately, these NEHRP seismic areas correspond to Uniform Building Code (UBC) seismic zones as follows: UBC Zone 4 = NEHRP Area 7, UBC Zone 3 = NEHRP Areas 5-6 and UBC Zones 1-2 = NEHRP Areas 1-4.

For the existing building inventory in Portland, it is appropriate to consider NEHRP Areas 1-4 (UBC Zones 1-2) because the designation to UBC Zone 3 only occurred in 1993 and thus the vast majority of existing buildings were constructed to lower seismic design levels of Zone 2 or lower.

## 2.3 Seismic Vulnerability of Existing Buildings: Portland

### 2.3.1 Relative Life Safety Risk

All building types present some degree of life safety hazard in the "complete" damage state. However, wood frame, 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 do 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 (see descriptions in Technical Appendix 3). 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 2.3. 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 Volume One, Chapter 6, Table 6.1, page 22. These 10 building classes are those for which we have developed Portland-specific building fragility curves.

### 2.3.2 Fragility Curves for Portland's Existing Building Inventory

The fragility curve format is conceptually more rigorous than the damage function format because fragility curves are based on engineering analyses of the capacity of the structural elements of buildings (cf. NIBS report[3], Chapter 5). Because of this rigorous base and because the NIBS fragility curve data are ten years more recent than the ATC-13 data, our preliminary intent was to use the NIBS fragility curve data as the basis for estimating the seismic vulnerability of the existing building inventory in Portland.

However, a more detailed review of the NIBS data, which is available in draft form only, revealed several inconsistencies and inaccuracies. For example, for the "complete" damage state for NEHRP Areas 1-4 (applicable to Portland), unreinforced masonry buildings are less vulnerable to seismic damage than are reinforced masonry (RM2) buildings. Therefore, we conclude that, at least for NEHRP map areas 1-4, the draft NIBS fragility curve data are unusable at this time.

In lieu of using the draft NIBS fragility curve data, we have formulated seismic vulnerability estimates appropriate for Portland's existing building inventory using the fragility curve format. These Portland fragility curve estimates, Figures 2.1 through 2.10, have been made for the 10 building classes deemed to pose potentially significant life safety hazards, for the height range (low-, mid-, high-rise) containing the bulk of the Portland inventory for each building class. Thus, we have generated fragility curve estimates for 8 classes of low-rise buildings and 2-classes of mid-rise buildings. We note that most of the high-rise buildings in Portland are in building classes not deemed to pose potentially significant life safety hazards.

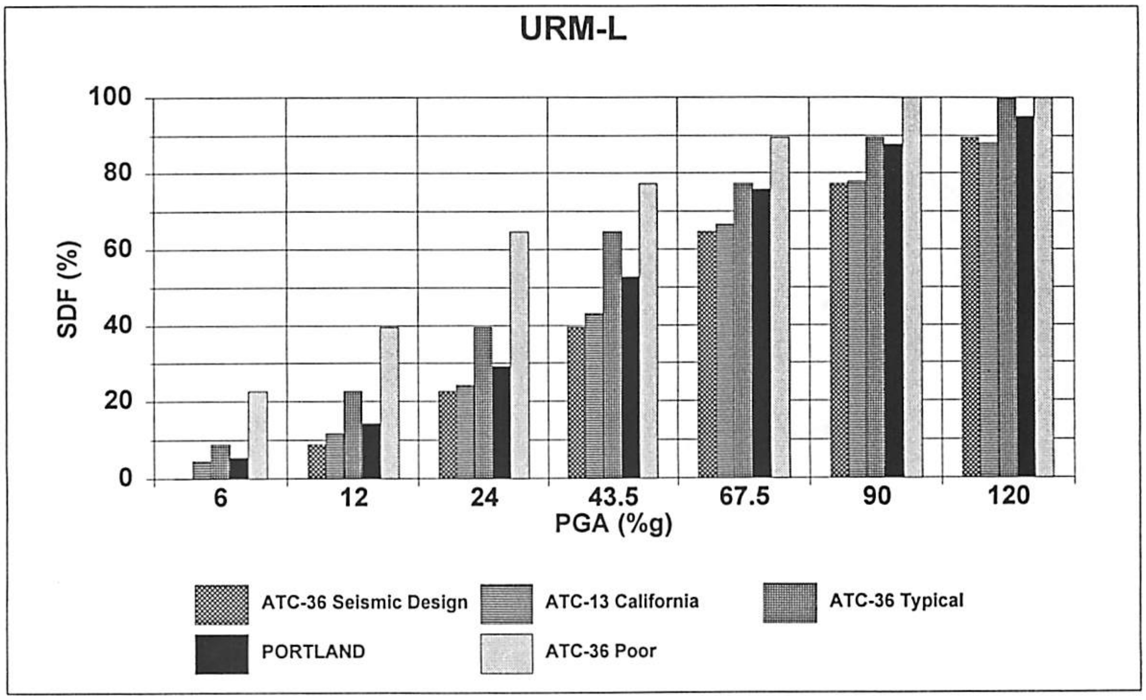
The Portland fragility curves shown in Figures 2.1 through 2.10 are empirical, based on our judgement and experience. The median PGA values and betas for the four damage states (slight, moderate, extensive and complete) were adjusted to be reasonably concordant with engineering judgement and the principles in the NIBS report. However, the principal calibration of these fragility curves was via comparison to the ATC-13 and ATC-36 damage

**Table 2.3**
**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, Volume One.

**Figure 2.1**
**Fragility Curve Data: URM-L Buildings**




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 4.65 | 8.96 | 5.42 | 22.63 |
| 7 | 12 | 8.96 | 11.68 | 22.63 | 14.18 | 39.53 |
| 8 | 24 | 22.63 | 24.21 | 39.53 | 29.09 | 64.78 |
| 9 | 43.5 | 39.53 | 43.12 | 64.78 | 52.77 | 77.17 |
| 10 | 67.5 | 64.78 | 66.65 | 77.17 | 75.70 | 89.41 |
| 11 | 90 | 77.17 | 77.75 | 89.41 | 87.75 | 100.00 |
| 12 | 120 | 89.41 | 87.97 | 100.00 | 95.06 | 100.00 |

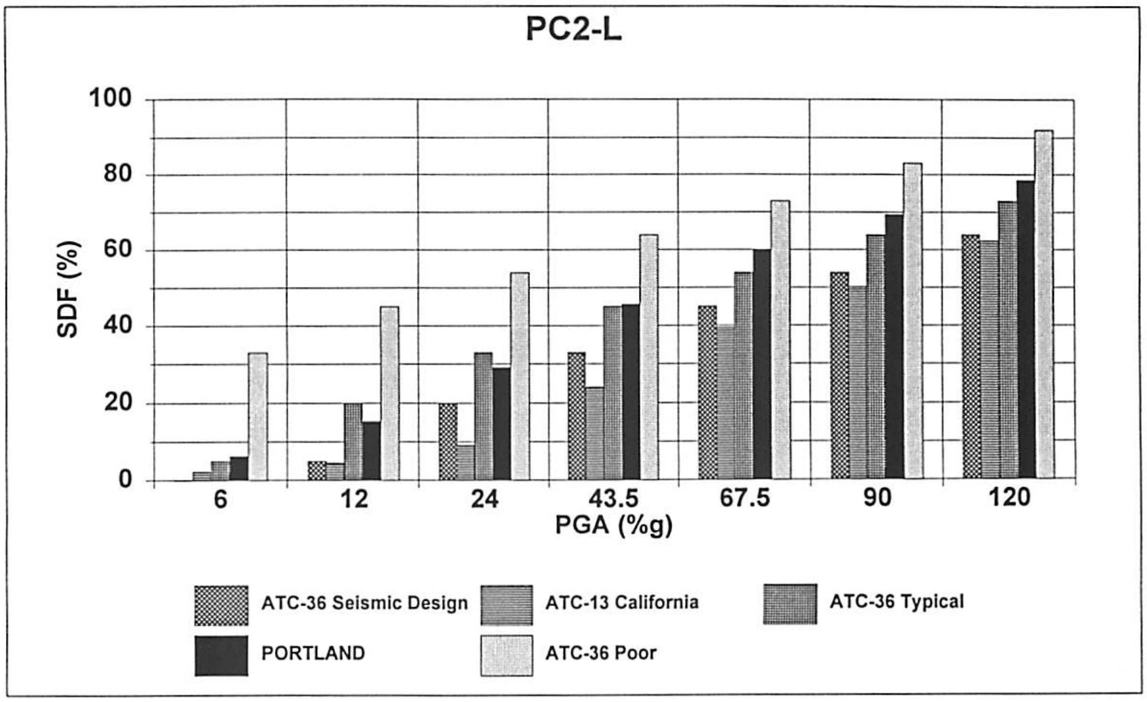
NOTE: ATC-36 Typical appears too high at the low PGA levels

| | Median PGAs | Betas |
|---|---|---|
| **Slight** | 0.080 | 1.000 |
| **Moderate** | 0.110 | 0.750 |
| **Extensive** | 0.330 | 0.750 |
| **Complete** | 0.580 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.097 | 0.080 | 0.057 |
| 0.150 | 0.110 | 0.075 |
| 0.565 | 0.330 | 0.228 |
| 1.227 | 0.580 | 0.411 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 3.28 | 5.42 | 9.47 |
| 7 | 12 | 9.25 | 14.18 | 21.08 |
| 8 | 24 | 18.94 | 29.09 | 41.65 |
| 9 | 43.5 | 30.37 | 52.77 | 71.25 |
| 10 | 67.5 | 43.17 | 75.70 | 89.73 |
| 11 | 90 | 55.21 | 87.75 | 96.06 |
| 12 | 120 | 69.34 | 95.06 | 98.79 |

## Figure 2.2
## Fragility Curve Data: PC2-L Buildings




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 2.28 | 5.00 | 6.26 | 33.00 |
| 7 | 12 | 5.00 | 4.49 | 20.00 | 15.24 | 45.00 |
| 8 | 24 | 20.00 | 9.08 | 33.00 | 29.13 | 54.00 |
| 9 | 43.5 | 33.00 | 24.11 | 45.00 | 45.49 | 64.00 |
| 10 | 67.5 | 45.00 | 39.29 | 54.00 | 59.80 | 73.00 |
| 11 | 90 | 54.00 | 50.20 | 64.00 | 69.46 | 83.00 |
| 12 | 120 | 64.00 | 62.35 | 73.00 | 78.51 | 92.00 |

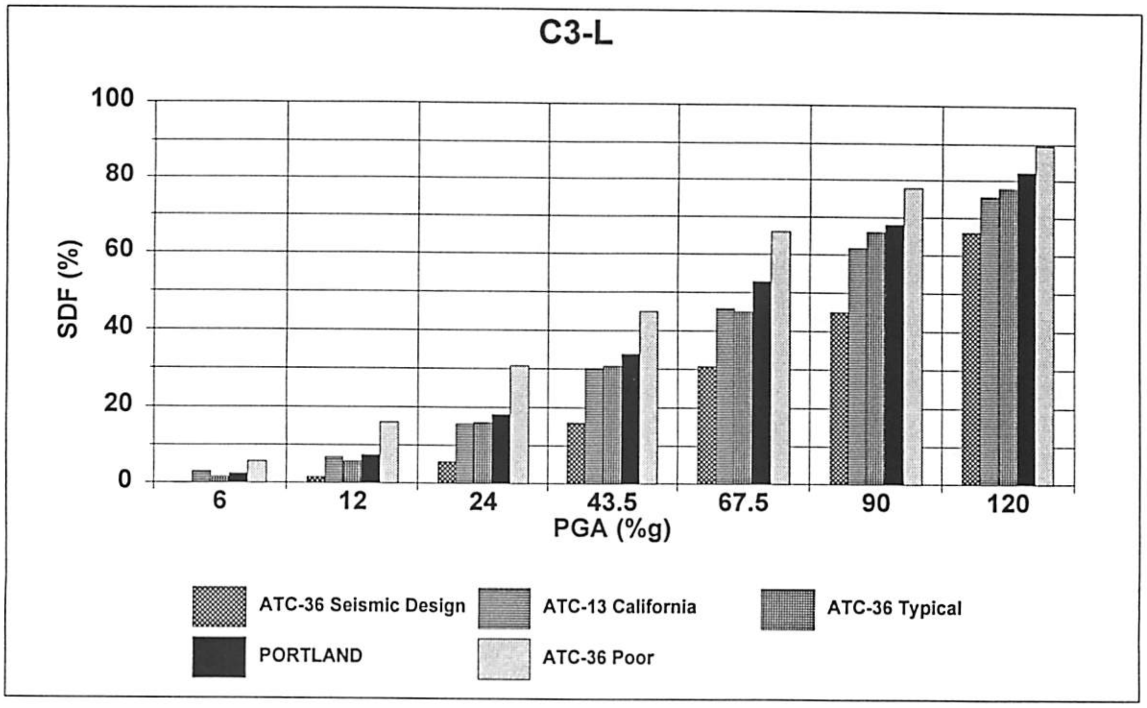
NOTE: ATC-36 much higher than ATC-13

| | Median PGAs | Betas |
|---|---|---|
| Slight | 0.070 | 1.000 |
| Moderate | 0.100 | 0.750 |
| Extensive | 0.330 | 0.750 |
| Complete | 1.000 | 0.750 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.070 | 0.070 | 0.047 |
| 0.115 | 0.100 | 0.065 |
| 0.554 | 0.330 | 0.224 |
| 2.125 | 1.000 | 0.703 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 5.11 | 6.26 | 11.02 |
| 7 | 12 | 11.96 | 15.24 | 22.54 |
| 8 | 24 | 21.05 | 29.13 | 39.07 |
| 9 | 43.5 | 31.32 | 45.49 | 57.30 |
| 10 | 67.5 | 41.09 | 59.80 | 71.78 |
| 11 | 90 | 48.48 | 69.46 | 80.49 |
| 12 | 120 | 56.59 | 78.51 | 87.72 |

## Figure 2.3
## Fragility Curve Data: C3-L Buildings




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 3.01 | 1.55 | 2.41 | 5.66 |
| 7 | 12 | 1.55 | 6.76 | 5.66 | 7.44 | 16.11 |
| 8 | 24 | 5.66 | 15.68 | 16.11 | 18.11 | 30.81 |
| 9 | 43.5 | 16.11 | 30.18 | 30.81 | 33.83 | 44.92 |
| 10 | 67.5 | 30.81 | 45.76 | 44.92 | 52.86 | 66.11 |
| 11 | 90 | 44.92 | 61.84 | 66.11 | 68.10 | 77.79 |
| 12 | 120 | 66.11 | 75.61 | 77.79 | 82.07 | 89.47 |

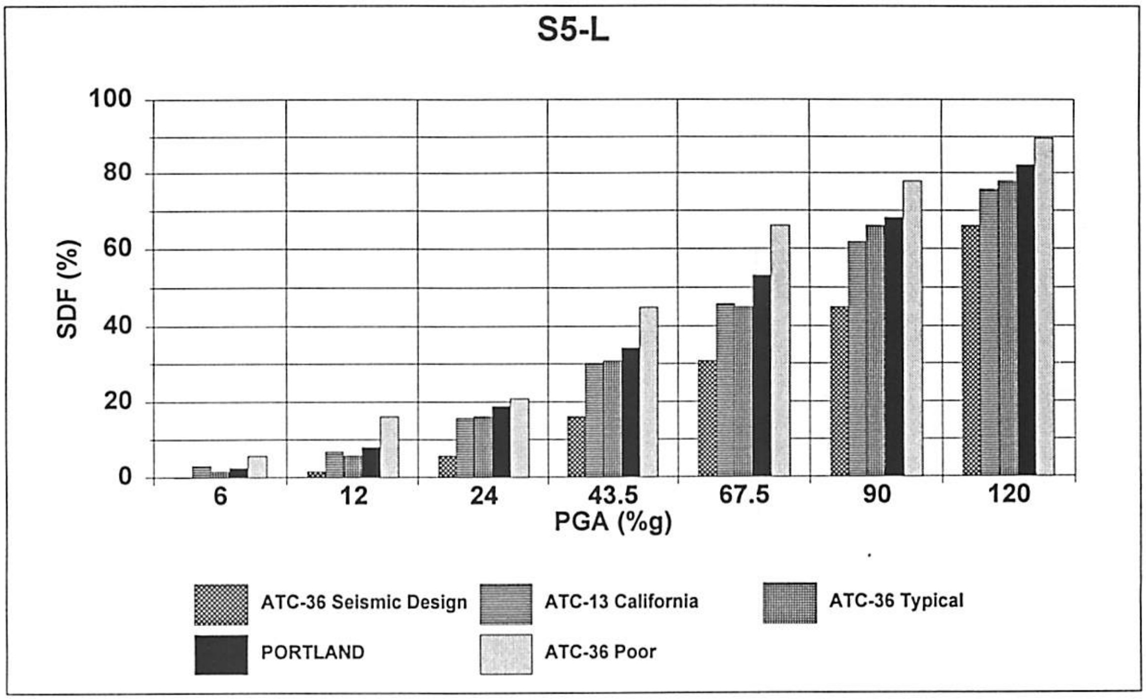
NOTE:

| | Median PGAs | Betas |
|---|---|---|
| Slight | 0.100 | 1.000 |
| Moderate | 0.200 | 0.750 |
| Extensive | 0.500 | 0.750 |
| Complete | 0.900 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.113 | 0.100 | 0.069 |
| 0.275 | 0.200 | 0.133 |
| 0.919 | 0.500 | 0.338 |
| 1.980 | 0.900 | 0.573 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 1.65 | 2.41 | 4.70 |
| 7 | 12 | 4.74 | 7.44 | 12.78 |
| 8 | 24 | 11.40 | 18.11 | 28.00 |
| 9 | 43.5 | 20.34 | 33.83 | 52.49 |
| 10 | 67.5 | 29.08 | 52.86 | 75.81 |
| 11 | 90 | 36.59 | 68.10 | 87.87 |
| 12 | 120 | 46.67 | 82.07 | 95.12 |

Figure 2.4
Fragility Curve Data: S5-L Buildings




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 3.01 | 1.55 | 2.50 | 5.66 |
| 7 | 12 | 1.55 | 6.76 | 5.66 | 7.95 | 16.11 |
| 8 | 24 | 5.66 | 15.68 | 16.11 | 18.77 | 20.81 |
| 9 | 43.5 | 16.11 | 30.18 | 30.81 | 34.22 | 44.92 |
| 10 | 67.5 | 30.81 | 45.76 | 44.92 | 53.03 | 66.11 |
| 11 | 90 | 44.92 | 61.84 | 66.11 | 68.18 | 77.79 |
| 12 | 120 | 66.11 | 75.61 | 77.79 | 82.11 | 89.47 |

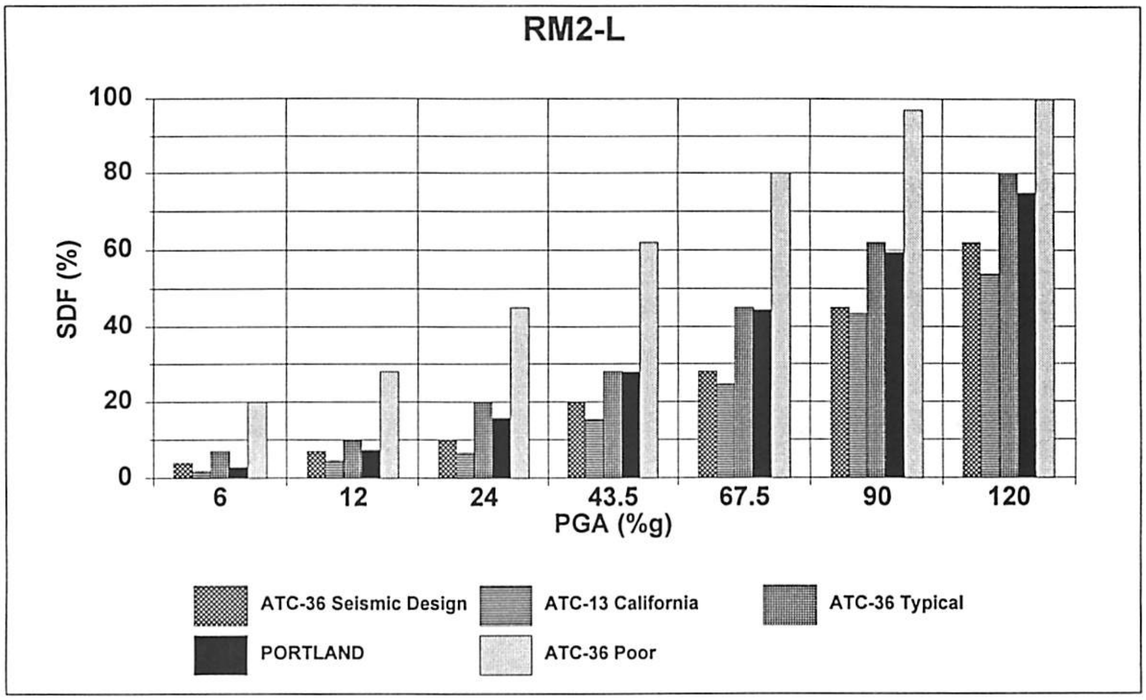
NOTE:

| | Median PGAs | Betas |
|---|---|---|
| Slight | 0.110 | 1.000 |
| Moderate | 0.180 | 0.750 |
| Extensive | 0.500 | 0.750 |
| Complete | 0.900 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.117 | 0.110 | 0.076 |
| 0.249 | 0.180 | 0.125 |
| 0.924 | 0.500 | 0.339 |
| 2.096 | 0.900 | 0.580 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 1.70 | 2.50 | 4.83 |
| 7 | 12 | 5.12 | 7.95 | 13.12 |
| 8 | 24 | 12.10 | 18.77 | 28.13 |
| 9 | 43.5 | 20.87 | 34.22 | 52.10 |
| 10 | 67.5 | 29.14 | 53.03 | 75.32 |
| 11 | 90 | 36.10 | 68.18 | 87.52 |
| 12 | 120 | 45.39 | 82.11 | 94.94 |

## Figure 2.5
## Fragility Curve Data: RM2-L Buildings




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 4.00 | 1.90 | 7.00 | 2.76 | 20.00 |
| 7 | 12 | 7.00 | 4.60 | 10.00 | 7.29 | 28.00 |
| 8 | 24 | 10.00 | 6.61 | 20.00 | 15.67 | 45.00 |
| 9 | 43.5 | 20.00 | 15.35 | 28.00 | 27.81 | 62.00 |
| 10 | 67.5 | 28.00 | 24.55 | 45.00 | 44.35 | 80.00 |
| 11 | 90 | 45.00 | 43.43 | 62.00 | 59.39 | 97.00 |
| 12 | 120 | 62.00 | 53.88 | 80.00 | 74.89 | 100.00 |

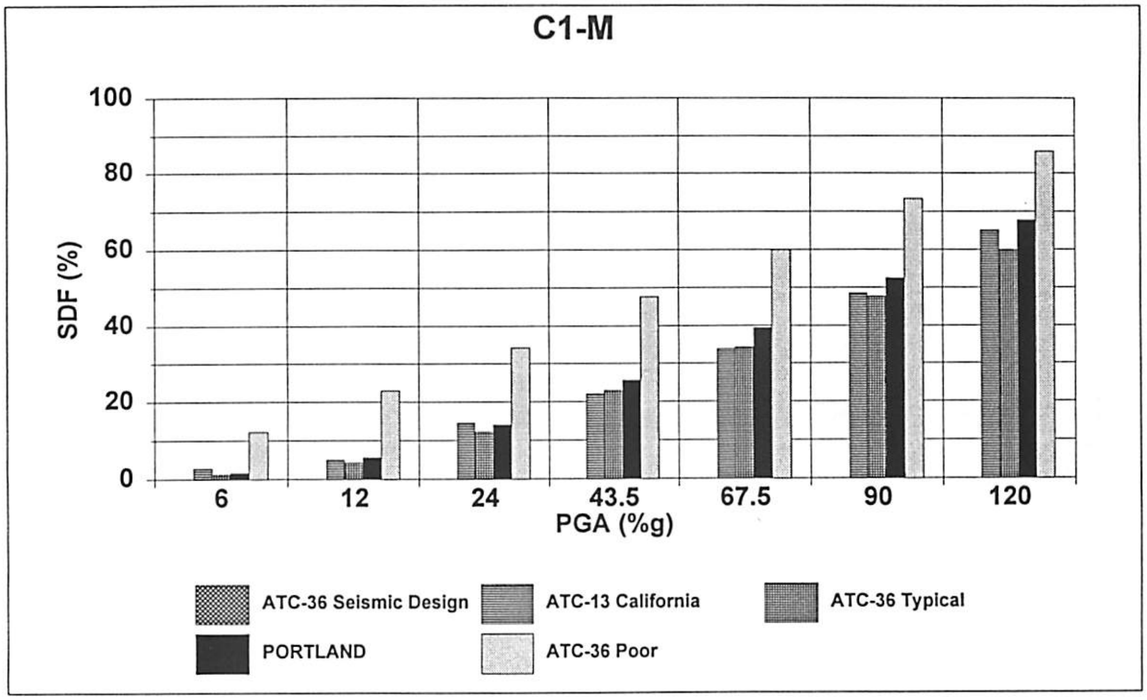
NOTE: ATC-13 is generic RM.
ATC-36 seems high at lower PGAs.

| | Median PGAs | Betas |
|---|---|---|
| Slight | 0.080 | 1.000 |
| Moderate | 0.200 | 0.750 |
| Extensive | 0.700 | 0.750 |
| Complete | 1.000 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.080 | 0.080 | 0.053 |
| 0.252 | 0.200 | 0.135 |
| 1.289 | 0.700 | 0.461 |
| 2.173 | 1.000 | 0.653 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 2.35 | 2.76 | 4.91 |
| 7 | 12 | 5.74 | 7.29 | 11.60 |
| 8 | 24 | 11.82 | 15.67 | 23.21 |
| 9 | 43.5 | 18.53 | 27.81 | 43.47 |
| 10 | 67.5 | 24.82 | 44.35 | 66.85 |
| 11 | 90 | 30.72 | 59.39 | 81.26 |
| 12 | 120 | 39.44 | 74.89 | 91.33 |

## Figure 2.6
## Fragility Curve Data: C1-M Buildings




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | N/A | 2.80 | 1.27 | 1.63 | 12.21 |
| 7 | 12 | N/A | 5.10 | 4.21 | 5.62 | 23.00 |
| 8 | 24 | N/A | 14.43 | 12.21 | 14.05 | 34.23 |
| 9 | 43.5 | N/A | 22.00 | 23.00 | 25.58 | 47.63 |
| 10 | 67.5 | N/A | 33.83 | 34.23 | 39.36 | 60.00 |
| 11 | 90 | N/A | 48.46 | 47.63 | 52.46 | 73.41 |
| 12 | 120 | N/A | 65.14 | 60.00 | 67.68 | 85.78 |

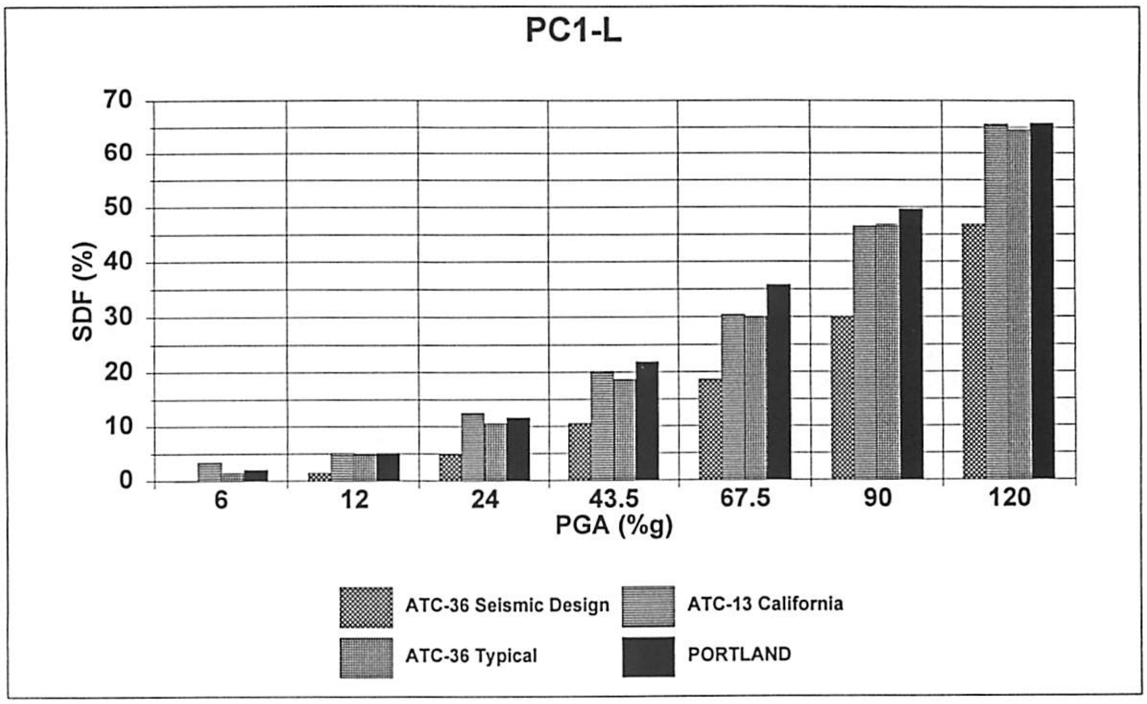
NOTE: No ATC-36 Seismic class.

| | Median PGAs | Betas |
|---|---|---|
| Slight | 0.140 | 1.000 |
| Moderate | 0.220 | 0.750 |
| Extensive | 0.700 | 0.750 |
| Complete | 1.200 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.233 | 0.140 | 0.093 |
| 0.399 | 0.220 | 0.144 |
| 1.532 | 0.700 | 0.462 |
| 3.129 | 1.200 | 0.786 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 0.52 | 1.63 | 3.56 |
| 7 | 12 | 2.10 | 5.62 | 10.12 |
| 8 | 24 | 6.50 | 14.05 | 21.58 |
| 9 | 43.5 | 13.26 | 25.58 | 38.59 |
| 10 | 67.5 | 19.83 | 39.36 | 59.43 |
| 11 | 90 | 24.96 | 52.46 | 74.59 |
| 12 | 120 | 31.23 | 67.68 | 86.98 |

**Figure 2.7**
**Fragility Curve Data: PC1-L Buildings**




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 3.40 | 1.45 | 2.02 | n/a |
| 7 | 12 | 1.45 | 5.11 | 4.81 | 5.11 | n/a |
| 8 | 24 | 4.81 | 12.55 | 10.54 | 11.68 | n/a |
| 9 | 43.5 | 10.54 | 20.10 | 18.65 | 21.82 | n/a |
| 10 | 67.5 | 18.65 | 30.44 | 30.05 | 35.77 | n/a |
| 11 | 90 | 30.05 | 46.44 | 46.81 | 49.65 | n/a |
| 12 | 120 | 46.81 | 65.55 | 64.50 | 65.76 | n/a |

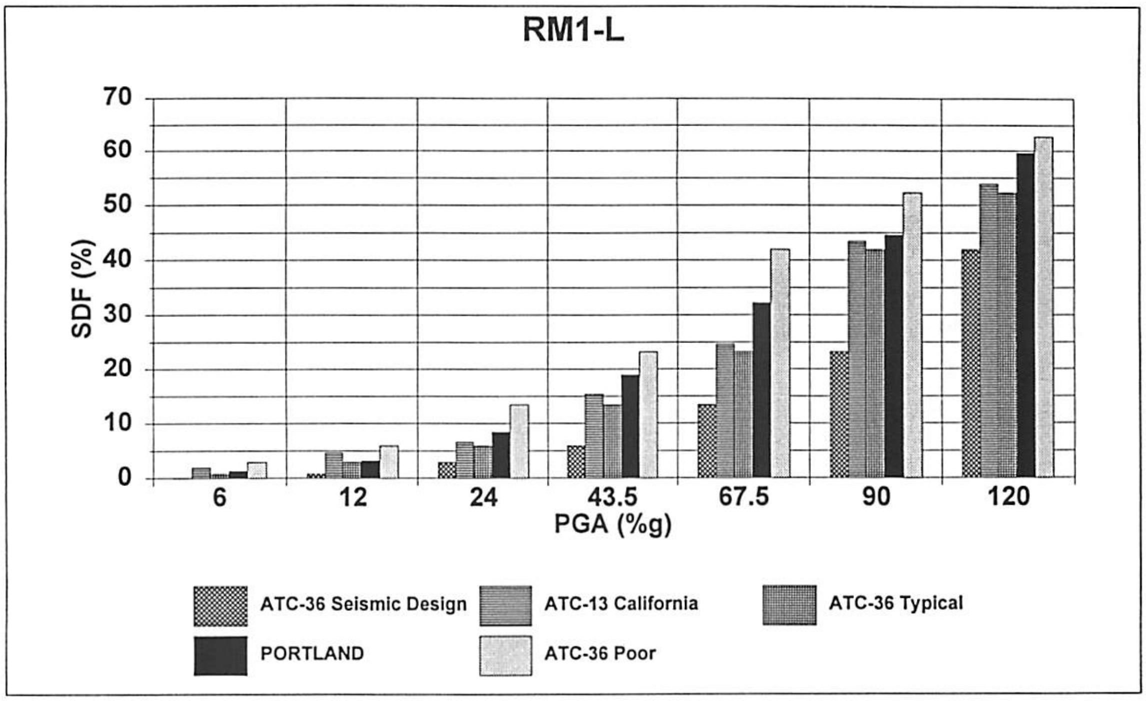
NOTE: No ATC-36 Poor class.

| | Median PGAs | Betas |
|---|---|---|
| **Slight** | 0.090 | 1.000 |
| **Moderate** | 0.280 | 0.750 |
| **Extensive** | 0.900 | 0.750 |
| **Complete** | 1.150 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.104 | 0.090 | 0.059 |
| 0.373 | 0.280 | 0.187 |
| 1.553 | 0.900 | 0.630 |
| 2.436 | 1.150 | 0.819 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 1.57 | 2.02 | 3.54 |
| 7 | 12 | 3.77 | 5.11 | 8.39 |
| 8 | 24 | 8.36 | 11.68 | 17.39 |
| 9 | 43.5 | 14.69 | 21.82 | 32.41 |
| 10 | 67.5 | 20.88 | 35.77 | 52.90 |
| 11 | 90 | 26.29 | 49.65 | 68.96 |
| 12 | 120 | 33.95 | 65.76 | 82.93 |

## Figure 2.8
## Fragility Curve Data: RM1-L Buildings




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 1.90 | 0.84 | 1.27 | 2.90 |
| 7 | 12 | 0.84 | 4.60 | 2.90 | 3.18 | 5.97 |
| 8 | 24 | 2.90 | 6.61 | 5.97 | 8.39 | 13.50 |
| 9 | 43.5 | 5.97 | 15.35 | 13.50 | 18.91 | 23.24 |
| 10 | 67.5 | 13.50 | 24.55 | 23.24 | 32.21 | 41.93 |
| 11 | 90 | 23.24 | 43.43 | 41.93 | 44.57 | 52.34 |
| 12 | 120 | 41.93 | 53.88 | 52.34 | 59.63 | 62.75 |

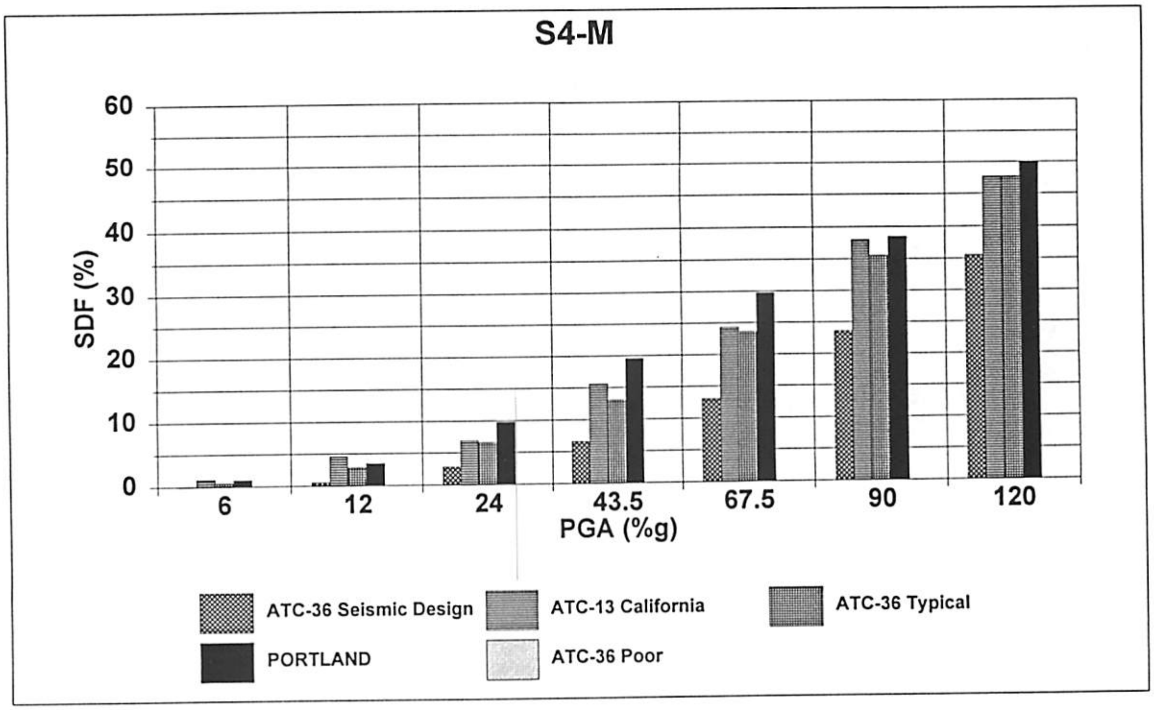
NOTES: ATC-13 higher than ATC-36 Typical
ATC-13 is generic RM

| | Median PGAs | Betas |
|---|---|---|
| **Slight** | 0.120 | 1.000 |
| **Moderate** | 0.500 | 0.750 |
| **Extensive** | 0.720 | 0.750 |
| **Complete** | 1.400 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.172 | 0.120 | 0.078 |
| 0.857 | 0.500 | 0.339 |
| 1.428 | 0.720 | 0.488 |
| 3.055 | 1.400 | 0.929 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 0.73 | 1.27 | 2.21 |
| 7 | 12 | 1.88 | 3.18 | 5.49 |
| 8 | 24 | 4.08 | 8.39 | 14.50 |
| 9 | 43.5 | 8.56 | 18.91 | 30.63 |
| 10 | 67.5 | 15.03 | 32.21 | 50.32 |
| 11 | 90 | 21.08 | 44.57 | 66.03 |
| 12 | 120 | 28.76 | 59.63 | 80.62 |

**Figure 2.9**
**Fragility Curve Data: S4-M Buildings**




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 1.11 | 0.54 | 1.00 | N/A |
| 7 | 12 | 0.54 | 4.57 | 2.81 | 3.40 | N/A |
| 8 | 24 | 2.81 | 6.88 | 6.55 | 9.70 | N/A |
| 9 | 43.5 | 6.55 | 15.53 | 13.02 | 19.55 | N/A |
| 10 | 67.5 | 13.02 | 24.29 | 23.61 | 29.70 | N/A |
| 11 | 90 | 23.61 | 37.99 | 35.54 | 38.48 | N/A |
| 12 | 120 | 35.54 | 47.61 | 47.63 | 50.00 | N/A |

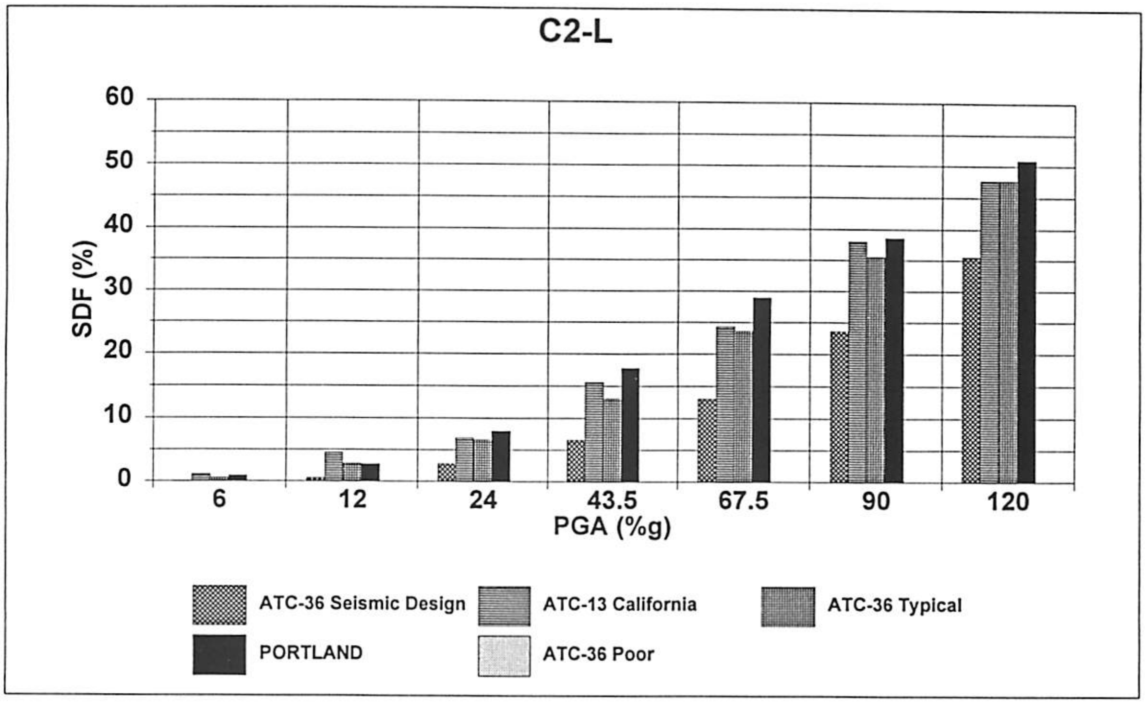
NOTE: No ATC-36 Poor class.

| | Median PGAs | Betas |
|---|---|---|
| Slight | 0.160 | 1.000 |
| Moderate | 0.330 | 0.750 |
| Extensive | 0.850 | 0.750 |
| Complete | 1.800 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.267 | 0.160 | 0.107 |
| 0.614 | 0.330 | 0.223 |
| 1.868 | 0.850 | 0.588 |
| 4.275 | 1.800 | 1.125 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 0.35 | 1.00 | 2.05 |
| 7 | 12 | 1.29 | 3.40 | 6.32 |
| 8 | 24 | 3.96 | 9.70 | 15.59 |
| 9 | 43.5 | 9.06 | 19.55 | 28.57 |
| 10 | 67.5 | 15.00 | 29.70 | 43.67 |
| 11 | 90 | 19.86 | 38.48 | 57.29 |
| 12 | 120 | 25.49 | 50.00 | 72.23 |

## Figure 2.10
## Fragility Curve Data: C2-L Buildings




## FIRM SOIL

| MMI | PGA | 36-Seismic | 13-Calif. | 36-Typ | PORTLAND | 36-Poor |
|---|---|---|---|---|---|---|
| 6 | 6 | 0.00 | 1.11 | 0.54 | 0.88 | N/A |
| 7 | 12 | 0.54 | 4.57 | 2.81 | 2.69 | N/A |
| 8 | 24 | 2.81 | 6.88 | 6.55 | 7.93 | N/A |
| 9 | 43.5 | 6.55 | 15.53 | 13.02 | 17.82 | N/A |
| 10 | 67.5 | 13.02 | 24.29 | 23.61 | 28.94 | N/A |
| 11 | 90 | 23.61 | 37.99 | 35.54 | 38.58 | N/A |
| 12 | 120 | 35.54 | 47.61 | 47.63 | 50.89 | N/A |

NOTE: No ATC-36 poor class.

| | Median PGAs | Betas |
|---|---|---|
| Slight | 0.160 | 1.000 |
| Moderate | 0.450 | 0.750 |
| Extensive | 0.800 | 0.750 |
| Complete | 1.750 | 0.500 |

| ROCK | FIRM | SOFT |
|---|---|---|
| 0.160 | 0.160 | 0.107 |
| 0.581 | 0.450 | 0.300 |
| 1.389 | 0.800 | 0.547 |
| 3.829 | 1.750 | 1.153 |

| MMI | PGA | ROCK | FIRM | SOFT |
|---|---|---|---|---|
| 6 | 6 | 0.84 | 0.88 | 1.70 |
| 7 | 12 | 2.22 | 2.69 | 5.04 |
| 8 | 24 | 5.36 | 7.93 | 13.82 |
| 9 | 43.5 | 11.27 | 17.82 | 27.62 |
| 10 | 67.5 | 18.36 | 28.94 | 43.15 |
| 11 | 90 | 24.12 | 38.58 | 56.74 |
| 12 | 120 | 30.57 | 50.89 | 71.64 |

functions. Generally, the Portland fragility curves for firm soil sites were adjusted so that mean damage percentages at various PGA levels were similar to or slightly higher than the ATC-36 *Typical* Utah values. Then, fragility curves for rock and soft soil sites were estimated based on differences in the response spectrum (Figure 1.5) and the differences in duration of shaking expected on rock, firm soil and soft soil sites.

The previous 10 figures illustrate these Portland building fragility curves. The data on these figures are interpreted as follows:

> For the purposes of comparison with ATC-13 and ATC-36 data, the mean damage percentages (expressed in percentages of building replacement value) for the Portland fragility curves have been calculated for each MMI/PGA range (for firm soil sites). The graph and the first table show the five data sets in the order of generally-expected-to-increase from ATC-36 seismic design, to ATC-13 typical California, to ATC-36 typical Utah, to Portland, to ATC-36 poor. However, as noted in section 2.3.2 there are some, relatively-minor inconsistencies in the ATC-13 and ATC-36 data sets.
>
> The second and third tables on each Portland fragility curve page show the median PGA values and betas for the four damage states. These values are expressed as fractions of g, the acceleration of gravity (i.e., 0.16 indicates 16% of g). These median PGA values express the PGA levels at which 50% of a population of buildings would be expected to be in the given damage state or higher. The second table has these values for the damage states on firm soil (for direct comparison to ATC-13 and ATC-36); the third table has the median PGA values for the damage states on rock and soft soil sites (for direct comparison between the three site types for Portland). The same betas were used for all three site type calculations.
>
> The fourth table expresses building damage estimates as percentages of building replacement value for rock, firm soil, and soft soil sites. These data illustrate the greater vulnerability of a given building class for those buildings located on firm soil and soft soil sites, relative to those located on rock sites.

We believe that these "Portland" fragility curves reasonably represent the relative seismic vulnerabilities between major building classes and across the three major site types. We believe that these fragility curves also approximately represent the absolute seismic vulnerabilities, albeit with a higher degree of uncertainty than for the relative vulnerabilities. For each building class, the fragility curves differ substantially for buildings on rock, firm, soil and soft soil sites (i.e., the numerical values of the median PGAs for a given damage state depend strongly on site type). These differences arise because we have presented the data normalized to PGA instead of to period-dependent spectral acceleration. If the fragility curves had been presented in spectral acceleration or in terms of drift, instead of PGA, the numerical median values for given damage states would vary much less than when presented in terms of PGA. However, regardless of what form the numerical fragility curves are presented in, buildings' seismic vulnerabilities do vary markedly depending on site conditions (rock, firm soil, soft soil), because soil sites may (relative to rock sites): amplify ground motions, experience greater duration of ground motion and have ground motion at frequencies (periods) more damaging to buildings. Thus, buildings' vulnerability to seismic damage must be evaluated separately for rock, firm soil and soft soil sites in Portland.

## 2.4 Casualty Rate Estimates

Because of the City's paramount interest in the life safety aspect of seismic performance, casualty estimates for the 10 building classes which constitute potentially significant life safety hazards are central to our analysis of retrofit alternatives. Data on the relationships between building damages and casualties are sparse for buildings in the United States because of the small numbers of earthquake deaths that have occurred in recent decades in the United States. Therefore, the best casualty estimates currently available are based primarily on expert opinion of knowledgeable earthquake engineering practitioners. There are two major sources of such estimates: ATC-13[1] and the NIBS report[3].

ATC-13 casualty estimates assume that (within the present uncertainty) casualty rates for all building types (other than wood frame and light steel) are the same and depend only on the damage state of the building. ATC-13 casualty estimates for the four damage states considered in the fragility curve formulation adopted in this report are shown in Table 2.4. For reference, the complete ATC-13 casualty estimates (interpolated in increments of 1% damage) are given in Table 2.5. These estimates assume that deaths arise predominantly from full or partial collapse. At lower damage states, only a few deaths are expected - primarily as a result of falling hazards. Thus, in the ATC-13 estimates, the death rate is only 10 per 1,000 at 80% damage but 200 per 1,000 at 100% damage. In detail, the ATC-13 casualty estimates reflect the judgement that casualties other than minor injuries arise predominantly from full or partial collapse of buildings. Thus, the estimated death rate of 200 per 1,000 occupants at 100% damage does not indicate that all buildings with 100% economic loss will have this casualty rate. Rather the expected rate will be higher for those buildings with substantial degrees of collapse and lower for those buildings without collapse. The increasing death rates with mean damage percentages above 50% reflects predominantly a gradual increase in the fraction of buildings which suffer full or partial collapse.

The draft NIBS report[3] contains casualty estimates for the 36 building classes covered for the four damage states (slight, moderate, extensive and complete). In addition, at the complete damage state, estimates are provided for 100% damage with and without entrapment of occupants, along with estimated entrapment percentages at 100% damage. These estimates cover three types of injuries (light, requiring hospitalization and life-threatening) and deaths (see Table 2.6). For reference, these draft NIBS casualty rate estimates are given in Tables 2.7 through 2.12.

At first review, the draft NIBS casualty estimates, which have more detailed breakdowns than the estimates of ATC-13, appear superior. However, closer examination reveals inconsistencies and apparent departures from consensus opinion. For example, the injury rates at slight, moderate and extensive damage states appear exceptionally low: at extensive damage (50%) the light injury rates for most building classes are 10 per 1000 occupants or less. These rates are seven or more times lower than ATC-13 and do not appear consistent with observed injury rates. The death rates for extensive damage (50%) and complete damage (100%) without entrapment are identical even though higher casualties would be expected at 100% damage due to falling objects etc.

**Table 2.4**
**ATC-13 Casualty Estimates: Rates Per 1,000 Occupants**

| Damage State | Percent Damage | Minor Injuries | Major Injuries | Deaths |
|---|---|---|---|---|
| slight | 5 | 0.30 | 0.04 | 0.01 |
| moderate | 20 | 3.00 | 0.40 | 0.10 |
| extensive | 50 | 68.57 | 9.14 | 2.29 |
| complete | 100 | 400 | 400 | 200 |

## Table 2.5
## Interpolated ATC-13 Death and Injury Rates

| % DAMAGE | MINOR INJUR RATE | MAJOR INJUR RATE | DEATH RATE |
|---|---|---|---|
| 0 | 0.00 | 0.00 | 0.00 |
| 1 | 0.03 | 0.00 | 0.00 |
| 2 | 0.10 | 0.01 | 0.00 |
| 3 | 0.17 | 0.02 | 0.01 |
| 4 | 0.23 | 0.03 | 0.01 |
| 5 | 0.30 | 0.04 | 0.01 |
| 6 | 0.48 | 0.06 | 0.02 |
| 7 | 0.66 | 0.09 | 0.02 |
| 8 | 0.84 | 0.11 | 0.03 |
| 9 | 1.02 | 0.14 | 0.03 |
| 10 | 1.20 | 0.16 | 0.04 |
| 11 | 1.38 | 0.18 | 0.05 |
| 12 | 1.56 | 0.21 | 0.05 |
| 13 | 1.74 | 0.23 | 0.06 |
| 14 | 1.92 | 0.26 | 0.06 |
| 15 | 2.10 | 0.28 | 0.07 |
| 16 | 2.28 | 0.30 | 0.08 |
| 17 | 2.46 | 0.33 | 0.08 |
| 18 | 2.64 | 0.35 | 0.09 |
| 19 | 2.82 | 0.38 | 0.09 |
| 20 | 3.00 | 0.40 | 0.10 |
| 21 | 4.08 | 0.54 | 0.14 |
| 22 | 5.16 | 0.69 | 0.17 |
| 23 | 6.24 | 0.83 | 0.21 |
| 24 | 7.32 | 0.98 | 0.24 |
| 25 | 8.40 | 1.12 | 0.28 |
| 26 | 9.48 | 1.26 | 0.32 |
| 27 | 10.56 | 1.41 | 0.35 |
| 28 | 11.64 | 1.55 | 0.39 |
| 29 | 12.72 | 1.70 | 0.42 |
| 30 | 13.80 | 1.84 | 0.46 |
| 31 | 14.88 | 1.98 | 0.50 |
| 32 | 15.96 | 2.13 | 0.53 |
| 33 | 17.04 | 2.27 | 0.57 |
| 34 | 18.12 | 2.42 | 0.60 |
| 35 | 19.20 | 2.56 | 0.64 |
| 36 | 20.28 | 2.70 | 0.68 |
| 37 | 21.36 | 2.85 | 0.71 |
| 38 | 22.44 | 2.99 | 0.75 |
| 39 | 23.52 | 3.14 | 0.78 |
| 40 | 24.60 | 3.28 | 0.82 |
| 41 | 25.68 | 3.42 | 0.86 |
| 42 | 26.76 | 3.57 | 0.89 |
| 43 | 27.84 | 3.71 | 0.93 |
| 44 | 28.92 | 3.86 | 0.96 |
| 45 | 30.00 | 4.00 | 1.00 |
| 46 | 37.71 | 5.03 | 1.26 |
| 47 | 45.43 | 6.06 | 1.51 |
| 48 | 53.14 | 7.09 | 1.77 |
| 49 | 60.86 | 8.11 | 2.03 |
| 50 | 68.57 | 9.14 | 2.29 |

**Table 2.5 Continued**
**Interpolated ATC-13 Death and Injury Rates**

| | | | |
|---|---|---|---|
| 51 | 76.29 | 10.17 | 2.54 |
| 52 | 84.00 | 11.20 | 2.80 |
| 53 | 91.71 | 12.23 | 3.06 |
| 54 | 99.43 | 13.26 | 3.31 |
| 55 | 107.14 | 14.29 | 3.57 |
| 56 | 114.86 | 15.31 | 3.83 |
| 57 | 122.57 | 16.34 | 4.09 |
| 58 | 130.29 | 17.37 | 4.34 |
| 59 | 138.00 | 18.40 | 4.60 |
| 60 | 145.71 | 19.43 | 4.86 |
| 61 | 153.43 | 20.46 | 5.11 |
| 62 | 161.14 | 21.49 | 5.37 |
| 63 | 168.86 | 22.51 | 5.63 |
| 64 | 176.57 | 23.54 | 5.89 |
| 65 | 184.29 | 24.57 | 6.14 |
| 66 | 192.00 | 25.60 | 6.40 |
| 67 | 199.71 | 26.63 | 6.66 |
| 68 | 207.43 | 27.66 | 6.91 |
| 69 | 215.14 | 28.69 | 7.17 |
| 70 | 222.86 | 29.71 | 7.43 |
| 71 | 230.57 | 30.74 | 7.69 |
| 72 | 238.29 | 31.77 | 7.94 |
| 73 | 246.00 | 32.80 | 8.20 |
| 74 | 253.71 | 33.83 | 8.46 |
| 75 | 261.43 | 34.86 | 8.71 |
| 76 | 269.14 | 35.89 | 8.97 |
| 77 | 276.86 | 36.91 | 9.23 |
| 78 | 284.57 | 37.94 | 9.49 |
| 79 | 292.29 | 38.97 | 9.74 |
| 80 | 300.00 | 40.00 | 10.00 |
| 81 | 305.00 | 58.00 | 19.50 |
| 82 | 310.00 | 76.00 | 29.00 |
| 83 | 315.00 | 94.00 | 38.50 |
| 84 | 320.00 | 112.00 | 48.00 |
| 85 | 325.00 | 130.00 | 57.50 |
| 86 | 330.00 | 148.00 | 67.00 |
| 87 | 335.00 | 166.00 | 76.50 |
| 88 | 340.00 | 184.00 | 86.00 |
| 89 | 345.00 | 202.00 | 95.50 |
| 90 | 350.00 | 220.00 | 105.00 |
| 91 | 355.00 | 238.00 | 114.50 |
| 92 | 360.00 | 256.00 | 124.00 |
| 93 | 365.00 | 274.00 | 133.50 |
| 94 | 370.00 | 292.00 | 143.00 |
| 95 | 375.00 | 310.00 | 152.50 |
| 96 | 380.00 | 328.00 | 162.00 |
| 97 | 385.00 | 346.00 | 171.50 |
| 98 | 390.00 | 364.00 | 181.00 |
| 99 | 395.00 | 382.00 | 190.50 |
| 100 | 400.00 | 400.00 | 200.00 |

**Table 2.6**
**NIBS Injury Classification Scale**

| Injury Severity Level | Injury Description |
|---|---|
| Level 1 | Injuries requiring basic medical aid without requiring hospitalization |
| Level 2 | Injuries requiring a greater degree of medical care and hospitalization, but not expected to progress to a life threatening status |
| Level 3 | Injuries which pose an immediate life threatening condition if not treated adequately land expeditiously. The majority of these injuries are the result of structural collapse and subsequent entrapment or impairment of the occupants |
| Level 4 | Instantaneously killed or mortally injured |

## Table 2.7
## NIBS Casualty Rates by Model Building Type for Slight Structural Damage

| # | Building Type | Casualty Level | | | |
|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 | Level 4 |
| 1 | W1 | 3/1,000,000 | 1/2,500,000 | 1/20,000,000 | 0 |
| 2 | W2 | 3/1,000,000 | 1/2,500,000 | 1/20,000,000 | 0 |
| 3 | S1L | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 4 | S1M | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 5 | S1H | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 6 | S2L | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 7 | S2M | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 8 | S2H | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 9 | S3 | 3/1,000,000 | 1/2,500,000 | 1/20,000,000 | 0 |
| 10 | S4L | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 11 | S4M | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 12 | S4H | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 13 | S5L | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 14 | S5M | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 15 | S5H | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 16 | C1L | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 17 | C1M | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 18 | C1H | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 19 | C2L | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 20 | C2M | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 21 | C2H | 3/100,000 | 1/250,000 | 1/3,000,000 | 0 |
| 22 | C3L | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 23 | C3M | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 24 | C3H | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 25 | PC1 | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 26 | PC2L | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 27 | PC2M | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 28 | PC2H | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 29 | RM1L | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 30 | RM1M | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 31 | RM2L | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 32 | RM2M | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 33 | RM2H | 3/10,000 | 1/25,000 | 1/300,000 | 0 |
| 34 | URML | 3/5,000 | 1/10,000 | 1/150,000 | 0 |
| 35 | URMM | 3/5,000 | 1/10,000 | 1/150,000 | 0 |
| 36 | MH | 3/10,000 | 1/20,000 | 1/300,000 | 0 |
| B1 | Major Bridge | n/a | n/a | n/a | n/a |
| B2 | Continuous Bridge | n/a | n/a | n/a | n/a |
| B3 | S.S. Bridge | n/a | n/a | n/a | n/a |

**Table 2.8**
**NIBS Casualty Rates by Model Building Type for Moderate Structural Damage**

| # | Building Type | Casualty Level | | | |
|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 | Level 4 |
| 1 | W1 | 3/50,000 | 1/100,000 | 1/1,000,000 | 1/1,000,000 |
| 2 | W2 | 3/50,000 | 1/100,000 | 1/1,000,000 | 1/1,000,000 |
| 3 | S1L | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 4 | S1M | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 5 | S1H | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 6 | S2L | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 7 | S2M | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 8 | S2H | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 9 | S3 | 3/50,000 | 1/100,000 | 1/1,000,000 | 1/1,000,000 |
| 10 | S4L | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 11 | S4M | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 12 | S4H | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 13 | S5L | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 14 | S5M | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 15 | S5H | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 16 | C1L | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 17 | C1M | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 18 | C1H | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 19 | C2L | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 20 | C2M | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 21 | C2H | 3/5,000 | 1/10,000 | 1/500,000 | 1/500,000 |
| 22 | C3L | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 23 | C3M | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 24 | C3H | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 25 | PC1 | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 26 | PC2L | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 27 | PC2M | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 28 | PC2H | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 29 | RM1L | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 30 | RM1M | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 31 | RM2L | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 32 | RM2M | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 33 | RM2H | 1/1,000 | 1/5,000 | 1/50,000 | 1/50,000 |
| 34 | URML | 3/1,000 | 1/2,500 | 1/20,000 | 1/20,000 |
| 35 | URMM | 3/1,000 | 1/2,500 | 1/20,000 | 1/20,000 |
| 36 | MH | 1/1,000 | 1/10,000 | 1/100,000 | 1/150,000 |
| B1 | Major Bridge | n/a | n/a | n/a | n/a |
| B2 | Continuous Bridge | n/a | n/a | n/a | n/a |
| B3 | S.S. Bridge | n/a | n/a | n/a | n/a |

## Table 2.9
## NIBS Casualty Rates by Model Building Type for Extensive Structural Damage

| # | Building Type | Casualty Level | | | |
|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 | Level 4 |
| 1 | W1 | 3/5,000 | 1/15,000 | 1/100,000 | 1/100,000 |
| 2 | W2 | 3/5,000 | 1/15,000 | 1/100,000 | 1/100,000 |
| 3 | S1L | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 4 | S1M | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 5 | S1H | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 6 | S2L | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 7 | S2M | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 8 | S2H | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 9 | S3 | 3/5,000 | 1/15,000 | 1/100,000 | 1/100,000 |
| 10 | S4L | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 11 | S4M | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 12 | S4H | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 13 | S5L | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 14 | S5M | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 15 | S5H | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 16 | C1L | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 17 | C1M | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 18 | C1H | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 19 | C2L | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 20 | C2M | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 21 | C2H | 3/500 | 1/1,500 | 1/50,000 | 1/50,000 |
| 22 | C3L | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 23 | C3M | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 24 | C3H | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 25 | PC1 | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 26 | PC2L | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 27 | PC2M | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 28 | PC2H | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 29 | RM1L | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 30 | RM1M | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 31 | RM2L | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 32 | RM2M | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 33 | RM2H | 1/100 | 1/500 | 1/5,000 | 1/5,000 |
| 34 | URML | 3/100 | 1/250 | 1/2,000 | 1/2,000 |
| 35 | URMM | 3/100 | 1/250 | 1/2,000 | 1/2,000 |
| 36 | MH | 1/100 | 1/1,000 | 1/50,000 | 1/50,000 |
| B1 | Major Bridge | n/a | n/a | n/a | n/a |
| B2 | Continuous Bridge | n/a | n/a | n/a | n/a |
| B3 | S.S. Bridge | n/a | n/a | n/a | n/a |

**Table 2.10**
**NIBS Casualty Rates by Model Building Type for Complete Structural Damage**
**(No Entrapment)**

| # | Building Type | Casualty Level | | | |
|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 | Level 4 |
| 1 | W1 | 3/500 | 1/1,200 | 1/100,000 | 1/100,000 |
| 2 | W2 | 3/500 | 1/1,200 | 1/100,000 | 1/100,000 |
| 3 | S1L | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 4 | S1M | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 5 | S1H | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 6 | S2L | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 7 | S2M | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 8 | S2H | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 9 | S3 | 3/500 | 1/1,200 | 1/100,000 | 1/100,000 |
| 10 | S4L | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 11 | S4M | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 12 | S4H | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 13 | S5L | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 14 | S5M | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 15 | S5H | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 16 | C1L | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 17 | C1M | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 18 | C1H | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 19 | C2L | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 20 | C2M | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 21 | C2H | 3/50 | 1/120 | 1/50,000 | 1/50,000 |
| 22 | C3L | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 23 | C3M | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 24 | C3H | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 25 | PC1 | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 26 | PC2L | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 27 | PC2M | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 28 | PC2H | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 29 | RM1L | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 30 | RM1M | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 31 | RM2L | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 32 | RM2M | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 33 | RM2H | 1/10 | 1/50 | 1/5,000 | 1/5,000 |
| 34 | URML | 3/10 | 1/25 | 1/2,000 | 1/2,000 |
| 35 | URMM | 3/10 | 1/25 | 1/2,000 | 1/2,000 |
| 36 | MH | 3/10 | 1/100 | 1/50,000 | 1/50,000 |
| B1 | Major Bridge | 17/100 | 20/100 | 37/100 | 7/100 |
| B2 | Continuous Bridge | 17/100 | 20/100 | 37/100 | 7/100 |
| B3 | S.S. Bridge | 5/100 | 25/100 | 20/100 | 5/100 |

## Table 2.11
## NIBS Casualty Rates by Model Building Type for Complete Structural Damage (Entrapment)

| # | Building Type | Casualty Level | | | |
|---|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 | Level 4 |
| 1 | W1* | n/a | n/a | n/a | n/a |
| 2 | W2* | n/a | n/a | n/a | n/a |
| 3 | S1L | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 4 | S1M | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 5 | S1H | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 6 | S2L | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 7 | S2M | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 8 | S2H | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 9 | S3* | n/a | n/a | n/a | n/a |
| 10 | S4L | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 11 | S4M | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 12 | S4H | 0.7/100 | 1/100 | 1/100 | 0.7/100 |
| 13 | S5L | 0.7/10 | 1/10 | 1/10 | 0.7/10 |
| 14 | S5M | 0.7/10 | 1/10 | 1/10 | 0.7/10 |
| 15 | S5H | 0.7/10 | 1/10 | 1/10 | 0.7/10 |
| 16 | C1L | 1/10 | 4/10 | 1/10 | 4/10 |
| 17 | C1M | 1/10 | 4/10 | 1/10 | 4/10 |
| 18 | C1H | 1/10 | 4/10 | 1/10 | 4/10 |
| 19 | C2L | 1/10 | 4/10 | 1/10 | 4/10 |
| 20 | C2M | 1/10 | 4/10 | 1/10 | 4/10 |
| 21 | C2H | 1/10 | 4/10 | 1/10 | 4/10 |
| 22 | C3L | 1/10 | 4/10 | 1/10 | 4/10 |
| 23 | C3M | 1/10 | 4/10 | 1/10 | 4/10 |
| 24 | C3H | 1/10 | 4/10 | 1/10 | 4/10 |
| 25 | PC1 | 1/10 | 4/10 | 1/10 | 4/10 |
| 26 | PC2L | 1/10 | 4/10 | 1/10 | 4/10 |
| 27 | PC2M | 1/10 | 4/10 | 1/10 | 4/10 |
| 28 | PC2H | 1/10 | 4/10 | 1/10 | 4/10 |
| 29 | RM1L | 2/10 | 3/10 | 3/10 | 2/10 |
| 30 | RM1M | 2/10 | 3/10 | 3/10 | 2/10 |
| 31 | RM2L | 2/10 | 3/10 | 3/10 | 2/10 |
| 32 | RM2M | 2/10 | 3/10 | 3/10 | 2/10 |
| 33 | RM2H | 2/10 | 3/10 | 3/10 | 2/10 |
| 34 | URML | 2/10 | 3/10 | 3/10 | 2/10 |
| 35 | URMM | 2/10 | 3/10 | 3/10 | 2/10 |
| 36 | MH* | n/a | n/a | n/a | n/a |
| B1 | Major Bridge | n/a | n/a | n/a | n/a |
| B2 | Continuous Bridge | n/a | n/a | n/a | n/a |
| B3 | S.S. Bridge | n/a | n/a | n/a | n/a |

## Table 2.12
## NIBS Entrapment Rates by Model Building Type for Complete Structural Damage

| # | Building Type | Entrapment Rate (% of Occupants) |
|---|---|---|
| 1 | W1 | 0 |
| 2 | W2 | 0 |
| 3 | S1L | 1 |
| 4 | S1M | 1 |
| 5 | S1H | 1 |
| 6 | S2L | 1 |
| 7 | S2M | 1 |
| 8 | S2H | 1 |
| 9 | S3 | 0 |
| 10 | S4L | 1 |
| 11 | S4M | 1 |
| 12 | S4H | 1 |
| 13 | S5L | 10 |
| 14 | S5M | 15 |
| 15 | S5H | 20 |
| 16 | C1L | 10 |
| 17 | C1M | 15 |
| 18 | C1H | 20 |
| 19 | C2L | 10 |
| 20 | C2M | 15 |
| 21 | C2H | 20 |
| 22 | C3L | 20 |
| 23 | C3M | 25 |
| 24 | C3H | 30 |
| 25 | PC1 | 25 |
| 26 | PC2L | 15 |
| 27 | PC2M | 20 |
| 28 | PC2H | 25 |
| 29 | RM1L | 15 |
| 30 | RM1M | 25 |
| 31 | RM2L | 20 |
| 32 | RM2M | 25 |
| 33 | RM2H | 30 |
| 34 | URML | 20 |
| 35 | URMM | 40 |
| 36 | MH | 0 |
| B1 | Major Bridge | n/a |
| B2 | Continuous Bridge | n/a |
| B3 | S.S. Bridge | n/a |

The underlying approach adopted in the NIBS casualty estimation methodology is sound and some of the major trends in the variation of casualties with building class may be valid. However, given the preliminary nature of the draft report estimates, the lack of complete peer review and the apparent inconsistencies in some of the data, these NIBS casualty estimates do not appear usable at this time.

Therefore, for the Portland project, we have used the ATC-13 casualty estimates. We recognize that these estimates may be conservative (estimates may be high in some cases). For many building classes, the draft NIBS death rates at 100% damage (combining with and without entrapment) are lower than ATC-13 by factors of 2 or 3. Furthermore, the ATC-13 estimates are based on limited U.S. data and thus there is significant uncertainty in these or any other casualty estimates. However, we believe that combining these casualty estimates with reasonable estimates of the vulnerability of major building classes to seismic damages (i.e., the fragility curves discussed in Section 2.3) will result in reasonable estimates of the **relative** extent of life safety hazard posed by the major building classes.

Quantitative estimates of the degree of life safety hazard posed by the existing building inventory in Portland depends on several factors besides the casualty rate estimates: most important of these are the probabilities of damaging earthquakes, the building class fragility curves, site characteristics (rock, firm soil, soft soil) and occupancy. By considering all of these factors and using the ATC-13 casualty rate estimates, we believe that our approach will properly reflect the **relative** extent of life safety hazards posed by the major building classes.

## 2.5 References


1. Applied Technology Council, ATC-13: "Earthquake Damage Evaluation Data for California," 1985.

2. Applied Technology Council, ATC-36: "Earthquake Loss Evaluation Methodology and Data Bases for Utah," in press, 1995.

3. National Institute of Building Sciences, "Development of a Standardized Earthquake Loss Estimation Methodology," Two volumes, Draft Technical Manual, February 8, 1995.

# TECHNICAL APPENDIX 3

# BUILDING CLASS AND DAMAGE STATE DESCRIPTIONS

In this appendix, we present descriptions of the 16 main building classes listed in Technical Appendix 2 and descriptions of the damage states by building class. These descriptions are closely based on those in the NIBS report[1]. The alphanumeric symbols for each building class (e.g., W1) are the same as given previously in Technical Appendix 2; the suffices, L, M and H, refer to low-, mid- and high-rise buildings, respectively.

## 3.1 Building Class Descriptions

### Wood Light Frame (W1)

These are typically single- or multiple-family dwellings. The essential structural feature of these buildings is repetitive framing by wood rafters or joists on wood stud walls. Loads are light and spans are small. These buildings may have relatively heavy masonry chimneys and may be partially or fully covered with masonry veneer. Most of these buildings, especially the single-family residences, are not engineered but constructed in accordance with conventional construction provisions of building codes (e.g., Sections 2516 and 2517 of the UBC). Hence, they usually have the components of a lateral-force-resisting system even though it may be incomplete. Lateral loads are transferred by diaphragms to shear walls. The diaphragms are roof panels and floors which may be sheathed with wood, plywood or fiberboard sheathing. Shear walls are exterior walls sheathed with wood siding, stucco, plaster, plywood, gypsum board, particle board or fiberboard. Interior partition walls are commonly sheathed with plaster or gypsum board.

### Wood Commercial and Industrial (W2)

These buildings usually are commercial or industrial buildings with a floor area of 5,000 square feet or more and with few if any interior walls. The essential structural character of these buildings is framing by beams over columns. The beams may be glued-laminated (glu-lam) wood or steel beams or trusses. Lateral loads usually are resisted by wood diaphragms and exterior walls sheathed with plywood, stucco, plaster, or other paneling. The walls may have diagonal rod bracing. Large openings for stores and garages often require post-and-beam framing. Lateral load resistance on those lines may be achieved with steel rigid frames or diagonal bracing.

### Steel Moment Frame (S1L, S1M, S1H)

These buildings have a frame of steel columns and beams. In some cases, the beam-column connections have very small moment resisting capacity but, in other cases, some of the beams and columns are fully developed as moment frames to resist lateral forces.

structure is concealed on the outside by exterior walls, which can be of almost any material (curtain walls, brick masonry, or precast concrete panels) and on the inside by ceilings and column furring. Lateral loads are transferred by diaphragms to moment resisting frames. The diaphragms can be almost any material. The frames develop their stiffness by full or partial moment connections. The frames can be located almost anywhere in the building. Usually the columns have their strong directions oriented so that some columns act primarily in one direction while the others act in the other direction and the frames consist of lines of strong columns and their intervening beams. Steel moment frame buildings are typically more flexible than shear wall buildings. This low stiffness can result in large interstory drifts that may lead to relatively greater nonstructural damage.

**Steel Braced Frame (S2L, S2M, S2H)**

These buildings are similar to steel moment frame buildings except that the vertical components of the lateral-force-resisting system are braced frames rather than moment frames.

**Steel Light Frame (S3)**

These buildings are pre-engineered and prefabricated with transverse rigid frames. The roof and walls consist of lightweight panels. The frames are designed for maximum efficiency often with tapered beam and column sections built up of light steel plates. The frames are built in segments and assembled in the field with bolted joints. Lateral loads in the transverse direction are resisted by the rigid frames with loads distributed to them by shear elements. Loads in the longitudinal direction are resisted entirely by shear elements which can be either the roof and wall sheathing panels, an independent system of tension-only rod bracing, or a combination of panels and bracing.

**Steel Frame with Cast-In-Place Concrete Shear Walls (S4L, S4M, S4H)**

The shear walls in these buildings are cast-in-place concrete and may be bearing walls. The steel frame is designed for vertical loads only. Lateral loads are transferred by diaphragms of almost any material to the shear walls. The steel frame may provide a secondary lateral-force-resisting system depending on the stiffness of the frame and the moment capacity of the beam-column connections. In modern dual systems, the steel moment frames are designed to work together with the concrete shear walls in proportion to their relative rigidities.

**Steel Frame with Unreinforced Masonry Infill Walls (S5L, S5M, S5H)**

This is one of the older types of buildings. The infill walls usually are offset from the exterior frame members, wrap around them and present a smooth masonry exterior with no indication of the frame. Solidly-infilled masonry panels, when they fully engage the surrounding frame members (i.e., lie in the same plane), provide stiffness and lateral load resistance to the structure.

### Reinforced Concrete Moment Resisting Frames (C1L, C1M, C1H)

These buildings are similar to steel moment frame buildings except that the frames are reinforced concrete. There is a large variety of frame systems. Some older concrete frames may be proportioned and detailed such that brittle failure of the frame members can occur in earthquakes leading partial or full collapse of the buildings. Modern frames in zones of high seismicity are proportioned and detailed for ductile behavior and are likely to undergo large deformations during an earthquake without brittle failure of frame members or collapse.

### Concrete Shear Walls (C2L, C2M, C2H)

The vertical components of the lateral-force-resisting system in these buildings are concrete shear walls that are usually bearing walls. In older buildings, the walls often are quite extensive and the wall stresses are low, but reinforcing is light. In newer buildings, the shear walls often are limited in extent, generating concerns about boundary members and overturning forces.

### Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3L, C3M, C3H)

These buildings are similar to steel frame buildings with unreinforced masonry infill walls except that the frame is of reinforced concrete. In these buildings, the shear strength of the columns after cracking of the infill may limit the semi-ductile behavior of the system.

### Precast Concrete Tilt-Up Walls (PC1)

These buildings have a wood or metal deck roof diaphragm, which often is very large, that distributes lateral forces to precast concrete shear walls. The walls are thin but relatively heavy, while the roofs are relatively light. Older buildings often have inadequate connections for anchorage of the walls to the roof for out-of-plane forces and the panel connections often are brittle. Tilt-up buildings often have more than one story. Walls can have numerous openings for doors and windows of such size that the wall looks more like a frame than a shear wall.

### Precast Concrete Frames with Concrete Shear Walls (PC1L, PC2M, PC2H)

These buildings contain floor and roof diaphragms typically composed of precast concrete elements with or without cast-in-place concrete topping slabs. The diaphragms are supported by precast concrete girders and columns. The girders often bear on column corbels. Closure strips between precast floor elements and beam-column joints usually are cast-in-place concrete. Welded steel inserts often are used to interconnect precast elements. Lateral loads are resisted by precast or cast-in-place concrete shear walls. Buildings with precast frames and concrete shear walls should perform well if the details used to connect the structural elements have sufficient strength and displacement capacity. However, in some cases, the connection details between the precast elements have negligible ductility.

### Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1L, RM1M)

These buildings have perimeter bearing walls of reinforced brick or concrete-block masonry. These walls are the vertical elements in the lateral-force-resisting system. The floors and roofs are framed either with wood joists and beams with plywood or straight or diagonal sheathing or with steel beams with metal deck with or without a concrete fill. Wood floor framing is supported by interior wood posts or steel columns. Steel beams are supported by steel columns.

### Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2L, RM2M, RM2H)

These buildings have bearing walls similar to those of reinforced masonry bearing wall structures with wood or metal deck diaphragms, but the roof and floors are composed of precast concrete elements such as planks or tee-beams and the precast roof and floor elements are supported on interior beams and columns of steel or concrete (cast-in-place or precast). The precast horizontal elements often have a cast-in-place topping.

### Unreinforced Masonry Bearing Walls (URML, URMM)

These buildings include structural elements that vary depending on the building's age and to a lesser extent its geographic location. In buildings built before 1900, the majority of floor and roof construction consists of wood sheathing supported by wood subframing. In large multistory buildings, the floors are cast-in-place concrete supported by the unreinforced masonry walls and/or steel or concrete interior framing. In unreinforced masonry constructed after 1950, wood floors usually have plywood rather than board sheathing. In regions of lower seismicity, buildings of this type constructed more recently can include floor and roof framing that consists of metal deck and concrete fill supported by steel framing elements. The perimeter walls and possibly some interior walls, are unreinforced masonry. The walls may or may not be anchored to the diaphragms. Ties between the walls and diaphragms are more common for the bearing walls than for walls that are parallel to the floor framing. Roof ties usually are less common and more erratically spaced than those at the floor levels. Interior partitions that interconnect the floors and roof can have the effect of reducing diaphragm displacements.

### Mobile Homes (MH)

These are prefabricated housing units that are transported to location on wheels or moving platforms. At the site, the units are placed on isolated piers or masonry block foundations usually without any positive anchorage. Floors and roofs of mobile homes usually constructed with plywood and outside surfaces are covered with sheet metal.

### 3.2 Damage States

The prediction of damage for the various classes of buildings is done using fragility curves. For each building class, a fragility curve is developed for each of four damage states:

- Collapse
- Extensive
- Moderate
- Slight

These damage states are descriptive. From the descriptions of the damage states provided in this section, the user can understand the nature and extent of the physical damage to a building type from the damage prediction output. From these descriptions, life-safety, societal and monetary losses which result from the damage can be estimated. Building damage can best be described in terms of the nature and extent of damage exhibited by its components (beams, columns, walls, ceilings, piping, HVAC equipment, etc.). For example, such component damage descriptions as "shear walls are cracked", "ceiling tiles fell", "diagonal bracing buckled", "wall panels fell out", etc., used together with such terms as "some" and "most" would be sufficient to describe the nature and extent of overall building damage.

Damage to nonstructural components of buildings (i.e., architectural components, such as partition walls and ceilings and building mechanical/electrical systems) primarily affect monetary and societal losses while damage to structural components (i.e., the gravity and lateral load resisting systems) of buildings affect the expected casualty estimates, as well as other losses. For this project, we have provided fragility curves only for damage to the structural components and not the nonstructural components.

Another characteristic of building damage is that it varies from "none" to "complete" as a continuous function of building deformations (building response). Wall cracks may vary from invisible or hairline cracks to cracks of several inches width. Furthermore, damage of different nature or form may occur at different building deformations. As it is impractical to linguistically describe building damage as a continuous function, it is necessary to develop general descriptions for ranges of damage.

This methodology describes extent and severity of damage to structural components of a building separately by one of four ranges of damage or damage states: slight, moderate, extensive and complete. General descriptions of these damage states are provided for all model building types with reference to observable damage incurred. Damage predictions resulting from this physical damage estimation method are then expressed in terms of the probability of a building being in any of these four damage states.

### 3.3 Damage State Descriptions by Building Class

General descriptions for slight, moderate, extensive and complete structural damage states for the 36 building types are provided below. It is noted that, in some cases the structural damage is not directly observable because the structural elements are inaccessible or not visible due to architectural finishes or fireproofing. Hence, these structural damage states are described when necessary with reference to certain effects on nonstructural elements which may be indicative of the structural damage state of concern.

### Wood Light Frame (W1)

**Slight Structural Damage:** Small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections [small cracks are assumed throughout this section to be visible cracks with a maximum width of less than 1/8". Cracks wider than 1/8" are referred to as "large" cracks]; small cracks in masonry chimneys and masonry veneer.

**Moderate Structural Damage:** Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall - masonry chimneys.

**Extensive Structural Damage:** Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of room-over-garage or other soft-story configurations; small foundations cracks.

**Complete Structural Damage:** Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load resisting system; some structures may slip and fall off the foundations; large foundation cracks.

### Wood Commercial and Industrial (W2)

**Slight Structural Damage:** Small cracks at comers of door and window openings and wall-ceiling intersections; small cracks on stucco and plaster walls. Some slippage may be observed at bolted connections.

**Moderate Structural Damage:** Larger cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by cracks in stucco and gypsum wall panels; minor slack in diagonal rod bracing requiring re-tightening [minor slack in tension rod bracing is assumed to result from less than 1/8" extension of the rod]; Slack resulting from greater extension of the rod is considered to be large.; minor lateral set at store fronts and other large openings; small cracks or wood splitting may be observed at bolted connections.

**Extensive Structural Damage:** Large diagonal cracks across shear wall panels; large slack in diagonal rod braces and/or broken braces; permanent lateral movement of floors and roof; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of soft-story configurations; bolt slippage and wood splitting at bolted connections.

**Complete Structural Damage:** Structure may have large permanent lateral displacement, may collapse or be in imminent danger of collapse due to failed shear walls, broken brace rods or failed framing connections; it may fall off its foundations; large cracks in the foundations.

### Steel Moment Frame (S1L, S1M, S1H)

**Slight Structural Damage:** Minor deformations in connections or hairline cracks in few welds.

**Moderate Structural Damage:** Some steel members have yielded exhibiting observable permanent rotations at connections; few welded connections may exhibit major cracks through welds or few bolted connections may exhibit broken bolts or enlarged bolt holes.

**Extensive Structural Damage:** Most steel members have exceeded their yield capacity resulting in significant permanent lateral deformation of the structure. Some of the structural members or connections may have exceeded their ultimate capacity exhibited by major permanent member rotations at connections, buckled flanges and failed connections. Partial collapse of portions of structure is possible due to failed critical elements and/or connections.

**Complete Structural Damage:** Significant portion of the structural elements have exceeded their ultimate capacities or some critical structural elements or connections have failed resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building.

### Steel Braced Frame (S2L, S2M, S2H)

**Slight Structural Damage:** Few steel braces have yielded which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.

**Moderate Structural Damage:** Some steel braces have yielded exhibiting observable stretching and/or buckling of braces; few braces, other members or connections have indications of reaching their ultimate capacity exhibited by buckled braces, cracked welds, or failed bolted connections.

**Extensive Structural Damage:** Most steel braces and other members have exceeded their yield capacity resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity exhibited by buckled or broken braces, flange buckling, broken welds or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of structure is possible due to failure of critical elements or connections.

**Complete Structural Damage:** Most the structural elements have reached their ultimate capacities or some critical members or connections have failed resulting in dangerous permanent lateral deflection and partial collapse or collapse of the building.

### Steel Light Frame (S3)

These structures are mostly single story structures combining rod-braced frames in one direction and moment frames in the other. Due to repetitive nature of the structural systems, the type of damage to structural members is expected to be rather uniform throughout the structure.

**Slight Structural Damage:** Few steel rod braces have yielded which may be indicated by minor sagging of rod braces; minor cracking at welded connections or minor deformations at bolted connections of moment frames may be observed.

**Moderate Structural Damage:** Most steel braces have yielded exhibiting observable significantly sagging rod braces; few brace connections may be broken; some weld cracking may be observed in the moment frame connections.

**Extensive Structural Damage:** Significant permanent lateral deformation of the structure due to broken brace rods, stretched anchor bolts and permanent deformations at moment frame members; some screw or welded attachments of roof and wall siding to steel framing may be broken; some purlin and girt connections may be broken.

**Complete Structural Damage:** Structure is collapsed or in imminent danger of collapse due to broken rod bracing, failed anchor bolts or failed structural members or connections.

### Steel Frame with Cast-In-Place Concrete Shear Walls (S4L, S4M, S4H)

This is a composite structural system where primary lateral-force-resisting system is the concrete shear walls. Hence, slight, moderate and extensive damage states are likely to be determined by the shear walls while the collapse damage state would be determined by the failure of the structural frame.

**Slight Structural Damage:** Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at few locations.

**Moderate Structural Damage:** Most shear wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities exhibited by larger diagonal cracks and concrete spalling at wall ends.

**Extensive Structural Damage:** Most concrete shear walls have exceeded their yield capacities; few walls have reached or exceeded their ultimate capacity exhibited by large through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement; partial collapse may occur due to failed connections of steel framing to concrete walls; some damage may be observed in steel frame connections.

**Complete Structural Damage:** Structure may be in danger of collapse or collapse due to total failure of shear walls and loss of stability of the steel frames.

### Steel Frame with Unreinforced Masonry Infill Walls (S5L, S5M, S5H)

This is a composite structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the steel frames braced by the infill walls acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate due to compression failure of the masonry struts and the steel frame loses its stability.

**Slight Structural Damage:** Diagonal sometimes horizontal hairline cracks on most infill walls; cracks at frame-infill interfaces.

**Moderate Structural Damage:** Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections.

**Extensive Structural Damage:** Most infill walls exhibit large cracks; some bricks may be dislodged and fall; some infill walls may bulge out-of-plane; few walls may fall off partially or fully; some steel frame connections may have failed; structure may exhibit permanent lateral deformation or partial collapse due to failure of some critical members.

**Complete Structural Damage:** Structure is collapsed or in danger of imminent collapse due to total failure of infill walls and loss of stability of the steel frames.

### Reinforced Concrete Moment Resisting Frames (C1L, C1M, C1H)

**Slight Structural Damage:** Flexural or shear type hairline cracks in some beams and columns near joints or within joints.

**Moderate Structural Damage:** Most beams and columns exhibit hairline cracks; in ductile frames some of the frame elements have reached yield capacity indicated by larger flexural cracks and some concrete spalling; nonductile frames may exhibit larger shear cracks and spalling.

**Extensive Structural Damage:** Some of the frame elements have reached their ultimate capacity indicated in ductile frames by large flexural cracks, spalled concrete and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices which may result in partial collapse.

**Complete Structural Damage:** Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability.

### Concrete Shear Walls (C2L, C2M, C2H)

**Slight Structural Damage:** Diagonal hairline cracks on most concrete shear wall surfaces; minor concrete spalling at few locations.

**Moderate Structural Damage:** Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded yield capacity indicated by larger diagonal cracks and concrete spalling at wall ends.

**Extensive Structural Damage:** Most concrete shear walls have exceeded their yield capacities; some walls have exceeded their ultimate capacities indicated by large, through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement; partial collapse may occur due to failure of nonductile columns not designed to resist lateral loads.

**Complete Structural Damage:** Structure has collapsed or is in imminent danger of collapse due to failure of most of the shear walls and failure of some critical beams or columns.

### Concrete Frame Buildings with Unreinforced Masonry Infill Walls (C3L, C3M, C3H)

This is a composite structural system where the initial lateral resistance is provided by the infill walls. Upon cracking of the infills, further lateral resistance is provided by the concrete frame braced by the infill acting as diagonal compression struts. Collapse of the structure results when the infill walls disintegrate due to compression failure of the masonry struts and the frame loses stability, or when the concrete columns suffer shear failures due to reduced effective height and the high shear forces imposed on them by the masonry compression struts.

**Slight Structural Damage:** Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.

**Moderate Structural Damage:** Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections; diagonal shear cracks may be observed in concrete beams or columns.

**Extensive Structural Damage:** Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; few walls may fall partially or fully; few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation.

**Complete Structural Damage:** Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and nonductile failure of the concrete beams and columns.

### Precast Concrete Tilt-Up Walls (PC1)

**Slight Structural Damage:** Diagonal hairline cracks on concrete shear wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; minor concrete spalling at few locations; minor separation of walls from the floor and roof diaphragms; hairline cracks around metal connectors between wall panels and at connections of beams to walls.

**Moderate Structural Damage:** Most wall surfaces exhibit diagonal cracks; larger cracks in walls with door or window openings; few shear walls have exceeded their yield capacities indicated by larger diagonal cracks and concrete spalling; cracks may appear at top of walls near panel intersections indicating chord yielding; some walls may have visibly pulled away from the roof some welded panel connections may have been broken, indicated by spalled concrete around connections; some spalling may be observed at the connections of beams to walls.

**Extensive Structural Damage:** In buildings with relatively large area of wall openings most concrete shear walls have exceeded their yield capacities and some have exceeded their ultimate capacities indicated by large, through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement; the plywood diaphragms may exhibit cracking and separation along plywood joints; partial collapse of the roof may result from the failure of the wall-to-diaphragm anchorages and falling of wall panels.

**Complete Structural Damage:** Structure is collapsed or is in imminent danger of collapse due to failure of the wall-to-roof anchorages, splitting of ledgers, or failure of plywood-to-ledger nailing; failure of beams connections at walls; failure of roof or floor diaphragms; failure of the wall panels.

### Precast Concrete Frames with Concrete Shear Walls (PC2L, PC2M, PC2H)

**Slight Structural Damage:** Diagonal hairline cracks on most shear wall surfaces; minor concrete spalling at a few connections of precast members.

**Moderate Structural Damage:** Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded their yield capacities indicated by larger cracks and concrete spalling at wall ends; observable distress or movement at connections of precast frame connections, some failures at metal inserts and welded connections.

**Extensive Structural Damage:** Most concrete shear walls have exceeded their yield capacities; some walls may have reached their ultimate capacities indicated by large, through-the wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement; some critical precast frame connections may have failed resulting in partial collapse.

**Complete Structural Damage:** Structure has collapsed or is in imminent danger of collapse due to failure of the shear walls and/or failures at precast frame connections.

### Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms (RM1L, RM1M)

**Slight Structural Damage:** Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; minor separation of walls from the floor and roof diaphragms.

**Moderate Structural Damage:** Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger diagonal cracks; some walls may have visibly pulled away from the roof.

**Extensive Structural Damage:** In buildings with relatively large area of wall openings most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities indicated by large, through-the wall diagonal cracks and visibly buckled wall reinforcement; the plywood diaphragms may exhibit cracking and separation along plywood joints; partial collapse of the roof may result from failure of the wall-to-diaphragm anchorages or the connections of beams to walls.

**Complete Structural Damage:** Structure has collapsed or is in imminent danger of collapse due to failure of the wall anchorages or due to failure of the wall panels.

### Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms (RM2L, RM2M, RM2H)

**Slight Structural Damage:** Diagonal hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings.

**Moderate Structural Damage:** Most wall surfaces exhibit diagonal cracks; some of the shear walls have exceeded their yield capacities indicated by larger cracks.

**Extensive Structural Damage:** In buildings with relatively large area of wall openings most shear walls have exceeded their yield capacities and some of the walls have exceeded their ultimate capacities exhibited by large, through-the wall diagonal cracks and visibly buckled wall reinforcement; the diaphragms may also exhibit cracking.

**Complete Structural Damage:** Structure is collapsed or is in imminent danger of collapse due to failure of the walls.

### Unreinforced Masonry Bearing Walls (URML, URMM)

**Slight Structural Damage:** Diagonal, stair-step hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; movements of lintels; cracks at the base of parapets.

**Moderate Structural Damage:** Most wall surfaces exhibit diagonal cracks; some of the walls exhibit larger diagonal cracks; masonry walls may have visible separation from diaphragms; significant cracking of parapets; few individual masonry units may fall off the walls or parapets.

**Extensive Structural Damage:** In buildings with relatively large area of wall openings most walls have suffered extensive cracking; some parapets and gable end walls have fallen. Beams or trusses may have moved relative to their supports.

**Complete Structural Damage:** Structure has collapsed or is in imminent danger of collapse due to in-plane or out-of-plane failure of the walls.

### Mobile Homes (MH)

**Slight Structural Damage:** Slight movement of mobile home on its supports requiring realignment.

**Moderate Structural Damage:** Major movement of the mobile home over its supports resulting in some damage to metal siding and stairs.

**Extensive Structural Damage:** Mobile home has fallen partially off its supports.

**Complete Structural Damage:** Mobile home has totally fallen off its supports.

## 3.4 References


1. National Institute of Building Sciences, "Development of a Standardized Earthquake Loss Estimation Methodology," Two volumes, Draft Technical Manual, February 8, 1995.

# TECHNICAL APPENDIX 4

# TYPICAL RETROFIT COSTS

## 4.1 Typical Seismic Retrofits

Enhancing life safety has been the prime motivation for the vast majority of seismic retrofits which have been completed in the United States. Ancillary benefits -- reducing future damages and other economic costs -- may play a role in the decision making. However, for both mandatory and voluntary retrofits the belief that the level of life safety hazard posed by an existing building was unacceptably high has been the primarily reason for retrofit.

Because such a high percentage of retrofits to date have been designed for life safety, "typical" retrofits are life-safety driven and, therefore, the costs of "typical" retrofits are the costs of life-safety retrofits. FEMA has recently undated and revised its publication on the Typical Costs of Seismic Rehabilitation of Buildings[1]. This publication represents a major nationwide data collection, compilation and interpretation effort and thus provides by far the best available description of the typical costs of seismic retrofits.

## 4.2 Typical Costs of Life-Safety Retrofits

### 4.2.1 Structural Costs

Table 4.1 which is based on data from Volume 1 of the FEMA Typical Costs[1] publication summarizes the typical structural costs for life safety retrofits in high seismicity areas. High seismicity areas include UBC Zone 3 and thus includes Portland. These costs are structural costs <u>**only**</u>. These typical structural costs apply to all types of buildings, including institutional, commercial and industrial.

For seven of the eight building costs groups, these "typical" structural costs appear reasonable. However, for Group 3 (precast concrete tilt-up walls and reinforced masonry with metal or wood diaphragms) the costs seem unreasonably high compared to actual costs of retrofit performed on these buildings in Los Angeles and other California cities. Many life-safety retrofits of these building classes only require better connections between roof diaphragms and walls, or for buildings above one story between roof and floor diaphragms and walls. In a few cases, substantial strengthening or stiffening of diaphragms may be required and this may account for the higher costs used in the FEMA publication. For "typical" Group 3 buildings, we believe that lower costs are more common. For small, medium, large and very large buildings in Cost Group 3, we believe that $5.50, $4.25, $2.50 and $1.50 per square foot are reasonable typical structural costs. For all other Cost Groups we use the typical costs shown in the FEMA Typical Costs table.

In addition to structural costs, there are other costs which are an integral part of retrofit costs: 1) restoration of architectural finishes after structural work, 2) non-structural mitigation work in conjunction with structural work, 3) other project costs such as architectural and engineering

**Table 4.1**
**Typical Structural Retrofit Costs ($/sf)**

| | | Building Area | | | |
|---|---|---|---|---|---|
| **Building Group** | **Building Types** | **Small** | **Medium** | **Large** | **Very Large** |
| 1 | URM | $13.74 | $13.61 | $12.93 | $10.89 |
| 2 | W1, W2 | $10.61 | $11.16 | $14.00 | $17.94 |
| 3[a] | PC1, RM1 | $5.50 | $4.25 | $2.50 | $1.50 |
| 4 | C1, C3 | $19.42 | $18.89 | $18.00 | $14.97 |
| 5 | S1 | $19.47 | $19.14 | $18.30 | $13.93 |
| 6 | S2, S3 | $7.59 | $7.21 | $5.79 | $3.28 |
| 7 | S5 | $22.22 | $22.10 | $21.16 | $18.59 |
| 8 | C2, PC2, RM2, S4 | $17.10 | $16.64 | $15.71 | $12.79 |

[a] For Cost Group 3, these costs are our estimates; all other structural costs are from FEMA Typical Costs, Volume 1.

Typical costs vary with building size. For all groups, except wood frame, costs per square foot decrease with increasing building size. For wood frame buildings, costs per square foot increase with increasing buildings size because the structural details differ for large wood buildings compared to smaller wood buildings.

Small buildings are less than 10,000 square feet.
Medium buildings are 10,000 to 49,999 square feet.
Large buildings are 50,000 to 99,999 square feet.
Very large buildings are 100,000 or greater square feet.

fees, testing, permits, management, and 4) relocation costs if buildings are vacated (and temporary space rented).

### 4.2.2 Restoration of Architectural Finishes

The typical structural costs presented above do not include the necessary costs of demolition and restoration of architectural finishes necessary for access to the structural members be upgraded. In some cases, disruption and restoration of electrical, plumbing and mechanical systems may also be required.

FEMA Typical Costs, Volume 2, estimates these costs as shown in Table 4.2. These costs vary with building type because of typical differences in the type and extent of architectural finishes. Thus, restoration costs are highest for institutional buildings and lowest for industrial buildings.

### 4.2.3 Non-Structural Mitigation

Some extent of non-structural mitigation, such as bracing of ceilings, light fixtures and mechanical systems, is normally done in conjunction with structural retrofits. In some cases such measures are code mandated.

FEMA Typical Costs, Volume 2, estimates these costs as shown in Table 4.3. The lower costs are for "light" non-structural mitigation and the higher costs are for "complete" non-structural mitigation.

For the purposes of estimating typical costs for benefit-cost analysis of life-safety retrofit alternatives we use the low cost "light" non-structural mitigation values. This decision assumes that some degree of non-structural mitigation is a necessary (and probably code-required in some cases) and therefore, would normally be an integral part of a life-safety retrofit. "Complete" non-structural mitigation is assumed to be an owner's option predicated more on damage avoidance and preservation of functionality than on life safety.

### 4.2.4 Other Costs

In addition to structural, restoration and non-structural costs, all life safety retrofits involve direct costs for architectural and engineering design fees, testing, permits, insurance and project management. FEMA Typical Costs, Volume 2, estimates that such costs generally total about 30% of direct construction costs. Using this value, we add 30% to the **sum** of the structural, restoration and non-structural construction costs estimated in the previous three sections.

**Table 4.2**
**Typical Restoration Costs per Square Foot**

| Building Type | Cost per sf |
|---|---|
| average, all buildings | $3.00 |
| commercial buildings | $3.00 |
| institutional buildings | $4.00 |
| industrial buildings | $1.00 |

These data are from FEMA Typical Costs, Volume 2.

**Table 4.3**
**Typical Non-Structural Costs per Square Foot**

| Building Type | Cost per sf | |
|---|---|---|
| | light | complete |
| average, all buildings | $3.00 | $7.00 |
| commercial buildings | $3.00 | $7.00 |
| institutional buildings | $4.00 | $10.00 |
| industrial buildings | $2.00 | $10.00 |

These data are from FEMA Typical Costs, Volume 2.

### 4.2.5 Relocation Costs

In many cases, major structural retrofits may require relocation of occupants from the building while retrofit work is completed. In other cases, retrofit work can be done on a rotating basis through a building with partial relocations or much of the work can be done during off-hours. Either of these latter alternatives also entails increased costs compared to retrofitting a vacant building. Relocation costs are commonly a necessary and integral part of a seismic retrofit.

Relocation times necessary may vary from zero to as long as two or three years for very major projects on large, monumental buildings. For "typical" medium-sized commercial or institutional buildings, six months of relocation is assumed to be the norm. For industrial buildings and Cost Group 3 retrofits, typical relocation times will be much shorter because retrofit work in these buildings can often be accomplished with continued occupancy. For these cases, we assume one month of relocation (on average).

On average, for Portland, we assume relocation costs of $1.50 per month per square foot. Therefore, for typical retrofits we assume a relocation of $9.00/sf (six months). This additional cost represents a significant fraction of total retrofit costs (approximately 25%). For industrial buildings and Cost Group 3 retrofits we assume a relocation cost of $1.50/sf.
We recognize, of course, that individual building retrofits may have relocation costs which vary markedly from these assumed averages.

## 4.3 Total Life Safety Retrofit Costs

As outlined above, typical total life safety retrofit costs are estimated as follows:

a) total construction costs are the sum of structural, restoration, non-structural costs,

b) other costs of 30% are added to the subtotal above, and

c) relocation costs of $9.00/sf for all non-industrial buildings except those in Cost Group 3 and $1.50/sf for Cost Group 3 and industrial buildings are added to the costs listed under "a" and "b", above.

These estimated total costs are shown in Tables 4.4, 4.5 and 4.6 which contain "typical" costs for average or commercial buildings, institutional and industrial buildings, respectively.

**Table 4.4**
**Total Life Safety Retrofit Costs for Average or Commercial Buildings, $/sf**

| | | Building Area | | | |
|---|---|---|---|---|---|
| **Building Group** | **Building Types** | **Small** | **Medium** | **Large** | **Very Large** |
| 1 | URM | $34.66 | $34.49 | $33.61 | $30.96 |
| 2 | W1, W2 | $30.59 | $31.31 | $35.00 | $40.12 |
| 3 | PC1, RM1 | $16.45 | $14.83 | $12.55 | $11.25 |
| 4 | C1, C3 | $42.05 | $41.36 | $40.20 | $36.26 |
| 5 | S1 | $42.11 | $41.68 | $40.59 | $34.91 |
| 6 | S2, S3 | $26.67 | $26.17 | $24.33 | $21.06 |
| 7 | S5 | $45.69 | $45.41 | $44.31 | $40.97 |
| 8 | C2, PC2, RM2, S4 | $41.73 | $41.13 | $39.92 | $36.13 |

Total life safety retrofit costs are the sum of total construction costs (structural, restoration of architectural finishes and non-structural), other costs (30% of construction costs), plus relocation costs ($9.00/sf for all buildings except Group 3 which are $1.50/sf).

**Table 4.5**
**Total Life Safety Retrofit Costs for Institutional Buildings, $/sf**

| | | Building Area | | | |
|---|---|---|---|---|---|
| Building Group | Building Types | Small | Medium | Large | Very Large |
| 1 | URM | $37.26 | $37.09 | $36.21 | $33.56 |
| 2 | W1, W2 | $33.19 | $33.91 | $37.60 | $42.72 |
| 3 | PC1, RM1 | $19.05 | $17.43 | $15.15 | $13.85 |
| 4 | C1, C3 | $44.65 | $43.96 | $42.80 | $38.86 |
| 5 | S1 | $44.71 | $44.28 | $43.19 | $37.51 |
| 6 | S2, S3 | $29.27 | $28.77 | $26.93 | $23.66 |
| 7 | S5 | $48.29 | $48.01 | $46.91 | $43.57 |
| 8 | C2, PC2, RM2, S4 | $44.33 | $43.73 | $42.52 | $38.73 |

Total life safety retrofit costs are the sum of total construction costs (structural, restoration of architectural finishes and non-structural), other costs (30% of construction costs), plus relocation costs ($9.00/sf for all buildings except Group 3 which are $1.50/sf).

**Table 4.6**
**Total Life Safety Retrofit Costs for Industrial Buildings, $/sf**

| | | Building Area | | | |
|---|---|---|---|---|---|
| **Building Group** | **Building Types** | **Small** | **Medium** | **Large** | **Very Large** |
| 1 | URM | $23.26 | $23.09 | $22.21 | $19.56 |
| 2 | W1, W2 | $19.19 | $19.91 | $23.60 | $28.72 |
| 3 | PC1, RM1 | $12.55 | $10.93 | $8.65 | $7.35 |
| 4 | C1, C3 | $30.65 | $29.96 | $28.80 | $24.86 |
| 5 | S1 | $30.71 | $30.28 | $29.19 | $23.51 |
| 6 | S2, S3 | $15.27 | $14.77 | $12.93 | $9.66 |
| 7 | S5 | $34.29 | $34.01 | $32.91 | $29.57 |
| 8 | C2, PC2, RM2, S4 | $30.33 | $29.73 | $28.52 | $24.73 |

Total life safety retrofit costs are the sum of total construction costs (structural, restoration of architectural finishes and non-structural), other costs (30% of construction costs), plus relocation costs of $1.50/sf.

## 4.4 Excluded Costs

The preceding sections have outlined our compilation of typical costs for life safety retrofits for use in a benefit-cost analysis. There are other costs associated with retrofit that for other purposes, would be included in total retrofit costs. These include the costs for remodeling, abatement of hazardous materials such as asbestos, fire or other safety upgrades and improved disabled access.

The following costs have been excluded from the benefit-cost analysis since they are not relevant to **seismic** life safety benefits:

refurbishing/remodeling/upgrading; such efforts are voluntary on the part of the building owner and are intended to enhance the esthetics, functionality or marketability of the building;

abatement of hazardous materials such as asbestos (which may be undertaken either voluntarily or because of code mandates);

fire safety or other safety measures (which may be undertaken either voluntarily of because of code mandates); and

retrofit/remodeling which may in some cases trigger code provisions requiring enhanced access for disabled persons.

## 4.5 References

1. FEMA, "Typical Costs of Seismic Rehabilitation of Buildings," Volume 1 - Summary, 1994.

2. FEMA, "Typical Costs of Seismic Rehabilitation of Buildings," Volume 2 - Supporting Documentation, Draft, 1995.

# TECHNICAL APPENDIX 5

# BENEFIT-COST ANALYSIS: ASSUMPTIONS

## 5.1 Introduction

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) was designed primarily for public-sector buildings, but is applicable to private-sector buildings as well.

The benefit-cost analyses presented in Volume One of this report were conducted with proprietary software similar to the second FEMA methodology (FEMA 255 & 256, 1994). The justification for the procedures and the selection of variables 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. More accurately, benefits are the net present value of the difference in expected future damages and losses before and after retrofit or the net present value of avoided damages and losses. "Damages and losses" considered include casualties, building damages, contents damages, displacement costs due to seismic damage, rental and business income losses, and loss of public/nonprofit services. The precise timing and severity of future earthquakes are unknown. Therefore, expected future damages and losses must be estimated probabilisticly using seismic hazard curves, building fragility curves, and relationships between building damages, casualties, and economic losses.

**Is it worth is?** This is the central question about seismic retrofits -- either for a single building or for a prospective retrofit ordinance provision which might require the retrofit of thousands of buildings. The focus of our benefit-cost analyses for this project for the City of Portland is to compare the costs and benefits of life-safety retrofits for the 10 classes of buildings deemed to pose potentially significant life safety hazards. Key questions to be answered separately for typical buildings on rock, firm soil and soft soil sites, include:

1) What level of life safety hazards are posed by these building classes?

2) Are retrofits economically justified solely on the basis of casualties avoided?

3) Are retrofits economically justified when the full range of benefits are considered?

4) How do these conclusions vary with building size/use/occupancy?

The key steps in this benefit-cost methodology are outlined below:

A) EXISTING BUILDING INVENTORY

1) The expected annual probabilities of duration-adjusted PGAs are calculated for Portland for rock, firm soil and soft soil sites. These probabilities for rock, firm soil and soil sites are calculated as described in Technical Appendix 1.

2) Building fragility curves are defined which determine the expected extent of building damages vs. PGA. The Portland fragility curves for 10 classes of buildings on the three site types are as given in Technical Appendix 2.

3) Casualty rates are estimated from building damage vs. casualty relationships. The building damage vs. casualty relationship used in these analyses is based on ATC-13 as described in Technical Appendix 2.

4) Other economic losses are estimated from building damage vs. other economic loss relationships. These relationships are as described in the FEMA benefit cost models.[1,2]

Steps 1 through 4 define the seismic vulnerability of existing buildings both with respect to life safety (casualties) and economic losses.

B) POST-RETROFIT BUILDINGS

5) Typical retrofit costs per square foot are estimated. The sources of estimates and resulting total costs/sf for various building classes are as described in Technical Appendix 4.

6) Retrofit effectiveness is estimated both with respect to casualty avoidance and with respect to damage and economic loss avoidance.

7) A project useful lifetime and a discount rate are defined and determine, in conjunction with the expected average annual damages, losses, and casualties avoided, the net present value of benefits from the retrofit.

Steps 7 and 8 are discussed below.

## 5.2 Retrofit Effectiveness Estimates

Life safety retrofits are designed to prevent full or partial collapse of buildings and thus to minimize deaths. Even in the best designed new or retrofit buildings, occasional deaths are unavoidable due to stray falling objects and other consequences of strong ground motions. In estimating the fraction of casualties avoided from typical life safety retrofits, we follow the peer-reviewed consensus numbers used in the FEMA benefit-cost analysis. Life safety retrofits are assumed to reduce the death rate by factor of 1,000, to reduce the major injury rate by a factor of 100, and to reduce the minor injury rate by a factor of 10. Thus, we assume that life safety retrofits are indeed quite effective in achieving their designed purpose of avoiding collapse and thus minimizing future casualties.

Life safety retrofits do not make a building earthquake proof, do not completely eliminate casualties, and do not eliminate non-life safety damages and losses. However, life safety retrofits are generally expected to reduce future building damages and thereby to also reduce other economic losses which are derivative from building damages (i.e., damages to contents and loss of functionality costs)..

The effectiveness of a life safety retrofit in reducing future damages and losses will vary from building to building depending on the details of the retrofit and the extent of existing building deficiencies which are addressed by the retrofit. For "typical" life-safety retrofits of "typical" buildings we assume that retrofit effectiveness percentages are as shown in the Table 5.1. In this table, percentage effectiveness means the percentage of damages avoided. Thus, for example, a retrofit which is 30% effective at some PGA level is estimated to avoid 30% of the building damages expected without retrofit. For building damages, retrofit effectiveness varies with the intensity of ground shaking. At very high levels of ground shaking building damages may be high (retrofit effectiveness low), even though casualties are low, because a life safety retrofit prevents collapse but may not prevent major, even unrepairable, damages to a building.

Seismic retrofits are sometimes designed to higher than life safety standards. That is, they may be designed to reduce damages and/or to maintain post-earthquake functionality for essential facilities. Such non-life safety retrofits are not considered in this report.

## 5.3 Retrofit Project Useful Lifetime and Discount Rate

The useful lifetime of a retrofit project is the time over which expected future benefits are accrued and discounted to net present value. For major building projects, 30 to 50 year lifetimes are commonly assumed. For these benefit-cost analyses, we assumed a project lifetime of 50 years. Our benefit-cost results are not strongly dependent on the choice of project useful lifetime. For a discount rate of 7% (see paragraph below), net present values increase only slightly with increasing project lifetimes, especially above 30 years (see Table 5.2).

The discount rate determines, in conjunction with the project useful lifetime, the present value of each $1.00 per year in future benefits. Following the guidance from the United States Office of Management and Budget as applicable to investments which are not internal Federal government investments, we suggest that a discount rate of approximately 7% is appropriate for most private and public-sector seismic retrofit projects. Using lower discount rates values future benefits more highly, while using higher discount rates values future benefits less highly. For completeness, Table 5.2 shows the present value coefficient (the net present value of $1.00 per year in future benefits) for a wide range of combinations of discount rates and project useful lifetimes. A 7% discount rate has been used for all

**Table 5.1**
**Effectiveness Estimates for Avoided Building Damages**
**Life Safety Seismic Retrofits**
**(percent of damages avoided)**

| PGA (%g) | W1 | W2 | S1L | S1M | S1H | S2L | S2M | S2H | S3 |
|---|---|---|---|---|---|---|---|---|---|
| 4 - 8 | 80% | 50% | 35% | 35% | 35% | 35% | 35% | 35% | 35% |
| 8 - 16 | 75% | 50% | 35% | 35% | 35% | 35% | 35% | 35% | 35% |
| 16 - 32 | 65% | 43% | 31% | 31% | 31% | 31% | 31% | 31% | 31% |
| 32 - 55 | 50% | 35% | 28% | 28% | 28% | 28% | 28% | 28% | 28% |
| 55 - 80 | 35% | 28% | 24% | 24% | 24% | 24% | 24% | 24% | 24% |
| 80 - 100 | 20% | 20% | 20% | 20% | 20% | 20% | 20% | 20% | 20% |
| >100 | 20% | 20% | 20% | 20% | 20% | 20% | 20% | 20% | 20% |

| PGA (%g) | S4L | S4M | S4H | S5L | S5M | S5H | C1L | C1M | C1H |
|---|---|---|---|---|---|---|---|---|---|
| 4 - 8 | 25% | 30% | 30% | 40% | 35% | 35% | 35% | 35% | 35% |
| 8 - 16 | 25% | 30% | 30% | 40% | 35% | 35% | 35% | 35% | 35% |
| 16 - 32 | 21% | 26% | 26% | 36% | 31% | 31% | 31% | 31% | 31% |
| 32 - 55 | 18% | 23% | 23% | 33% | 28% | 28% | 28% | 28% | 28% |
| 55 - 80 | 14% | 19% | 19% | 29% | 24% | 24% | 24% | 24% | 24% |
| 80 - 100 | 10% | 15% | 15% | 25% | 20% | 20% | 20% | 20% | 20% |
| >100 | 10% | 15% | 15% | 25% | 20% | 20% | 20% | 20% | 20% |

| PGA (%g) | C2L | C2M | C2H | C3L | C3M | C3H | PC1 | PC2L | PC2M |
|---|---|---|---|---|---|---|---|---|---|
| 4 - 8 | 50% | 35% | 30% | 40% | 40% | 40% | 50% | 40% | 40% |
| 8 - 16 | 50% | 35% | 30% | 40% | 40% | 40% | 50% | 40% | 40% |
| 16 - 32 | 45% | 31% | 26% | 36% | 36% | 36% | 45% | 36% | 36% |
| 32 - 55 | 40% | 28% | 23% | 33% | 33% | 33% | 40% | 33% | 33% |
| 55 - 80 | 35% | 24% | 19% | 29% | 29% | 29% | 35% | 29% | 29% |
| 80 - 100 | 30% | 20% | 15% | 25% | 25% | 25% | 30% | 25% | 25% |
| >100 | 30% | 20% | 15% | 25% | 25% | 25% | 30% | 25% | 25% |

| PGA (%g) | PC2H | RM1L | RM1M | RM2L | RM2M | RM2H | URML | URMM | MH |
|---|---|---|---|---|---|---|---|---|---|
| 4 - 8 | 40% | 40% | 40% | 30% | 30% | 30% | 50% | 50% | 80% |
| 8 - 16 | 40% | 40% | 40% | 30% | 30% | 30% | 50% | 50% | 75% |
| 16 - 32 | 36% | 35% | 35% | 26% | 26% | 26% | 45% | 45% | 65% |
| 32 - 55 | 33% | 30% | 30% | 23% | 23% | 23% | 40% | 40% | 50% |
| 55 - 80 | 29% | 25% | 25% | 19% | 19% | 19% | 35% | 35% | 35% |
| 80 - 100 | 25% | 20% | 20% | 15% | 15% | 15% | 30% | 30% | 25% |
| >100 | 25% | 20% | 20% | 15% | 15% | 15% | 30% | 30% | 25% |

The effectiveness estimates are similar to those in FEMA 227, with adjustments made by the project team in 1995, based on engineering judgement.

## Table 5.2
## Present Value Coefficients

| | | | | PRESENT VALUE COEFFICIENTS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | DISCOUNT RATE | | | | | | | | | | |
| | 0% | 1% | 2% | 3% | 4% | 5% | 6% | 7% | 8% | 9% | 10% |
| YEARS | | | | | | | | | | | |
| 1 | 1.00 | 0.99 | 0.98 | 0.97 | 0.96 | 0.95 | 0.94 | 0.93 | 0.93 | 0.92 | 0.91 |
| 2 | 2.00 | 1.97 | 1.94 | 1.91 | 1.89 | 1.86 | 1.83 | 1.81 | 1.78 | 1.76 | 1.74 |
| 3 | 3.00 | 2.94 | 2.88 | 2.83 | 2.78 | 2.72 | 2.67 | 2.62 | 2.58 | 2.53 | 2.49 |
| 4 | 4.00 | 3.90 | 3.81 | 3.72 | 3.63 | 3.55 | 3.47 | 3.39 | 3.31 | 3.24 | 3.17 |
| 5 | 5.00 | 4.85 | 4.71 | 4.58 | 4.45 | 4.33 | 4.21 | 4.10 | 3.99 | 3.89 | 3.79 |
| 6 | 6.00 | 5.80 | 5.60 | 5.42 | 5.24 | 5.08 | 4.92 | 4.77 | 4.62 | 4.49 | 4.36 |
| 7 | 7.00 | 6.73 | 6.47 | 6.23 | 6.00 | 5.79 | 5.58 | 5.39 | 5.21 | 5.03 | 4.87 |
| 8 | 8.00 | 7.65 | 7.33 | 7.02 | 6.73 | 6.46 | 6.21 | 5.97 | 5.75 | 5.53 | 5.33 |
| 9 | 9.00 | 8.57 | 8.16 | 7.79 | 7.44 | 7.11 | 6.80 | 6.52 | 6.25 | 6.00 | 5.76 |
| 10 | 10.00 | 9.47 | 8.98 | 8.53 | 8.11 | 7.72 | 7.36 | 7.02 | 6.71 | 6.42 | 6.14 |
| 15 | 15.00 | 13.87 | 12.85 | 11.94 | 11.12 | 10.38 | 9.71 | 9.11 | 8.56 | 8.06 | 7.61 |
| 20 | 20.00 | 18.05 | 16.35 | 14.88 | 13.59 | 12.46 | 11.47 | 10.59 | 9.82 | 9.13 | 8.51 |
| 25 | 25.00 | 22.02 | 19.52 | 17.41 | 15.62 | 14.09 | 12.78 | 11.65 | 10.67 | 9.82 | 9.08 |
| 30 | 30.00 | 25.81 | 22.40 | 19.60 | 17.29 | 15.37 | 13.76 | 12.41 | 11.26 | 10.27 | 9.43 |
| 40 | 40.00 | 32.83 | 27.36 | 23.11 | 19.79 | 17.16 | 15.05 | 13.33 | 11.92 | 10.76 | 9.78 |
| 50 | 50.00 | 39.20 | 31.42 | 25.73 | 21.48 | 18.26 | 15.76 | 13.80 | 12.23 | 10.96 | 9.91 |
| 60 | 60.00 | 44.96 | 34.76 | 27.68 | 22.62 | 18.93 | 16.16 | 14.04 | 12.38 | 11.05 | 9.97 |
| 70 | 70.00 | 50.17 | 37.50 | 29.12 | 23.39 | 19.34 | 16.38 | 14.16 | 12.44 | 11.08 | 9.99 |
| 80 | 80.00 | 54.89 | 39.74 | 30.20 | 23.92 | 19.60 | 16.51 | 14.22 | 12.47 | 11.10 | 10.00 |
| 90 | 90.00 | 59.16 | 41.59 | 31.00 | 24.27 | 19.75 | 16.58 | 14.25 | 12.49 | 11.11 | 10.00 |
| 100 | 100.00 | 63.03 | 43.10 | 31.60 | 24.50 | 19.85 | 16.62 | 14.27 | 12.49 | 11.11 | 10.00 |
| 1000 | 1000.00 | 100.00 | 50.00 | 33.33 | 25.00 | 20.00 | 16.67 | 14.29 | 12.50 | 11.11 | 10.00 |

## 5.4 Statistical Value of Life

For the purposes of benefit-cost analysis it is necessary to place a statistical value on deaths and injuries so that casualties avoided can be valued in monetary terms. For these Portland calculations, we used the following values for statistical casualties:

| | |
|---|---|
| deaths | $2,200,000 |
| minor injury | $1,250 |
| major injury | $12,500. |

These values are based on those used in the FEMA benefit-cost methodologies[1,2], adjusted for inflation to 1995 values.

The original sources and a discussion of the statistical value of life is contained in Chapter 4 of FEMA 258[2].

## 5.5 Interpretation of Benefit-Cost Results: Uncertainty

### 5.5.1 Major Sources of Uncertainty

Benefit-cost analysis of seismic retrofit projects requires estimates of future damages, losses and casualties, both before and after retrofit. There are always significant uncertainties in the seismic hazard curve (probabilities of damaging ground motions), significant uncertainties in the estimated seismic vulnerability of buildings before and after retrofit and significant uncertainties in casualty estimates. There may also be uncertainties in many of the other data inputs required for benefit-cost analysis. Therefore, benefit-cost results are never exact numbers but rather are best estimates, based on the input data. Interpretation of benefit-cost results must consider the validity and accuracy of the input data and assumptions and the resulting uncertainty in numerical benefit-cost results.

The four major sources of uncertainty in benefit-costs results are 1) seismic hazard curves, 2) building fragility curves before retrofit, 3) building fragility curves after retrofit, and 4) relationships between building damages and casualties. Each of these sources of uncertainty is discussed below.

#### Seismic Hazard Curves

There is always significant uncertainty in seismic hazard curves, especially for moderate seismic hazard areas. Uncertainty about the size and frequency of future earthquakes arises because of incomplete geologic, tectonic, and seismologic understanding and is amplified by the long recurrence intervals between major earthquakes and thus the limited historical record of seismic activity. Further uncertainty in ground motions from a given earthquake arises because of uncertainty in attenuation relationships and site characteristics. Especially for moderate seismicity areas with relatively short historical records such as Portland, the overall uncertainty in seismic hazard curves may be a factor of two or more. Numerical benefit-cost results are linearly proportional to expected annual probabilities (the expected annual number) of earthquakes and are thus also subject to uncertainties of a factor of two or more.

However, uncertainties in seismic hazard curves have virtually no affect on the relative seismic vulnerability of building classes or on the relative degree of life safety posed by existing buildings. Thus, conclusions drawn about the relative degree of life safety posed by different building classes as a function of site type (rock, firm soil, soft soil) do not depend on uncertainties in seismic hazard curves. Furthermore, uncertainties in seismic hazard curve are symmetric; that is, while the actual seismic hazard might be a factor of two lower than our best, currently-available estimates, it might also be a factor of two higher. Therefore, uncertainty in seismic hazard curves does not appreciably affect the key public policy decisions about life safety risk posed by existing buildings. The best public policy decision is based on the best-available seismic hazard estimates.

### Building Fragility Curves Before Retrofit

Building fragility curves are estimated based on a combination of damage patterns experienced in past earthquakes and engineering judgements. There is significant uncertainty in the specific numerical amounts of damage expected for a given building class, but estimates generally agree to within 25% or 50%. Thus, uncertainties in building fragility curves are generally much smaller than uncertainties in seismic hazard curves. Moreover, there is a broad consensus in the engineering community about the relative fragility of different building classes. Thus, there is generally agreement that, for example, unreinforced masonry buildings and precast concrete buildings are highly vulnerable to seismic damages while concrete shear wall buildings with ductile detailing are much less vulnerable. Although uncertainty in building fragility curves may significantly affect numerical benefit-cost results, the affect of this uncertainty on the relative seismic vulnerability of different building classes is much smaller.

### Building Fragility Curves After Retrofit

Similarly, there is significant uncertainty in estimating building fragility curves after retrofit (or equivalently, estimating the effectiveness of a retrofit). As with the uncertainties in estimating building fragility curves before retrofit, this uncertainty is generally quite a bit smaller than that associated with seismic hazard curves. Again, conclusions drawn about the relative seismic vulnerabilities of a building before and after retrofit are much more robust and solid than are specific numerical fragility curve estimates. Furthermore, there is a firm consensus that major structural retrofits will prevent the collapse of buildings, to the design level of ground shaking, and thus be highly effective in reducing deaths. Thus, for life safety retrofits, the conclusion that nearly all deaths will be avoided appears sound. Thus, the uncertainty in building fragility curves has much less effect on life-safety benefit estimates than on non-life safety benefits.

### Casualty Rates

Relationships between building damage states and estimated casualty rates are subject to considerable uncertainty because of the limited data base of earthquake deaths and injuries in the United States. Uncertainties in death rates of a factor of two or three are possible, within the limitations of current knowledge. To put this uncertainty in perspective, however, it is important to note that the estimated death risk rates per 100,000 occupants for buildings in Portland vary by factors of more than 4,000 between unreinforced masonry buildings on soft soil sites and steel frame buildings with concrete shear walls on rock sites. The variation in life safety risk would be even greater if building types such as wood frame buildings which pose even less life safety risks were considered. Thus, once again, conclusions about the relative life safety risk posed by classes of buildings are robust, even if estimates of the actual casualty rates are subject to significant uncertainty. For example, the conclusion that certain classes of buildings, such as unreinforced masonry buildings, pose the greatest life safety risk in Portland are very solid.

When all of the uncertainties are combined, numerical benefit-cost results for seismic retrofits in moderate-seismicity areas may be subject to uncertainties of a factor of two or three. However, a great deal of this uncertainty in absolute benefit-cost results has little or no effect on the relative results of different classes of buildings located on different types of sites (rock, firm soil, soft soil). Thus, our conclusions about the relative extent of life safety risk posed by classes of existing buildings (e.g., Table 6.1 in Volume One) and our conclusions about the relative life-safety benefits of retrofits compared to typical costs for various levels of occupancies (Table 7.2 in Volume One) are robust, not withstanding the inherent uncertainties.

### 5.5.2 Interpretation of Benefit-Cost Results

Benefit-cost results are never exact, rather they help to separate prospective seismic retrofit projects into broad classes. Thus, four retrofit projects for different building classes on soft soil sites in Portland might have life safety benefits which are 300% of costs, 30% of costs, 3% of costs and 0.3% of costs. The relative differences between such projects are clearly delineated, even allowing for the substantial uncertainty. Given limited resources, focusing retrofits on the classes of buildings with benefit-cost ratios of 3 clearly makes much more sense than focusing on those with benefit cost ratios of 0.03!

At the other extreme, three retrofit projects might have benefits which are 98%, 100% and 102% of costs, respectively. Clearly, such projects are indistinguishable based on the uncertainties. Thus, such results should not be over-interpreted. Rather, the conclusion that for all of these buildings the benefits and costs of retrofit are similar is justified. An intermediate case would be where a series of projects differ by 10% or a few tens of percent in benefit-cost ratios. Such projects, may or may not be distinguishable, depending on the specific data used for the benefit-cost calculations.

In conclusion, even with all of the uncertainties, benefit-cost analysis is a powerful tool to help separate those classes, locations and occupancies of buildings where benefits are large compared to costs from those where benefits are small compared to costs. Thus, prioritization of retrofits in Portland based on the numerical results presented in Volume One would be almost certain to target those classes, locations and occupancies of buildings where the life safety risks are highest and thus to target those buildings where the benefits of life safety seismic retrofits are highest.

## 5.6 References

1. Federal Emergency Management Agency, "A Benefit-Cost Model for Seismic Rehabilitation of Buildings, Volume 1: A User's Manual, Volume 2: Supporting Documentation," FEMA 227 and FEMA 228, 1992.

2. Federal Emergency Management Agency, "Seismic Rehabilitation of Federal Buildings: A Benefit-Cost Model, Volume 1: A User's Manual, Volume 2: Supporting Documentation," FEMA 255 and FEMA 256, 1994.