# 5 RISK ASSESSMENT APPROACH

This section describes the risk assessment approach used for modeling losses due to ground shaking, ground failure, and the combination of ground shaking and ground failure.

## 5.1 Ground Shaking Damage

Damage to the 32 basic prototypical building variants due to ground motions from an IBC Design Level earthquake was estimated using the HAZUS Advanced Engineering Building Module (AEBM). It should be noted that the HAZUS model for estimating damage due to ground shaking does not consider multiple foundation types; the default configuration is a shallow foundation (e.g., spread footings). It is assumed that building performance of other foundation types subject to ground shaking would be similar.

This study made use of HAZUS, Hazards US, a loss modeling tool developed by the Federal Emergency Management Agency. This is the first time HAZUS has been used as a tool for creating land use regulations relative to seismically induced ground failure. However, HAZUS has been used widely for the development of planning scenarios that are then used for development of ordinances, capital improvement projects, and changes in operation to mitigate seismic risk. One example of a major earthquake scenario was developed for a magnitude 6.7 earthquake on the Seattle Fault by a team organized by the Earthquake Engineering Research Institute and the Washington State Emergency Management Division. HAZUS was also used as a basis for estimating losses due to a magnitude 7.8 earthquake on the southern section of the San Andreas Fault.

HAZUS is also widely used to assess earthquake and flood risks as part of the development of Hazard Mitigation Plans (HMPs) required by FEMA for communities seeking reimbursement for damage following hazard events. Cities and counties throughout the US have adopted these HMPs.

HAZUS AEBM results include estimates of daytime and nighttime casualties defined by HAZUS according to four severity levels (FEMA/DHS, 2003, Chapter 13):

- Severity 1 – “Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness.”

- Severity 2 – “Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are: third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration or exposure.”

- Severity 3 – “Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.”

- Severity 4 – “Instantaneously killed or mortally injured.”

For summary purposes, total casualties are reported as the sum of all four severity levels, with deaths (Severity 4) also reported separately.

Other AEBM results include estimates of dollar loss due to building damage (structural and non-structural damage), damage to building contents and commercial inventories, and building damage-related income or business interruption losses, including the cost of relocation, lost rental income, lost business income, and lost wages.

## 5.2 Ground Failure Fragilities

HAZUS is primarily designed to estimate losses due to ground shaking, and not ground failure. This section describes the process used to estimate losses due to ground failure.

Within the HAZUS methodological framework, there are five potential damage states (None, Slight, Moderate, Extensive, Complete), which are applicable to the building’s structural and non-structural components. Each structural or non-structural damage state is qualitatively described for each model building type within the HAZUS Earthquake Model Technical Manual (DHS/FEMA, 2007). For example, structural damage state descriptions are provided in terms of expected structural damage mechanisms:

> **Steel Moment Frame Structures (S1) - 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. (DHS/FEMA, 2007)

> **Reinforced Concrete Moment Frame Structures (C1) - 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. Approximately 13 percent (low-rise), 10 percent (mid-rise) or 5 percent (high-rise) of the total area of C1 buildings with Complete damage is expected to be collapsed. (DHS/FEMA, 2007)

The sum of the probabilities of being in each of these five damage states must equal 100 percent. For example for a “typical” vulnerable building subjected to very low ground motion, the distribution might be: None – 90 percent, Slight – 10 percent, Moderate – 0 percent, Extensive – 0 percent, and Complete – 0 percent. If the same building was subjected to very strong ground motion, the damage state probability distribution might be: None – 10 percent, Slight – 10 percent, Moderate – 20 percent, Extensive – 30 percent, and Complete – 30 percent.

For the determination of economic loss, structural and non-structural damage state probabilities are multiplied by an assumed mean percent loss for each component’s damage state. In general, “Complete” damage is expected to result in the total economic loss of the structure (i.e., the expected value of damage approaches the value of the structure). “Extensive” damage is expected to be repairable, but at a significant cost (e.g., on the order of 40 - 50 percent of replacement cost).

Discussion in the HAZUS Technical Manual of the topic of building damage due to ground failure is limited; there are only 1-1/2 pages of discussion on the topic in the 75 page chapter on Building Damage (Chapter 5). Regarding ground failure damage estimates employed within the HAZUS model, the Technical Manual (pp 5-64) states ”No attempt is made to distinguish damage based on building type, since model building descriptions do not include foundation type.” The HAZUS methodology has been used as the starting point in development of the ground deformation fragilities in this project. Accordingly, this project did not use HAZUS to directly estimate ground failure impacts on buildings.

As described in Section 5.5.1 of the HAZUS Technical Manual, the median and 10th percentile values of displacement (see below, from HAZUS TM Table 5.17) effectively define structural fragility functions for the “Extensive” and “Complete” damage states, for buildings on shallow foundations. (Ground failure is not expected to produce “Slight” or “Moderate” damage).

> 10 percent - PGD 2” V, 12” H – 8 percent buildings – extensive damage; 2 percent buildings – complete damage
>
> Median – PGD 10” V, 60” H – 40 percent buildings – extensive damage; 10 percent - complete damage

From these fragility curves, damage state probabilities for these two damage states may be determined for any level of PGD. For the current study, PGDs in the IBC Design Level earthquake have been developed as a vector combining horizontal and vertical displacements. The vector resulting from combining horizontal and vertical displacements used in HAZUS is less than 2 percent larger than the horizontal component. That is, the horizontal component is much larger than the vertical component. Thus, the horizontal component has been used in the current study.

In the graben zone and in the pressure ridge zone, it is likely that the vertical component of displacement (subsidence and uplift respectively) will be larger than the horizontal component. However, there is considerable uncertainty in calculating the width of the graben and pressure ridge areas. Because the fragilities need to be applicable across the entire zone, the ground deformation analysis was performed for the overall hazard zone, where the largest component of the deformation is horizontal due to the lateral movement of the block towards the bluff. (See Figure 1.2.)

The fragilities were developed taking into account the following three factors:

1. Foundation type – will affect the ability of the foundation to accommodate horizontal and vertical differential movement.

2. Building height– will affect the stability of the building if subjected to a vertical offset though the foot print (taller buildings would also tend to have a large footprint), and will affect the opportunity to repair the building if subjected to PGD.

3. Building structural system – more ductile structural systems would tend to have a lower percentage of buildings suffering compete damage, as compared to brittle structural systems, if the foundation suffers differential movement.

The median PGD values are used with a lognormal standard deviation value of 1.2 for buildings on shallow foundations. Shallow foundations are taken to be spread footings with grade beams. Comparable damage to buildings on heavy mat foundations is not expected to occur until the PGD is on the order of 5 times greater than that for spread footings with grade beams. It is expected that the mat foundations will carry differential vertical and horizontal displacements. Failure would not occur until the building tips or rotates. The difference between the expected performance of the two foundations is qualitative and was based on expert engineering judgment but did not involve any structural analysis.

Mid-rise buildings are taken to be the baseline for this study. Low-rise buildings are expected to perform better than mid-rise buildings requiring 1.5x the median PGD to result in the same level of damage. Similarly, high-rise buildings are expected to have comparable damage when undergoing 0.67x the median PGD. This is applicable to buildings both on spread footings and mat foundations.

Buildings of differing structural systems on spread footings with grade beams are expected to perform differently when subjected to the same level of PGD. The default assumption used by HAZUS to differentiate between "Extensive" and "Complete" damage was an 80 percent/20 percent distribution. This is the "baseline" applied to wood frame buildings in the current study. It is expected that relatively fewer steel frame buildings (both braced steel frame and moment frame buildings) will suffer "Complete" damage, with an assumed distribution of 90 percent "Extensive" and 10 percent "Complete" (50 percent less "Complete"). Concrete frame, concrete shear wall, and masonry buildings are expected to perform relatively worse, with an assumed distribution of 60 percent "Extensive" damage and 40 percent "Complete" damage (2x more "Complete" damage). This differentiation relates to the capability of the structure to hold together and resist collapse.

All building structure types are expected to perform similarly when constructed on a heavy mat foundation; the baseline 80 percent/20 percent distribution is applied across all structure types when built on mat foundations.

These fragility relationships were developed based on expert opinion from three project team members, as listed below. To the best of the project team's knowledge, there is no other ongoing work in this technical area (as per discussions with building officials with the cities of Seattle and San Francisco). It is understood that there is a high level of uncertainty associated with these relationships. Observation of buildings subjected to PGD would seem to provide the best source of information for supporting the assumed fragility relationships. Each of the team members has extensive experience in post earthquake reconnaissance, particularly in the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes. The three contributors are:

- Paul Summers, SE – MMI Engineering
- Charles Kircher, SE – Charles Kircher and Associates
- Donald Ballantyne, PE – MMI Engineering

It should also be noted that there was not complete concurrence among the contributors on the final fragility relationships. However, the items where there was disagreement tended to be insignificant relative to the overall methodology, and the application of the fragilities was evaluated using sensitivity analyses.

## 5.3 Ground Failure Damage

Damage to the full set of 64 prototypical buildings due to ground failure in the IBC Design Level earthquake was estimated in a customized spreadsheet model. Ground failure fragilities, as described above, were combined (according to the HAZUS ground failure estimation methodology) with ground failure probabilities by Hazard Zone (as documented in Seismic Displacement Technical Memorandum, Appendix D) to arrive at building-specific damage state probabilities. The ground failure damage state probability distributions were then used to estimate the same damage and loss measures utilized in the HAZUS AEBM.

The probability of failure of buildings was evaluated as a function of PGD. These probabilities were related to Hazard Zones by the distribution of PGDs within each hazard zone. A building with the same design parameters subjected to 12 inches of PGD would have the same probability of extensive damage whether it was in Hazard Zone 2 or Hazard Zone 5.

## 5.4 Combined Damage due to Ground Shaking and Ground Failure

As in the HAZUS methodology (see Section 5.6.3 of the HAZUS Technical Manual), it has been assumed for this study that damage due to ground shaking is independent of damage due to ground failure. To find the total damage, and avoid double-counting, the combined damage state probabilities are determined using standard probability theory for independent events and are used to estimate the same damage and loss measures utilized in the HAZUS AEBM.