Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation

Third Edition

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FEMA

THIRD EDITION
Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation

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Preface

In 2011, the Applied Technology Council (ATC), with funding from the Federal Emergency Management Agency (FEMA) under Task Order Contract HSFEHQ-08-D-0726, commenced a series of projects (ATC-71-4, ATC-71-5, and ATC-71-6) to update the FEMA 154 Report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook* (FEMA, 2002a) and the FEMA 155 report, *Rapid Visual Screening of Buildings for Potential Seismic Hazard: Supporting Documentation* (FEMA, 2002b). The purpose of FEMA 154 and the accompanying FEMA 155, which were developed by ATC under contract to FEMA (ATC-21 Project) and published in 1988, was to provide a methodology to evaluate the seismic safety of a large inventory of buildings quickly and inexpensively, with minimum access to the buildings, and determine those buildings that require a more detailed examination. In 2002, FEMA 154 and FEMA 155 were updated to create a *Second Edition*, based on (1) experience from the widespread use of the original FEMA 154 by federal, state, and municipal agencies and others; (2) new knowledge about the performance of buildings during damaging earthquakes; (3) new knowledge about seismic hazards; and (4) other then-new seismic evaluation and performance prediction tools, such as the FEMA 310 report, *Handbook for the Seismic Evaluation of Buildings - A Prestandard* (FEMA, 1998).

Since the publication of the second edition of FEMA 154 and FEMA 155, there have been several initiatives that have advanced the state-of-the-art in rapid visual screening of buildings for seismic risk. One of these was the development of FEMA P-154 *Rapid Observation of Vulnerability and Estimation of Risk* (ROVER) software for use on smart phones (FEMA, 2014), which enables users to document and transmit data gathered in the field. The rapid visual screening application of ROVER is based on the second edition of FEMA 154 and incorporates several improvements made possible by the electronic calculation capability of the device (e.g., site-specific determinations of the seismic shaking hazard). In addition, users in Oregon and Utah have made some modifications to their application of the FEMA 154 screening process in the course of performing extensive seismic screenings of schools and other buildings.

The objective of the *Third Edition* remains the same as its predecessors: to identify, inventory, and screen buildings that are potentially hazardous. This third edition of the FEMA P-155 provides the technical basis for the rapid visual screening procedure documented in the third edition of the FEMA P-154 (FEMA, 2015), which includes the following enhancements:

- Update of the Data Collection Form, and the addition of an optional more detailed page to the form,
- Update of the Basic Scores and Score Modifiers,
- Update of the ground motion definitions,
- Preparation of additional reference guides,
- Inclusion of additional building types that are prevalent,
- Inclusion of additional considerations, such as nonstructural hazards, existing retrofits, building additions, and adjacency,
- Addition of an optional electronic scoring methodology, and
- Additional information on how to run an effective screening program.

Note that per FEMA's current report numbering system, the third editions of FEMA 154 and FEMA 155 are now referred to as FEMA P-154 and FEMA P-155, respectively.

ATC is indebted to the leadership of Bret Lizundia, Project Technical Director, and to the members of the ATC-71-4, ATC-71-5, and ATC-71-6 Project Teams for their efforts in developing this updated *Supporting Documentation.* The Project Technical Committee, consisting of Michael Griffin, William Holmes, Brian Kehoe, Keith Porter, and Barry Welliver, managed and performed the technical development efforts. Updated scores were developed by Charles Kircher. Sarah Durphy, as a Project Working Group member, provided special assistance in the development of the updated *Handbook.* Andrew Bishop, Brian Kehoe, and Scott Hiner prepared the illustrations for the report. Nicolas Luco and Kenneth Rukstales prepared the seismicity maps in the document. The Project Review Panel, consisting of Charles Scawthorn (chair), Timothy Brown, Melvyn Green, Laura Kelly, Stephanie King, John Osteraas, Steven Sweeney, and Christine Theodoropoulos, provided technical review, advice, and consultation at key stages of the work. A workshop of invited experts was convened to obtain feedback on the updated *Handbook*, and input from this group was instrumental in shaping the final methodology and report. The names and affiliations of all who contributed to this report are provided in the list of Project Participants.

ATC also gratefully acknowledges Michael Mahoney (FEMA Project Officer), Mai Tong (FEMA Task Monitor), Erin Walsh (FEMA Task Monitor), and John Gillengerten (FEMA Technical Monitor) for their input and guidance in the preparation of this document. Ayse Hortacsu and Thomas McLane managed the project and Amber Houchen and Peter N. Mork provided report production services.

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Chapter 1

Introduction

1.1 Overview, Purpose, and Target Audience

The FEMA P-154 report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, (FEMA, 2015) describes a rapid visual screening (RVS) procedure for identifying those buildings that might pose serious risk of loss of life and injury when a damaging earthquake occurs due to collapse. The *Handbook* provides detailed guidance on what rapid visual screening is and how to conduct it effectively. This report provides the technical basis for the method.

> The RVS procedure utilizes a methodology based on a "sidewalk survey" approach that involves:
>
> - identification of the primary seismic force-resisting system and building materials,
> - assignment of a Basic Score, which relates to the probability of the building collapse for a specified earthquake recurrence interval, and
> - assignment of Score Modifiers that relate to significant seismic-related defects the screener may observe.
>
> Application of the procedure results in a ranking of surveyed buildings, which may be divided into two categories: (1) those acceptable as a risk to life safety, or (2) those that may be seismically hazardous and should be analyzed in more detail by a professional engineer experienced in seismic design.
>
> The RVS procedure was developed for a wide range of screeners including civil engineers, structural engineers, architects, design professionals, building officials, construction contractors, firefighters, architectural or engineering students, or other individuals with general familiarity or background in building design or construction.

Similar to the first and second editions of FEMA 154 and FEMA 155 (FEMA, 1988a,b and 2002a,b), two documents have been created for the *Third Edition*, in part because it is anticipated that there will be two different target audiences. FEMA P-154 is written for those who will screen buildings and for those policy makers tasked with determining what type of screening program to implement. FEMA P-155, on the other hand, is written for those who want to understand the details and assumptions that underlie the methodology and how Basic Scores and Score Modifiers were calculated.

A key goal in the third edition of FEMA P-155 is to provide sufficient information and clarity that a knowledgeable professional with some basic understanding of statistics, the capacity spectrum method, and fragility curves would be able to independently calculate the Basic Scores and Score Modifiers and arrive at the same answer as those contained in the *Handbook*.

This report also provides background on issues that were considered in the *Third Edition* update, and why key choices were made. Comparisons of scores between the *Second Edition* and *Third Edition* are provided.

1.2 Impetus for Updating the FEMA 154 *Handbook*

Since the publication of the second edition of FEMA 154, there have been several initiatives that have advanced the state-of-the-art in rapid visual screening of buildings for seismic risk.

Much has been learned over the last decade about the expected seismic performance of existing buildings, including new knowledge gained on a broad range of task order projects conducted under FEMA and National Earthquake Hazards Reduction (NEHRP) projects. These efforts provide insight into how observable building characteristics, such as vertical and plan irregularities, as well as other conditions, such as pounding, affect the seismic performance of buildings.

In addition, in the course of performing extensive seismic screenings of schools and other buildings in Oregon and Utah, some modifications to the FEMA 154 screening procedures were found desirable. These programs provided insight into improving the technical basis of the FEMA 154 methodology, as well as recommendations for improving the management and implementation of an RVS program. Details regarding these programs are provided in FEMA P-154 Chapter 5.

Finally, the development of FEMA P-154 *Rapid Observation of Vulnerability and Estimation of Risk* (ROVER) software (FEMA, 2014) for use on smartphones inspired the optional electronic scoring methodology presented in FEMA P-154. FEMA P-154 ROVER, which is based on the second edition of FEMA 154, enables users to document and transmit data gathered in the field and incorporates several tools made possible by the electronic calculation capability of the device (e.g., site-specific determinations of the seismic shaking hazard).

Updates to FEMA 154 chosen to be implemented were limited to those that would not change the unique and important role of FEMA 154 in the broad spectrum of seismic evaluation tools. The *Third Edition* remains a rapid visual screening tool, accessible to a broad audience of engineers, architects, building owners, state legislatures, city councils, private companies, facility managers, and the general public. Any individual with a general familiarity or background in building design or construction (including architects, design professionals, building officials, construction contractors, facility managers, firefighters, architectural or engineering students, and others) can be trained to perform screenings.

1.3 Technical Approach

The third edition update of FEMA P-154 occurred over the course of three years. In the first year, the project team:

- performed an extensive literature and research review that focused on RVS programs conducted since 2002, existing RVS procedures throughout the world, and new knowledge gained since 2002 about how a variety of building characteristics affect seismic performance;

- developed a draft rapid visual screening methodology;
- benchmarked the draft rapid visual screening methodology; and
- developed an outline for the third edition of FEMA P-154.

In the second year, the project team:

- developed a draft third edition of FEMA P-154;
- conducted a workshop to solicit feedback on the updated Handbook;
- completed a 95% draft of third edition of FEMA P-154; and
- completed a preliminary draft of the third edition of FEMA P-155.

In the third and final year, the project team:

- recalculated the Basic Scores and Score Modifiers using the most current information;
- conducted trial runs with the updated Basic Scores and Score Modifiers; and
- completed the final version of third edition of FEMA P-154 and FEMA P-155 reports.

1.4 Organization of this Report

This report documents the efforts undertaken to update the second edition of FEMA 154 and the technical basis for the updates. Chapter 2 describes the revisions that were considered and decisions reached. Chapter 3 describes the effort undertaken to update the building classification system. Chapter 4 describes the impetus for updating the *Second Edition* scores, and describes the methodology used to develop the *Third Edition* scores. Chapter 5 provides a comprehensive description of the steps and assumptions used to develop the *Third Edition* scores, including example calculations, and provides the results. Detailed information and assumptions used in the calculations are located in Appendix A. Chapter 6 describes the treatment of pounding in the *Third Edition*. Chapter 7 describes the treatment of building additions in the *Third Edition*. Chapter 8 discusses the risk associated with the RVS Score and introduces a new frequency-based risk score. Chapter 9 provides the technical background on the electronic scoring methodology. Chapter 10 describes the benchmarking studies that were conducted of the updated RVS methodology. References cited within this report are provided at the end of this report.

Chapter 2
Revision Considerations and Decisions

2.1 Introduction

For the third edition update of FEMA P-154, the project team sought to incorporate technical and practical lessons learned since the publication of the second edition of FEMA 154 in 2002. It was found that FEMA 154 fills a unique and important role in the broad spectrum of seismic evaluation tools. Accordingly, updates were limited to those that would preserve this role. As such, FEMA P-154 remains a rapid visual screening tool, accessible to a broad audience of engineers, architects, building owners, state legislatures, city councils, private companies, facility managers, and the general public. Any individual with a general familiarity or background in building design or construction (including architects, design professionals, building officials, construction contractors, facility managers, firefighters, architectural or engineering students, and others) can be trained to perform screenings.

The following sections provide a summary of the updates considered by the project team and describe those that were included in the third edition update.

2.2 Paper or Electronic Form

With the increasing use of computers and smartphones, the project team explored the option of an electronic form in lieu of the paper form used in the second edition of FEMA 154. However, in order to keep FEMA P-154 accessible for everyone, the paper form is retained as the primary screening tool. An optional electronic scoring methodology has been developed and is described in the *Handbook,* and additional details are provided in Chapter 9 of this document.

2.3 Reorganization of the Data Collection Form

The Data Collection Form used for rapid visual screening has been extended with an optional second page, where the first page represents a Level 1 screening and the second page represents an optional Level 2 screening. The Level 1 screening is similar to the procedure used in the second edition of the

Handbook, with the same objectives and same general level of expertise required from screeners.

The Level 1 screening form was reorganized so that data collection is concentrated towards the top of the page. Administrative fields, such as screener name and building address, are at the very top, followed by fields that describe attributes of the buildings, such as number of stories, year built, and soil type. The calculation of RVS score occurs in the middle of the page, and, finally, fields that document the extent of review and resulting action required are located at the bottom of the page.

The elimination of the sketch field was given detailed consideration, particularly as it increases the time required to complete the screening and many screeners do not have experience drawing plan and elevation sketches. However, the sketch field has been retained because the act of drawing a sketch may help the screener to better observe the building and enable the screener to note important features, such as levels where pounding may occur. The availability of a sketch will also help in the quality control process. A more detailed discussion of how to use the sketch field has been added to Chapter 3 of FEMA P-154.

Separating information that could be obtained during pre-field data collection, such as liquefaction potential, from information that can be determined in the field, such as falling hazards, was considered. However, it was found that too many items could be determined either way to make it practical to create such a separation. Instead, information was grouped by topic, allowing the screening process to flow more naturally to the final answer (i.e., whether Detailed Structural Evaluation and Detailed Nonstructural Evaluation are required.)

2.4 Optional Level 2 Form

The Level 2 screening is more detailed than the Level 1 screening, and the qualification requirements for the Level 2 screener are higher than those for the Level 1 screener. The Level 2 form is designed to take advantage of the added experience of the screener to determine a more accurate, less conservative score by allowing the Level 2 screener to apply more specific modifiers for vertical and plan irregularities, pounding, and existing retrofits.

2.5 Scoring Update

An important part of the *Third Edition* update was the development of updated Basic Scores and Score Modifiers. Chapters 4 and 5 describe the impetus for this scoring update, together with the methodology and assumptions, and detailed results are provided.

2.6 Ground Motions

The project team was faced early on with deciding what ground motions to consider in the *Third Edition*. Ground motions are continually evolving, and the time span between the publication of the *Second Edition* and the *Third Edition* was no exception. During this time, risk-targeted Maximum Considered Earthquake (MCE_R) ground motions were developed and adopted by ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010), replacing the uniform hazard Maximum Considered Earthquake (MCE) ground motions used in earlier versions of ASCE/SEI 7, ASCE/SEI 41, and the second edition of FEMA 154.

The older uniform seismic hazard maps of MCE specified shaking that had a 2% chance of being exceeded in 50 years. The risk-targeted ground motion maps take into account regional differences in the shape of the seismic hazard curve. The distinction between the MCE and MCE_R is that a risk-targeted design aims for a consistent probability of life-threatening damage during a particular period of time, as opposed to a consistent probability of damage given a single, particular level of shaking. MCE_R ground motions are higher than MCE in California and are generally smaller than MCE in other parts of the United States (Chapter 22 of ASCE/SEI 7-10).

ASCE/SEI 41-13, *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE, 2014), considers additional hazard levels, such as 5% in 50-year and 20% in 50-year ground motions. The project team considered using these ground motions in the *Third Edition*; however, the team decided that because FEMA P-154 is focused on assessing risk of collapse (rather than other performance objectives, such as life safety), the larger MCE_R ground motions, which are more often associated with collapse assessments, are more appropriate.

Within ASCE/SEI 41-13, MCE_R ground motions are referred to as "BSE-2N." These are the ground motions that users of *Third Edition* FEMA P-154 are directed to consider when determining a building's seismicity region, and they are the same as the ground motions in ASCE/SEI 7-10.

For calculations used to develop Basic Scores and Modifiers, the *Second Edition* used 2/3 of the MCE values. In the *Third Edition*, the demand is based on the full value of MCE_R. Use of the full value was found to produce a better correlation with the *Second Edition* Basic Scores and Modifiers and permit retaining the same cut-off score of S = 2.0. Note that the current version of FEMA P-154 *Rapid Observation of Vulnerability and Estimation of Risk* (ROVER) software, Version 2 (FEMA, 2014), is based on ground motions from the *Second Edition*.

2.7 Seismicity Regions

In the first and second editions of FEMA 154, the United States was divided into three seismicity regions (Low, Moderate, and High), with the High seismicity region representing a large range of seismicity. The scoring update provided the opportunity to subdivide the High seismicity region further to improve accuracy. A total of five seismicity regions are used in the *Third Edition*. This is described in more detail in Chapters 4 and 5.

2.8 Default Soil Type

In the second edition of FEMA 154, the Basic Scores assume Soil Type B, and Score Modifiers are provided for Soil Types C, D, and E. The most typical soil conditions, however, are Soil Type C and Soil Type D. Accordingly, the *Third Edition* Basic Scores are based on an average of Soil Type C and D, which is referred to as Soil Type CD. The difference between Soil Type C and CD or between Soil Type D and CD is small. Modifiers are provided to adjust from this average soil type to Soil Type B and to Soil Type E. This is believed to be a more accurate way than always adjusting from stiffer soil to softer soil as was necessary in the *Second Edition*.

2.9 Addressing Negative Scores

Feedback obtained during the literature and research review phase of the project included criticism that the RVS methodology can result in negative scores. Negative scores imply that the probability of collapse is greater than 100%, which is not possible. The following four approaches were considered for addressing this issue:

1. Revise the definition of the score, *S*, to be based on frequency of collapse, rather than probability of collapse.
2. Keep the current definition of the score, *S*, permit negative scores, but explain how frequency of collapse can be derived from *S*.
3. Keep current definition of the score, *S*, but require scores less than zero to be truncated at zero.
4. Keep the current definition of the score, *S*, but perform calculations assuming the worst combination of building characteristics to establish a minimum score. This rectifies the overly conservative approach of

linearly combining the various Score Modifiers and eliminates the possibility of negative scores.

The project team decided to use the fourth approach for determination of Final Scores. The score calculated from the worst combination of Score Modifiers is called the Minimum Score, S_{MIN}. In addition, a Risk Score, S_R, is defined in FEMA P-155 Chapter 8 that relates to the frequency of collapse, which can help to inform risk-management decisions. The relationship between S and S_R is described in detail in Chapter 8.

2.10 Inclusion of W1A and MH Building Types

FEMA Building Types W1A (multistory, multi-unit wood frame residential building) and MH (manufactured housing) have been added.

W1A buildings are similar in construction to W1 buildings, but are larger in plan and multistory. Many of these buildings are constructed with open front garages or commercial space at the first story, creating a potential irregularity. It was important to include the W1A building type because of what has been learned about the vulnerability of W1A buildings with open fronts (e.g., tuckunder buildings).

Manufactured housing is part of a larger class of prefabricated structures that includes modular buildings. Mobile home is an older term for a manufactured home, though mobile home remains in widespread use. It was important to include the MH building type because of its extensive use as housing. Approximately 7% of the housing units in the United States in 2008 were mobile homes (United States Census Bureau, 2014). They are also used as relocatable classrooms.

Typically, the RVS score is related to the risk of collapse and the related risk to life. The superstructure of the MH building type rarely collapses, but the buildings do fall off their supports, which can cause significant financial damage, fire following earthquake, and some risk to life. It was discussed whether applying an RVS score to MH is appropriate, given that the typical type of damage is different from other building types. It was decided to include the MH building type so that communities looking at large portfolios of buildings will be able to get a better indication of seismic risk.

The MH scores are developed using *Multi-hazard Loss Estimation Methodology, Earthquake Model, HAZUS-MH MR4 Technical Manual* (FEMA, 2009a). The methodology, referred to in this document as "HAZUS methodology," calculates probability of collapse using the spectral displacement of the roof. For MH, the primary mode of failure is falling off the support, so spectral roof displacement is less relevant. It was concluded, however, that this mode of failure is similar to the failure of W1 cripple walls and that the HAZUS methodology provided the most effective means to determine the FEMA P-154 scores for MH.

2.11 Update of Occupancy Classes

Utility and warehouse categories have been added to the occupancy class selections on the Data Collection Form. A field has been added to note the number of residential units, where applicable.

"Historic" and "Government" fields have been separated from the occupancy class. A "Shelter" field has been added based on user request to indicate when a building is intended for use as an emergency shelter. These three descriptors are now used as occupancy designation checkboxes.

The entry for occupancy load has been removed, because it was burdensome to calculate this value in the field, and the possibility of a wide range of estimates resulted in limited value. Additionally, occupancy load, if desired, can be easily calculated at a later time using the occupancy class and building area. It does not need to be calculated in the field.

2.12 Treatment of Vertical and Plan Irregularities

Feedback on the second edition of FEMA 154 included criticism that the vertical irregularity modifiers were overly severe. To address this, vertical irregularities have been separated into "Severe" and "Moderate" irregularities to reduce the penalty when only moderate irregularities exist. Appendix B of the updated *Handbook* includes reference guides to help screeners determine vertical and plan irregularities consistently and to reduce ambiguity.

2.13 Consideration of Geologic Hazards

Geologic hazards do not affect the Final Score; however, if there is risk of landslide, liquefaction, or surface rupture, the building should be referred for a Detailed Structural Evaluation. Without a Detailed Structural Evaluation, it will not be possible to determine with certainty that a building subject to one of these geologic risks is not seismically hazardous. If the existence of such hazards cannot be determined during preplanning activities, the screener is directed to ignore them because assuming they exist would be overly conservative and could potentially send whole portfolios of buildings without geologic hazard mapping to Detailed Structural Evaluations.

2.14 Consideration of Pounding

Pounding potential is an observable condition that can significantly affect the seismic performance of a building and should be captured by the rapid visual screening procedure. Within the Level 1 screening, if risk of pounding (as defined in the Pounding Reference Guide in Appendix B of FEMA P-154) is observed, a Detailed Structural Evaluation is triggered. Within the Level 2 screening, pounding is incorporated into the score with a negative modifier.

Six pounding conditions were identified; however, these were narrowed down to three easily observable conditions for the RVS procedure. For example, adjacent buildings with different floor levels are considered, but adjacent buildings with different floor masses are not, as this is difficult to determine during a rapid visual screening. Chapter 6 describes the treatment of pounding in the *Third Edition*.

2.15 Consideration of Building Additions

Guidance on screening buildings with additions has been expanded. The recommended RVS approach is carefully described in Chapters 3 and 4 of FEMA P-154, in the Level 1 and Level 2 Building Additions Reference Guides in Appendix B of FEMA P-154, and in the detailed discussion in Chapter 7 of this report.

2.16 Consideration of Damage and Deterioration

Significant damage and deterioration affect the seismic performance of a building. If there is significant damage or deterioration, such as extensive dry rot, corrosion, or concrete spalling, the building should be referred to a Detailed Structural Evaluation. Specific signs of damage or deterioration that might be observed during a rapid visual screening are discussed in in Chapter 3 of FEMA P-154 and in Appendix F of FEMA P-154.

2.17 Consideration of Retrofits

The treatment of buildings with existing retrofits was specifically considered. There was concern that a screener might believe a building has been retrofitted, when the upgrades are either only architectural or only mitigate a local hazard (such as the addition of parapet bracing). For this reason, the issue of retrofits is not addressed on the Level 1 form. The Level 2 screener is given the option of applying a retrofit modifier, but only if the retrofit is comprehensive (i.e., the full seismic force-resisting system has been strengthened).

2.18 Screener Qualifications and Supervising Engineer

The second edition of FEMA 154 noted that screening could be conducted by "informed, appropriately trained, members of the public." In the *Third Edition*, the following definition for Level 1 screeners was developed in an attempt to balance the benefits of keeping the pool of potential screeners as wide as possible with the desire to have screeners who can, with training, accurately identify FEMA Building Type and building characteristics to obtain accurate RVS scores:

> *"Structural engineer, architect, design professional, building official, construction contractor, facility manager, firefighter, architectural or engineering student, or another individual with a general familiarity or background in building design or construction."*

The second edition of FEMA 154 noted that all RVS programs should be overseen by a design professional knowledgeable in seismic design for quality assurance purposes. In addition, knowledge gained from RVS programs conducted since 2002 emphasized the need for oversight by a "Supervising Engineer" with specific qualification requirements and responsibilities. In the *Third Edition*, the importance of the Supervising Engineer is emphasized, and the qualifications and responsibilities of the Supervising Engineer are explicitly defined. Of key importance to the Supervising Engineer's responsibility is determining the code and benchmark years for the jurisdiction being screened.

2.19 Rapid Visual Screening in Low Seismicity

The project team discussed whether it is appropriate to screen buildings in Low Seismicity regions when even brand new buildings in these areas have limited seismic design requirements. It was decided to keep the Low seismicity form, so that FEMA P-154 screenings can be performed anywhere in the country. The *Handbook* recommends that screening in these areas focus on the most significant hazards, such as finding URM bearing wall buildings or unbraced URM parapets. The pounding criteria on the Low seismicity form are revised (the required separation is lower in Low seismicity areas).

2.20 Underlying Performance Objective

The project team considered updating the FEMA P-154 methodology to consider additional performance objectives, but decided to keep the focus of the previous editions of determining the probability of collapse or partial collapse. To understand the meaning of the Final Score, it was necessary to decide how the *Third Edition* should define the probability of collapse or partial collapse. HAZUS uses collapse probability differently than FEMA P-695 (FEMA, 2009b), and the two definitions produce significantly different values of the Final Score. FEMA P-154 Chapter 1 provides a general definition of collapse probability used. Chapter 4 of this report describes the issue in more technical detail. See Figure 4-1 for examples of collapse and partial collapse.

2.21 Using FEMA P-154 on High Importance Buildings

Application of the FEMA P-154 methodology to buildings of high importance, such as hospitals, was considered. The focus of the RVS procedure is collapse. Where higher performance is desired, such as continued functionality in a hospital, an alternate, more detailed evaluation should be performed.

2.22 Screening for Nonstructural Hazards

Additional guidance was added to the *Handbook* for Level 1 screening of nonstructural hazards. Creation of a scoring system for nonstructural hazards was considered, but not pursued. The Level 2 form presents nonstructural statements not contained on the Level 1 form. Building characteristics that will not be easily visible, such as pipe and duct bracing, and stair seats, were not included. Also, in order to limit the extent of effort and time required to obtain access to ceilings or mechanical rooms, questions regarding sprinkler bracing, unanchored life safety equipment, unbraced ceilings or heavy ceilings, were not included in the Level 2 form.

2.23 Update of FEMA P-154 ROVER

FEMA P-154 ROVER Version 2 is based on the second edition of FEMA 154. A project to update FEMA P-154 ROVER for the changes made in the third edition of FEMA P-154 is not currently planned. It is recommended the reader check the website (www.roverready.org) for the latest version of FEMA P-154 ROVER software.

RVS Programs can still use FEMA P-154 ROVER, but they will need to do so using the *Second Edition* methodology. Users will need continued access to the second edition of FEMA 154.

Chapter 3

Building Classification

3.1 Introduction

Urban communities are made up of many different types of structures, which are generally designed to withstand a prescribed set of environmental loads. If the actual loads are greater than the prescribed set, damage can occur, to an extent that depends on several engineering characteristics. Among the main engineering characteristics affecting the extent of damage are construction material and seismic force-resisting system. A building classification system helps to identify a building's earthquake-resistant characteristics, and thus the expected performance during earthquake shaking. *Third Edition* updates to the FEMA P-154 building classification system and occupancy classes (referring to building use) are discussed below.

3.2 Building Classification Systems in Previous Editions of FEMA 154

The first edition of the FEMA 154 *Handbook* (FEMA, 1988a) for rapid visual screening defined a building classification system that consisted of one type of wood structure, five types of steel structures, three types of concrete structures, and four other types of structures. Table 3-1 provides the building classification systems used in the *First Edition*.

Table 3-1 FEMA 154 (First Edition) Building Classifications

W	Wood frame buildings
S1	Steel moment-resisting frame buildings
S2	Braced steel frame buildings
S3	Light metal buildings
S4	Steel frame buildings with cast-in-place concrete shear walls
C1	Concrete moment-resisting frame buildings
C2	Concrete shear wall buildings
C3/S5	Concrete or steel frame buildings with unreinforced masonry infill walls
PC1	Tilt-up buildings
PC2	Precast concrete frame buildings
RM	Reinforced masonry
URM	Unreinforced masonry

The second edition of FEMA 154 expanded the number of building types to make it consistent with FEMA 178 (FEMA, 1992), its successor FEMA 310, *Handbook for the Seismic Evaluation of Buildings – A Prestandard* (FEMA, 1998), and other FEMA documents, such as the FEMA 273, *NEHRP Guidelines for the Seismic Rehabilitation of Existing Buildings* (FEMA, 1997), and FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (FEMA, 2000). The building classification system adopted for the second edition of the FEMA 154 *Handbook* is listed in Table 3-2.

Table 3-2 FEMA 154 (Second Edition) Building Classifications

W1	Light wood frame residential and commercial buildings smaller than or equal to 5,000 square feet
W2	Light wood frame buildings larger than 5,000 square feet
S1	Steel moment-resisting frame buildings
S2	Braced steel frame buildings
S3	Light metal buildings
S4	Steel frames with cast-in-place concrete shear walls
S5	Steel frame buildings with unreinforced masonry infill walls
C1	Concrete moment-resisting frame buildings
C2	Concrete shear wall buildings
C3	Concrete frame buildings with unreinforced masonry infill walls
PC1	Tilt-up buildings
PC2	Precast concrete frame buildings
RM1	Reinforced masonry buildings with flexible floor and roof diaphragms
RM2	Reinforced masonry buildings with rigid floor and roof diaphragms
URM	Unreinforced masonry bearing wall buildings

The *Second Edition* building classification system:

- included the building types defined in the classification system from the first edition of FEMA 154;
- expanded the *First Edition* list to include two types of wood frame buildings:
    - W1: light wood frame, residential and commercial buildings smaller than or equal to 5,000 square feet; and
    - W2: light wood frame buildings larger than 5,000 square feet;
- separated C3 buildings (concrete frame buildings with unreinforced masonry infill walls) and S5 buildings (steel frame buildings with unreinforced masonry infill walls) into two separate types; and

- subdivided the RM building type (reinforced masonry) into two types, one with flexible diaphragms and one with rigid diaphragms (other building types were not subdivided into subclasses reflecting flexible or rigid diaphragms in the floors and roof).

3.3 *Third Edition* Updates to the Building Classification System

The third edition of FEMA P-154 adopted the term "FEMA Building Type." There are 17 FEMA Building Types in the *Third Edition*, including the 15 used in the *Second Edition*, W1A (multi-unit, multi-story residential wood frame buildings) and MH (manufactured housing). The descriptions of FEMA Building Types in the *Third Edition* have also been updated to reflect the language of ASCE/SEI 31-03, *Seismic Evaluation of Existing Buildings* (ASCE, 2003), ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings* (ASCE, 2007), and ASCE/SEI 41-13, *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE, 2014).

W1A buildings are residential multi-story, similar in construction to W1 buildings, but have plan areas on each floor greater than 3,000 square feet. Older construction often has an open front or garage at the lowest story. The W1A building type was included because of their higher occupancy levels and the observed vulnerability of W1A buildings with open fronts (e.g., tuckunder buildings) in the 1989 Loma Prieta and 1994 Northridge earthquakes.

The manufactured housing building type is part of a larger class of prefabricated structures that includes modular buildings. The MH building type includes manufactured homes that are built in a factory on a permanent chassis and transported to the site. Mobile home is an older term for a manufactured home, though the term mobile home remains in widespread use. The focus for screening this building type is on buildings that are mobile, raised up off the ground, not anchored to the ground, and may or may not have an earthquake-resistant bracing system (ERBS). The MH building type was included because of their extensive use as housing and as relocatable school classrooms.

Construction and installation requirements for manufactured housing are addressed by varying entities. Several of the principal organizations and standards include:

- U.S. Department of Housing and Urban Development HUD 24CFR Part 3280;

- 2012 *International Building Code* Appendix G Flood Resistant Construction (ICC, 2012a);
- 2012 *International Residential Code* Appendix E Manufactured Housing used as Dwellings (ICC, 2012b); and
- State agencies such as State of California, Department of Housing and Community Development (HCD) policies and construction standards.

The first three principally address flood and wind loading; earthquake resistance is not treated as thoroughly. However, the State of California HCD does specifically address earthquake loading in their policies and construction standards.

It is important to be able to differentiate between a Manufactured Housing ground or tie-down strap system and an earthquake-resistant bracing system. The former is a requirement for flood and wind loading, and is not specifically engineered for resisting earthquake loads. Figure 3-1 shows two examples of typical ground anchor strap systems used for flood and wind resistance.

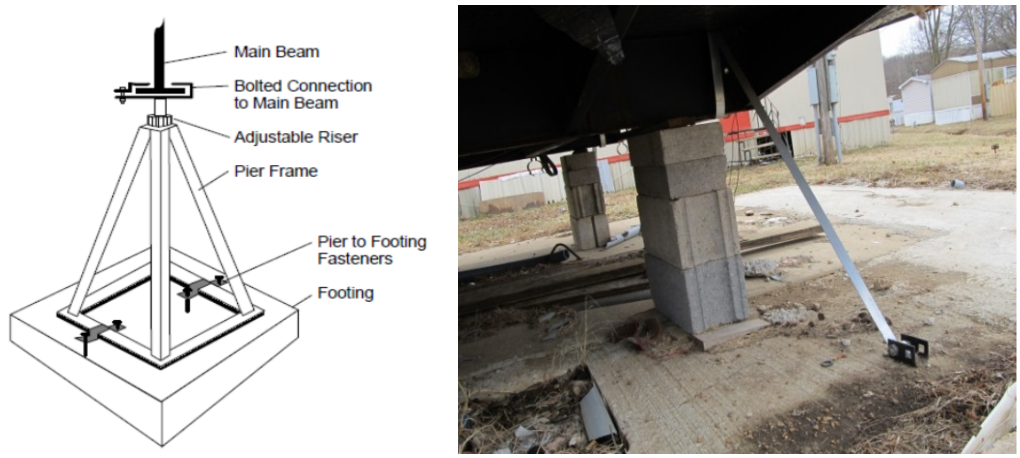


Figure 3-1 Examples of flood and wind tie-down systems for manufactured housing.

Earthquake-resistant bracing systems are engineered to resist earthquake forces. These types of systems may take many forms from a complete foundation perimeter or pony wall system very similar to a standard wood frame home on an engineered cripple wall to post installed units positively attached directly to the carriage and foundation system. A post-installed unit is illustrated in Figure 3-2. ERBS generally have increased structure, foundation and attachment detailing over the more simple straps and minimal attachments used in a typical flood/wind tie-down system.

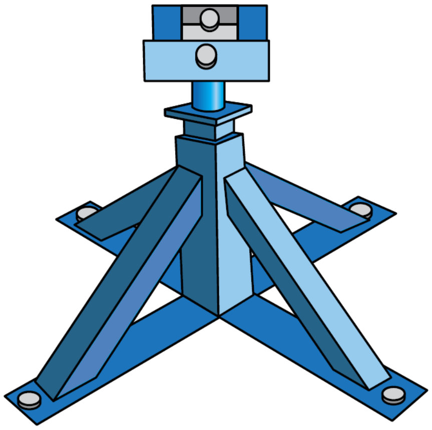


Figure 3-2 Illustration of an earthquake-resistant bracing system.

Identifying the type of restraint system for a manufactured housing unit can be difficult due to perimeter cosmetic coverings or skirts that conceal the underside of the carriage. Skirt construction may be corrugated metal or fiberglass material to match the siding, or built-up 2x4 framing and wood siding for pony-wall systems. Access hatches or skirt vent systems should be identified during the field review that may allow visual review of the under-carriage area to identify the anchoring system being used. Figure 3-3 shows photographs of two types of skirt construction.

Figure 3-3 Photographs of a metal skirt and pony-wall perimeter covering systems.

The 17 FEMA Building Types considered in the third edition of the FEMA P-154 *Handbook* are listed in Table 3-3.

3.4 Occupancy Classes

The occupancy classes defined in the second edition of FEMA 154 and listed on the *Second Edition* forms (shown in Table 3-4) were reviewed along with the Occupancy Groups defined in the 2012 *International Building Code*, and

Table 3-3 FEMA P-154 (*Third Edition*) Building Types

W1	Light wood frame single- or multiple-family dwellings of one or more stories in height
W1A	Light wood frame multi-unit, multi-story residential buildings with plan areas on each floor of greater than 3,000 square feet
W2	Wood frame commercial and industrial buildings with a floor area larger than 5,000 square feet. For commercial and industrial buildings with less than 5,000 square feet, the W2 type can be used as well.
S1	Steel moment-resisting frame buildings
S2	Braced steel frame buildings
S3	Light metal buildings
S4	Steel frame buildings with cast-in-place concrete shear walls
S5	Steel frame buildings with unreinforced masonry infill walls
C1	Concrete moment-resisting frame buildings
C2	Concrete shear wall buildings
C3	Concrete frame buildings with unreinforced masonry infill walls
PC1	Tilt-up buildings
PC2	Precast concrete frame buildings
RM1	Reinforced masonry buildings with flexible floor and roof diaphragms
RM2	Reinforced masonry buildings with rigid floor and roof diaphragms
URM	Unreinforced masonry bearing wall buildings
MH	Manufactured housing

the Building Occupancy Classes used in FEMA's multi-hazard loss estimation software, known as HAZUS (FEMA, 2009a). It was seen as particularly important to align the occupancy classes with those in HAZUS, so that results from rapid visual screenings could be more easily imported into HAZUS. The third edition of FEMA P-154 added the following two new occupancy classes to more closely reflect the building occupancy classes used in HAZUS:

- *Utility.* Facilities include buildings for public or private utilities for water, wastewater, power, gas, electric power plants, and substations.
- *Warehouse.* This class includes large warehouses used for storing products, and commercial warehouses where items are sold.

Additionally, the third edition of FEMA P-154 further refines building occupancy into occupancy classes and occupancy designations. The new occupancy designation added in the *Third Edition* includes:

- *Shelter.* This designation includes buildings specifically identified as shelters for post-event occupancy.

Table 3-4 FEMA 154 (*Second Edition*) Building Occupancy Classes

Assembly	Public assembly where 300 or more people gather. Examples include theaters, auditoriums, community centers, performance halls, and churches.
Commercial	Retail and wholesale businesses, financial institutions, restaurants, parking structure and light warehouses.
Emergency Services	Critical facilities including police, fire stations, hospitals, and communication centers.
Government	Local, state and federal non-emergency related buildings.
Historic	Many variations from community to community.
Industrial	Large facilities including factories, assembly plants, large warehouse and heavy manufacturing facilities.
Office	Typical office buildings that house clerical and management functions.
Residential	Houses, townhouses, dormitories, motels, hotels, apartments and condominiums, and residences for the aged or disabled.
School	All public and private educational facilities from nursery school to university level.

Government, Historic and Shelter are defined as occupancy designations in the *Third Edition*. Table 3-5 presents the occupancy classes and occupancy designations for the *Third Edition.*

Table 3-5 FEMA P-154 (*Third Edition*) Building Occupancy Classes and Occupancy Designations

Occupancy Classes	
Assembly	Public assembly where 300 or more people gather. Examples include theaters, auditoriums, community centers, performance halls, and churches.
Commercial	Retail and wholesale businesses, financial institutions, restaurants, parking structure, and light warehouses.
Emergency Services	Critical facilities including police, fire stations, hospitals, and communication centers.
Industrial	Large facilities including factories, assembly plants, and heavy manufacturing facilities.
Office	Typical office buildings that house clerical and management functions.
Residential	Houses, townhouses, dormitories, motels, hotels, apartments and condominiums, and residences for the aged or disabled.
School	All public and private educational facilities from nursery school to university level.
Warehouse	Large warehouses used for product and commercial warehouses. (The *Second Edition* "Industrial" class included large warehouses).
Utility	Water, wastewater, power, gas, and electric facilities. (Captured as "Industrial" class facilities in the *Second Edition*).
Occupancy Designations	
Government	Local, state, and federal non-emergency related buildings.
Historic	Many variations from community to community.
Shelter	Designated shelters or buildings specifically identified as shelters for post-event occupancy (Captured in "Emergency Services" of the *Second Edition*).

3.5 Occupancy Class Mapping

Many RVS Authorities (the entity performing the rapid visual screening program) are interested in importing FEMA P-154 data into HAZUS in order to develop a more robust building data set for the HAZUS risk assessment estimates. However, mapping 12 general categories of occupancy classes and occupancy designations in the third edition of FEMA P-154 into the nearly 100 occupancy classes contained in HAZUS is difficult. The mapping algorithm RedROVER, included in FEMA P-154 *Rapid Observation of Vulnerability and Estimation of Risk* (ROVER) software (FEMA, 2014) for the second edition of FEMA 154, which maps the nine occupancy classes into HAZUS, was used. In addition, the three new occupancy classes and occupancy designations were also aligned with the best match to HAZUS occupancy classes.

Table 3-6 presents the third edition of FEMA P-154 occupancy classes and occupancy designations, possible HAZUS occupancy class designations, and the suggested HAZUS default occupancy classes, if no further information is known regarding the building occupancy.

The HAZUS definitions for the suggested default occupancy classes used are:

- RES1: Single family dwelling or house
- RES3A: Duplex, apartment/condominium
- RES5: Group housing, college dormitories, military housing, jails
- COM1: Commercial retail or trade
- COM2: Wholesale trade, warehouse
- COM4: Professional or technical service offices
- COM9: Theaters
- IND1: Heavy industrial, factory
- GOV1: General services, office
- GOV2: Emergency response, police, fire, emergency operations center
- EDU1: Grade schools

Tables B.3 to B.18 in *Multi-hazard Loss Estimation Methodology, Earthquake Model, HAZUS-MH MR4 Technical Manual* (FEMA, 2009a) provide a complete description of the occupancy classes available within HAZUS.

Table 3-6 FEMA P-154 Occupancy Class HAZUS Mapping

FEMA P-154 Occupancy Classification/Designation	Possible HAZUS Occupancy Classes	Suggested HAZUS Default Occupancy Class
Second Edition		
Residential: - Dwellings - Hotels and Apartments - Dormitories	 RES1, RES2 RES3A-F, RES4, RES5, RES6 RES3A-F	 RES1 RES3A RES5
Commercial	COM1, COM2, COM3, COM5, COM10	COM1
Office	COM3, COM4, COM7	COM4
Industrial	IND1, IND2, IND3, IND4, IND5, IND6, AGR1	IND1
School	EDU1, EDU2	EDU1
Assembly	COM8, COM9, REL1	COM9
Emergency Services	COM6, GOV2	GOV2
Government	GOV1	GOV1
Historic	Any	COM1
Third Edition		
Shelter	EDU1, EDU2, REL1, GOV2 EFSI, EFS2	GOV2
Utility	Varies	IND1
Warehouse	COM1, COM2, IND1, IND2, IND3, IND4, IND5, IND6, AGR1	COM2

3.6 Occupancy Load Determination

The entry for occupancy load, reporting the number of persons in a given square foot of floor area was removed from the Data Collection Form in the third edition of FEMA P-154. Although the accurate estimation of the number of occupants is difficult to obtain in the field, the information is valuable because it can be used for prioritizing a large portfolio of community buildings in a mitigation planning effort. Thus, while the occupancy load information is not recorded on the Level 1 Data Collection Form, the RVS Authority may want to determine the building occupancy load for further prioritization efforts or for additional uses. Table 3-7 presents the third edition of FEMA P-154 occupancy classes and occupancy designations with their respective typical occupancy loads, which may be calculated from the building floor area square footage recorded on the Level 1 Data Collection Form.

Table 3-7 FEMA P-154 Occupancy Load Determination

Residential: - Dwellings - Hotels and Apartments - Dormitories	 1 Person / 300 sq ft 1 Person / 200 sq ft 1 Person / 100 sq ft
Commercial	1 Person / 50 - 200 sq ft
Office	1 Person / 100 - 200 sq ft
Industrial	1 Person / 200 sq ft
School	1 Person / 50 - 100 sq ft
Assembly	1 Person / 10 sq ft
Emergency Services	1 Person / 100 sq ft
Government	1 Person / 100 - 200 sq ft
Historic	Varies greatly
Shelter	1 Person / 50 sq ft
Utility	1 Person / 500 sq ft
Warehouse	1 Person / 100 - 500 sq ft

Chapter 4

Introduction to *Third Edition* Scoring

4.1 Introduction

An important part of the *Third Edition* update of FEMA P-154 is the development of new and improved Basic Scores and Score Modifiers. This chapter describes the impetus for updating the *Second Edition* scores, and describes the general methodology used to develop the *Third Edition* scores. Chapter 5 provides a comprehensive description of the steps and assumptions used to develop the *Third Edition* scores, and the resulting score values.

A key goal of FEMA P-155 is to provide all the information and assumptions needed for a knowledgable professional to calculate Basic Scores and Score Modifiers.

4.2 Review of *Second Edition* Scores

The *Second Edition* scores were developed using the loss estimation methodology documented in *Earthquake Loss Estimation Methodology Technical Manual, HAZUS99 Service Release 2* (FEMA, 2001). The methodology, referred to in this document as "HAZUS methodology," was first released by FEMA in 1997 and has been updated several times. The methodology remains current in *Multi-hazard Loss Estimation Methodology, Earthquake Model, HAZUS-MH MR4 Technical Manual* (FEMA, 2009a), referred to as HAZUS TM.

The basis of the *Second Edition* scores is thoroughly described in the *Second Edition* of FEMA 155. Basic Scores (previously known in the *Second Edition* as "Basic Structural Hazard Scores") and Score Modifiers were developed using capacity and fragility parameters provided in *HAZUS99 Service Release 2*. Engineering judgment was used in some cases, such as for vertical irregularity modifiers.

As part of the *Third Edition* update, the *Second Edition* scores were reviewed considering three criteria:

- Were the values of the Basic Scores and Score Modifiers provided in the *Second Edition* consistent with current engineering judgment?
- Was the development of the *Second Edition* Basic Scores and Score Modifiers consistent with the HAZUS methodology?

- Are there additional Basic Scores and Score Modifiers beyond what was provided in the *Second Edition* that would be beneficial to performing RVS?

Several issues were identified during the review of the *Second Edition* scores prompting the decision to update the scores for the *Third Edition* and ultimately to develop a more comprehensive, current set of scores. The identified issues are described in the following sections.

4.2.1 URM Scoring

During the development of the FEMA P-154 *Rapid Observation of Vulnerability and Estimation of Risk* (ROVER) software (FEMA, 2014) using the *Second Edition* methodology, it was observed that unreinforced masonry (URM) buildings in Low and Moderate seismicity regions sometimes scored higher than other FEMA Building Types. This is due to several factors. One is that the URM Basic Score is relatively close to that of several other FEMA Building Types and higher than a few. For example, in Moderate seismicity, the Basic Score for URM is 3.4 and for C3 (concrete frame with URM infill) it is 3.2. A second factor is that some of the negative Score Modifiers are smaller for URM than for other FEMA Building Types, particularly for vertical irregularities and soft soil. For example, in Moderate seismicity, the URM Vertical Irregularity Score Modifier is -1.5, while it is -2.0 for C3. When multiple modifiers are added linearly, the result is a lower score for FEMA Building Types other than URM.

4.2.2 Negative Scores

Negative scores occur for some combinations of modifiers, indicating a greater than 100% probability of collapse. Individual modifiers are calculated by varying one condition at a time and calculating the change in probability of collapse. When several conditions exist at once, summing the modifiers algebraically can result in a negative score, indicating a greater than 100% probability of collapse, which is not possible.

4.2.3 Beta Values

The set of lognormal standard deviation values (referred to as "beta" values) used in the development of the *Second Edition* scores were included within the HAZUS software at the time and were chosen because they were considered to be more accurate than the values provided in the *Technical Manual* (FEMA, 2001). Subsequently, concerns were identified with the beta values used, and they were removed from the HAZUS software.

Because the beta values were not documented in the *Second Edition* and are no longer publically available, a reader could not reproduce them.

4.2.4 Mid-Rise and High-Rise Modifiers

Second Edition mid-rise and high-rise modifiers are generally positive, indicating a benefit for taller buildings. The benefit is attributed in the *Second Edition* FEMA 155 discussion to the assumption that taller buildings have better designs, as reflected in the HAZUS parameters used in the *Second Edition* calculations. However, in recent earthquakes, low-rise buildings have often performed better than mid-rise buildings.

In the *Second Edition*, soil type and building height are considered with separate modifiers, thus ignoring their interaction. For example, the unique behavior of tall buildings on soft soils and the potential for resonance is ignored.

4.2.5 FEMA Building Types

Two new FEMA Building Types are added in the *Third Edition*: Multistory, multi-unit residential wood frame buildings (W1A) and manufactured housing (MH). New Basic Scores and Score Modifiers are required for these two types.

4.3 Scoring Enhancements for the *Third Edition*

Once the decision was made to update the Basic Scores and Score Modifiers in the *Third Edition*, a host of additional revisions to the RVS scoring basis, including whether to keep scores as part of the RVS procedure, were considered. Because FEMA P-154 is primarily a screening tool (i.e., it separates buildings into two bins: those that require additional detailed evaluation and those that do not), having a system that provides each building with a numerical score increases FEMA P-154's usefulness as a prioritization tool. Accordingly, the use of scores was kept and further, the definition of the score, $S = -\log_{10}$(Probability of Collapse), was not altered.

The following revisions to the RVS scoring basis were identified as desirable.

4.3.1 Ground Motions

The *Third Edition* scores are based on the most current version of risk-targeted Maximum Considered Earthquake (MCE_R) ground motions available from the USGS. As discussed in Chapter 2, the older uniform hazard Maximum Considered Earthquake (MCE) ground motions used in the

Second Edition are replaced in the *Third Edition* with the newer risk-targeted MCE_R ground motions.

Basic Score and Score Modifier values that appear on the *Second Edition* forms were calculated using 2/3 of the MCE values. In the *Third Edition*, the demand is based on the full value of MCE_R. Use of the full value of MCE_R was found to produce a better correlation with the *Second Edition* scores and permit retaining the same cut-off score of S = 2.0. See Chapter 5 for detailed comparisons of *Second Edition* and *Third Edition* scores.

4.3.2 Seismicity Regions

In the first and second editions of FEMA 154, the United States was divided into three seismicity regions (Low, Moderate, and High), with the High seismicity region representing a large range of seismicity. The Low seismicity region also covers a large range of seismicity, including areas of almost zero seismicity. In the *Second Edition*, the median seismicity of the Low region was used to develop Low seismicity scores. The median Low seismicity is so insignificant that probabilities of collapse are effectively zero. The *Third Edition* uses the upper part of the Low seismicity range as the basis, developing more meaningful scores. In addition, the High seismicity region was subdivided to provide further accuracy. A total of five seismicity regions are used in the *Third Edition.*

4.3.3 Default Soil Type

In the second edition of FEMA 154, the Basic Scores assume Soil Type B, and Score Modifiers are provided for Soil Types C, D, and E. The most typical soil conditions, however, are Soil Type C and Soil Type D. Accordingly, the *Third Edition* Basic Scores are based on an average of Soil Type C and D, which is referred to as Soil Type CD. The difference between Soil Type C and CD or between Soil Type D and CD is small. Modifiers are provided to adjust from this average soil type to Soil Type B and to Soil Type E. This is believed to be more accurate than always adjusting from stiffer soil to softer soil, as was necessary in the *Second Edition*.

4.3.4 Vertical and Plan Irregularity Score Modifiers

In the *Second Edition*, Vertical Irregularity Score Modifiers were based on engineering judgment. In High and Moderate seismicity regions, Vertical Irregularity Score Modifiers were assigned values such that, if that were the only modifier selected during the rapid visual screening process, the Final Score, S, would be less than the typical cut-off score of 2.0, thereby triggering a Detailed Seismic Evaluation of the building. In the Low seismicity region, the values assigned were generally comparable to those assigned for the Moderate seismicity region. Plan Irregularity Score Modifiers were developed by assuming an increased seismic load to approximate the effect of plan irregularity. For the third edition of FEMA P-154, the Score Modifiers for plan and vertical irregularity are determined using a procedure developed by the California Office of Statewide Health Planning and Development (OSHPD) that can be used to calculate the collapse probability of buildings considering specific types of plan and vertical irregularities. The details of the procedure are codified within the *California Administrative Code, California Code of Regulations,* (CAC, 2010) Title 24, Part 1, Chapter 6. The procedure's methodology is referred to in this document as the "OSHPD HAZUS methodology."

4.3.5 Minimum Scores

For each FEMA Building Type in each seismicity region, the probability of collapse considering the worst case combination of deficiencies is calculated. This probability of collapse is then converted to a Minimum Score. This Minimum Score is used in the *Third Edition* to avoid negative scores.

4.4 Methodology for Development of *Third Edition* Basic Scores and Score Modifiers

Similar to the *Second Edition*, Basic Scores and Score Modifiers are calculated by determining the probability of collapse, and then converting this to a score, S:

$$S = -\log_{10}(\mathrm{P}[Collapse|MCE_R\ ground\ motions]) \tag{4-1}$$

For the *Third Edition*, the probability of collapse is calculated using a modified version of the OSHPD HAZUS methodology (which is itself a modified version of the HAZUS methodology that was used to develop the *Second Edition* scores). This section first defines collapse for purposes of FEMA P-154, and then presents the method used here to calculate the probability of collapse. The differences between the portfolio analysis of multiple buildings used by HAZUS and the single building evaluation of FEMA P-154 are discussed.

4.4.1 Defining Collapse

To understand the meaning of FEMA P-154 scores, it is first necessary to understand how FEMA P-154 defines collapse probability. Collapse was not formally defined in the first or second editions of FEMA 154. Chapter 1 of the *Third Edition* provides a general definition of collapse where, in a portion of the building or in the entire building, the gravity load-carrying system (its beams, columns, floors, shear walls) loses the ability to carry its own weight and the weight of whatever else it supports. That failure leads to severe structural deformation of a potentially life-threatening nature, especially falling of all or portions of a structure. The word collapse, however, has no formal uniform definition in the relevant literature. From an analytical perspective, structural engineers sometimes treat large displacements or substantial reduction in tangent stiffness estimated during structural analysis to indicate that dynamic instability would occur in the real structural system, but collapse is the instability itself, not the proxy that engineering practitioners and researchers use to estimate it.

Even with the foregoing definition, collapse can reasonably be used different ways to mean different things, and the difference matters here. Five important terms—building collapse, collapsed area, collapsed portion, collapse factor, and collapse probability—related to collapse are discussed in the following sections.

4.4.1.1 Building Collapse

As used here, building collapse means that any part of the gravity system experiences dynamic instability leading to the loss of load bearing capacity. The dynamic instability leads to severe structural deformation of a potentially life-threatening nature, especially falling of all or portions of a structure. Note that, as used here, partial building collapse means that the dynamic instability occurs only in a portion of the building. The probability of at least partial building collapse refers to the expected value of the chance that partial collapse or collapse will occur, given some specified conditions. The conditions used here are knowledge of building features observed during the screening and occurrence of MCE_R shaking.

Some additional detail is required to understand what collapse means for manufactured housing (MH) and wood frame buildings (W1 and W1A). In the case of manufactured housing and wood frame buildings, building collapse also includes the condition that the manufactured home falls off one or more of its supports, or the cripple walls of a wood frame building experience a sidesway mechanism and lose their vertical load-carrying capacity, even if the resulting displacement. Even though this does not necessarily lead to falling of the superstructure, it can pose life safety risks and has often led to fires due to gas line damage. Building collapse does not include wood frame buildings sliding relative to their foundations if there is no vertical drop in any part of the floor or roof. Nor is the falling of a parapet from a URM building or brick veneer or chimney from any FEMA

Building Type considered to constitute building collapse. See Figure 4-1 for examples of collapse and partial collapse.

Figure 4-1 Examples of collapse and partial collapse.

4.4.1.2 Collapsed Area

The collapsed area of a collapsed building is defined here as the total square footage in which there a loss of load bearing capacity leading to severe structural deformation of a potentially life-threatening nature, especially falling of all or portions of a structure. It also includes the area littered with masonry fallen from unreinforced masonry walls or concrete fallen from concrete walls, even if that area is outside the pre-earthquake footprint of the building. It does *not* include the square footage of rooms or floors that fall in a rigid body fashion without deformation, such as the non-collapsed stories of a building that experiences sidesway collapse of one story. Collapsed area is measured in units of area, such as square feet. In the two buildings shown in Figure 4-1, the collapsed area includes the square footage of all the rooms where the floor of the room, the floor above the room, or the roof above the second-floor room, dropped. It also includes the area littered with heavy debris.

4.4.1.3 Collapsed Portion

The collapsed portion of the building is defined as the collapsed area divided by the total square footage of a building, given that the building has experienced partial or complete collapse. The collapsed portion is measured as a unitless fraction.

4.4.1.4 Collapse Factor

The collapse factor is the expected value of collapsed area given that the building is in the HAZUS Complete structural damage state. The difference between collapsed portion and the collapse factor is that collapsed portion is given that the building has experienced partial or complete collapse, and the latter is only given that the building is in the HAZUS Complete structural damage state, which might or might not include any collapse in any given building. The collapse factor will generally be smaller than the collapsed portion, because only some buildings in the HAZUS Complete structural damage state will have any collapse. The collapse factor includes this fraction and the collapsed portion does not.

4.4.1.5 Collapse Probability

As used in FEMA P-154 to calculate scores, collapse probability is defined as the probability that a building will be in the HAZUS Complete structural damage state when subjected to MCE_R shaking, times the collapse factor. The FEMA P-154 collapse probability also equals the probability of at least partial building collapse given that the building is subjected to MCE_R shaking, reduced by expected value of the collapsed portion.

It is important to recognize that the FEMA P-154 collapse probability is smaller than the probability of at least partial collapse given MCE_R shaking by a factor equal to the expected value of the collapsed portion. The expected value of the collapsed portion cannot exceed 1.0. Since it is typically less than 1.0, the FEMA P-154 collapse probability is generally less than the probability of at least partial building collapse.

The calculation of collapse probability is detailed later in Section 4.4.2, but to better understand it, consider two examples.

Example 1

Suppose one were examining an apartment building with tuckunder parking on the ground floor and two stories of living space above, and all three stories have the same plan area of 10,000 square feet each. Suppose in MCE_R ground motion one would expect the following: (1) one of every 10 such buildings to experience some collapse; and (2) the other nine not to collapse, but almost certainly experience complete structural damage. That is, the probability of the building experiencing at least partial collapse is 10%, and the probability of HAZUS Complete structural damage is near 100%. Suppose that if the building collapses, one would expect the ground story to pancake, that is, the whole area of the second floor falls and comes to rest on the ground, but the second and third stories remain generally intact.

In this example, the probability of the HAZUS Complete structural damage state is nearly 100%, and the estimated fraction of the total area in the HAZUS Complete structural damage state that is likely to collapse is 3.3% (10% chance of at least partial collapse times 33% expected value of the collapsed portion). So as used here, the FEMA P-154 collapse probability is $0.1 \times 0.33 = 0.033$, so the FEMA P-154 score $S = -\log_{10}(0.033) = 1.5$.

If the FEMA P-154 collapse probability had been defined as the probability of at least partial collapse, imagined in the example as 10%, the score would have been $S = -\log_{10}(0.1) = 1.0$.

Example 2

Suppose there are 10 buildings all of the same size, and at the MCE_R shaking, there is a 50% probability of being in the HAZUS Complete structural damage state and a collapse factor of 20%, assuming the building is in the HAZUS Complete damage state. The collapse probability is thus estimated to be $0.50 \times 0.20 = 0.10$, and the FEMA P-154 Final Score $S = -\log_{10}(0.1) = 1.0$. There are, however, many scenarios of how this might occur. Four scenarios are described below. In all of these scenarios, five of the 10 buildings or 50% are in the HAZUS Complete structural damage state.

- *Scenario 1:* One of the 10 buildings completely collapses, but none of the other buildings suffer any collapse or partial collapse. The collapse probability is thus (1 building with some collapse / 10 total buildings) × 100% collapsed portion in that building = 0.10 × 1.00 = 0.10.
- *Scenario 2*: Each of two buildings experiences a partial collapse with 50% collapsed portion, and no collapsed area in the other buildings. The collapse probability is thus (2 buildings with some collapse / 10 total buildings) × 50% collapsed portion in each of those buildings = 0.20 × 0.50 = 0.10.
- *Scenario 3:* This is the same as Scenario 2 except that there is a partial collapse involving 5% of the area in one of the buildings and 95% in the

other. The collapse probability is thus (1 building / 10 total) × 0.05 + (1 building / 10 total) × 0.95 = 0.10 × 0.05 + 0.10 × 0.95 = 0.10.

- *Scenario 4:* All five buildings in the complete damage state suffer some amount of partial collapse. In one, only 1% of the area in the building collapses, and the collapsed portion in the others is 9%, 15%, 25%, and 50%, respectively. The collapse probability is 0.10 × 0.01 + 0.10 × 0.09 + 0.10 × 0.15 + 0.10 × 0.25 + 0.10 × 0.25 = 0.10.

There are an infinite number of scenarios in Example 2 that could actually occur and yield the same collapse probability of 0.10. A key difference is that in Scenario 1 only one building suffers any form of collapse, but in Scenario 4, five do. Thus, while the collapse probability as defined here is the same, the number of buildings that suffers some form of collapse differs by a factor of five.

The probability of at least partial collapse is useful in a methodology whose objective is to measure the adequacy of a structural design. The FEMA P-154 definition of collapse probability is more appropriate to a methodology whose objective is to measure life safety, which is the underlying goal of FEMA P-154. With the assumption that the risk to life safety is proportional to being in the collapsed portion of the building (as HAZUS assumes), then the risk of dying in all four of the scenarios in Example 2 is the same, even though the number of buildings with some form collapse or partial collapse differs widely in each scenario.

If it is not known which building a person is in, then the risk of death to a building occupant is the chance of being in any given building, times the probability of dying if one were in that building, summed over all the buildings. Notice that the four scenarios in Example 2 could all reflect the behavior of the same building type with the same features. This means that the FEMA P-154 methodology does not require that all the buildings of a given type and with given features must behave identically.

Comparison to Portfolio Risk Analysis

It is useful to compare portfolio risk analysis (as in HAZUS), and risk analysis of a single building (as in FEMA P-154). Regardless of whether one is evaluating one building, or 10, or 100, the expected value of the performance measure (here, collapse probability) is the same. The reason is that the expected value of a sum of uncertain variables is the sum of the expected values. FEMA P-154 estimates the expected value of the collapsed area of a building subjected to MCE_R shaking. A portfolio risk analysis that calculates the expected value of the total collapsed area of many buildings can do so by calculating the sum of the expected values of the collapsed areas of individual buildings. Thus, it does not matter that HAZUS is a portfolio risk estimation tool and FEMA P-154 applies to single buildings. Portfolio risk analyses differ from analyses of single buildings in the estimation of other important parameter values, such as the uncertainty in collapsed area, but not in the estimation of the expected value of the collapsed area.

For example, if one were performing a portfolio risk analysis of an apartment complex with 10 identical buildings exactly like the one just discussed. Each building has 30,000 square feet of area, for a total of 300,000 square feet in the portfolio. In MCE_R shaking, each has a 10% probability of at least partial collapse, so on average, one would expect one of the 10 buildings to collapse. In that building, one expects the ground floor to pancake. The other buildings are assumed to be in the HAZUS Complete structural damage state. The expected collapsed area is 10,000 square feet out of a total of 300,000 square feet. The FEMA P-154 collapse probability is still 10,000/300,000 = 0.033. Whether one is looking at one building, or 10 identical buildings, or 100 identical buildings, the collapse probability is the same.

In the same portfolio risk analysis, one could alternatively suppose that the 10 buildings are perfectly correlated in their behavior, in which case in one earthquake out of 10 with MCE_R shaking at the apartment complex, all of the buildings collapse onto their parking floor and in the other nine earthquakes, none collapse, but in either case the buildings are almost certainly in the HAZUS Complete structural damage state. Even with this supposition, the collapse probability is the same: 10% chance that any given building collapses, with a collapsed portion of 33%, for a FEMA P-154 collapse probability of 0.033. For purposes of calculating the expected value of the collapsed area, it does not matter if one is performing the calculations on a single building or a portfolio of buildings.

When it comes to the risk to a single person, the portfolio case (like HAZUS) is indistinguishable from the single-building case (like FEMA P-154). But this does not require that every building with a given Final Score is expected to behave identically to every other building with that Final Score. A building with a score of 1.0, for example, could be one with a 10% probability of 100% of its area to collapse (as in the case of a mobile home that either falls off its supports or does not). It could be a URM building with a 20% probability of the exterior bearing walls falling out-of-plane and leading to collapse of half the floor area. Or it could be a building with a 100% probability that 10% of its area will collapse (as in the case of a 10-

story building with a weak story irregularity that is almost certain to experience sidesway collapse at the weak story).

As a final point, although the portfolio-based HAZUS approach to defining collapse probability was used in the *Second Edition* and continued in the *Third Edition*, rapid visual screening in FEMA P-154 focuses on the individual building, rather than on a portfolio analysis. While the statistics and examples above mathematically imply that in theory every building in a HAZUS Complete structural damage state could suffer some form of partial collapse, this is not a likely scenario and should not be taken as a literal estimate of the percentage of square feet of partial collapse in an individual building. Rather, the *S* score is a helpful quantitative metric based on collapse potential that is useful in assessing and ranking buildings for potential seismic hazards.

4.4.2 Calculating Probability of Collapse with HAZUS Methodology

This section introduces the process for calculating probability of collapse using the HAZUS methodology.

The method includes three distinct parts: (1) calculation of peak response (i.e., peak displacement for evaluation of damage to the structure) of the building for a given set of ground motions (e.g., MCE_R response spectral accelerations); (2) calculation of the probability of complete damage given the peak response; and (3) calculation of probability of collapse given the probability of complete damage.

Properties are provided for 35 different combinations of building type and height, known within HAZUS as "Model Building Types" or MBTs.

4.4.2.1 Part 1: Response Calculation

HAZUS methods are used to calculate the peak response of the building by finding the intersection of the building capacity curve (a plot of a building's lateral load resistance as a function of a characteristic lateral displacement) and the demand spectrum of earthquake ground motions. This method is illustrated in Figure 4-2 for two capacity curves and three example demand spectra. In this illustration, the demand spectra represent what can be considered as weak, medium, and strong ground shaking, and the two building capacity curves represent weaker and stronger construction. Different colors along the capacity curves correspond to the range of displacements associated with each of the four discrete states of structural damage (slight, moderate, extensive, and complete).

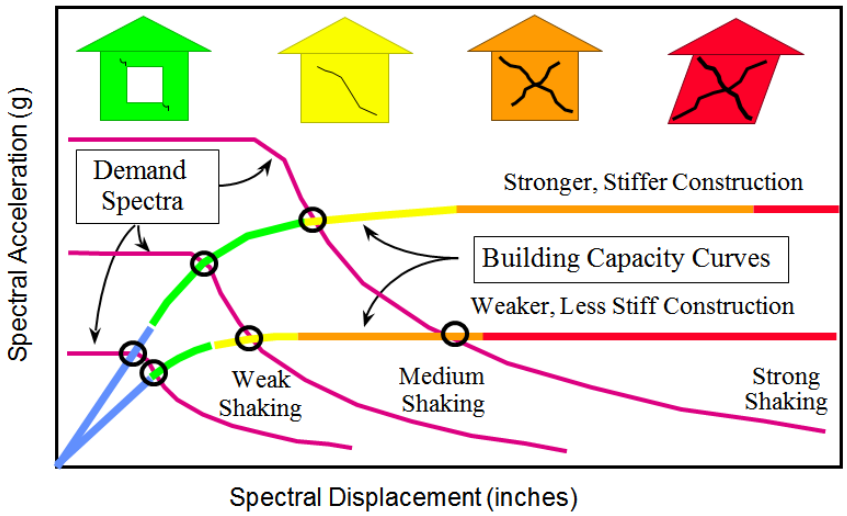


Figure 4-2 Example intersection of demand spectra and building capacity curves.

As shown in Figure 4-2, stronger and stiffer construction displaces less than weaker and less stiff construction for the same level of shaking. As seen in the color bands of the capacity curves in Figure 4-2, for similar displacement, the more ductile construction (i.e., construction with long green, yellow, and orange bands) will be in a less severe structural damage state than the less ductile construction (i.e., construction with short green, yellow, and orange bands). Therefore, for similar levels of shaking, the stronger and more ductile building will have less structural damage than the weaker, less ductile building.

The building capacity curve is a plot of a building's lateral load resistance as a function of a characteristic lateral displacement (i.e., a force-deflection plot). It is derived from a plot of static-equivalent base shear versus building displacement at the roof, known commonly as a pushover curve. In order to facilitate direct comparison with spectral demand, base shear is converted to spectral acceleration, and the roof displacement is converted to spectral displacement using modal properties that represent pushover response. Building capacity curves are constructed from values of the design coefficient, C_s, and other HAZUS capacity parameters as shown in Figure 4-3.

The capacity curve is defined by two control points: (1) the yield capacity point (D_y, A_y); and (2) the ultimate capacity point (D_u, A_u). The yield capacity represents the lateral strength of the building at initial yield and accounts for design strength, redundancies in design, conservatism in code requirements and expected (rather than nominal) strength of materials. The structure is assumed to be fully elastic up to the yield capacity point. The

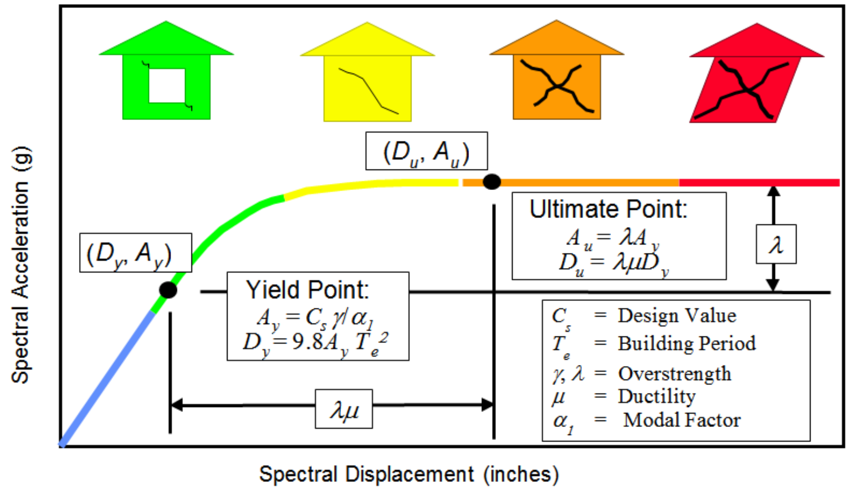


Figure 4-3 Example building capacity curve and control points.

ultimate capacity represents the displacement at which the full strength of the building is reached considering additional sources of overstrength.

Beyond the ultimate capacity point, the HAZUS method assumes the capacity curve is fully plastic (i.e., constant strength). Between the yield point and the ultimate point, the capacity curve is assumed to have an elliptical shape that is tangent to the elastic segment at yield capacity point and tangent to the plastic segment at the ultimate capacity point, which may be expressed as follows:

$$\frac{(D-D_u)^2}{a^2}+\frac{(A-k)^2}{b^2}=1 \qquad (4\text{-}2)$$

where the values of a, b, and k are given by the following equations:

$$a=\sqrt{\frac{D_y}{A_y}b^2\frac{(D_u-D_y)}{(A_y-k)}} \qquad (4\text{-}3)$$

$$b=A_u-k \qquad (4\text{-}4)$$

$$k=\frac{A_u^2-A_y^2+\frac{A_y^2}{D_y}(D_y-D_u)}{2(A_u-A_y)+\frac{A_y}{D_y}(D_y-D_u)} \qquad (4\text{-}5)$$

In reality, the red portion of the capacity curve does not continue as a flat line indefinitely. Loss of strength and a corresponding drop in the curve is expected. For analysis purposes, however, the HAZUS method assumes the structure maintains constant strength beyond the complete damage state.

The demand spectrum is constructed from the 5%-damped response spectrum of MCE_R ground motions by reducing spectral response for effective damping greater than 5% damping. The amount of effective damping is a function of the inherent elastic damping of the Model Building Type of interest and additional energy dissipated during post-yield, inelastic response, considering possible degradation of the structure during repeated cycles of inelastic response.

The 5%-damped response spectrum is reduced at each period by factors, R_A, in the acceleration domain and, R_V, in the velocity domain, as illustrated in Figure 4-4. Note that in Figure 4-4, spokes from the origin represent lines of constant period. As described previously, the intersection of the demand spectrum and the capacity curve define the point of peak building response (*D, A*).

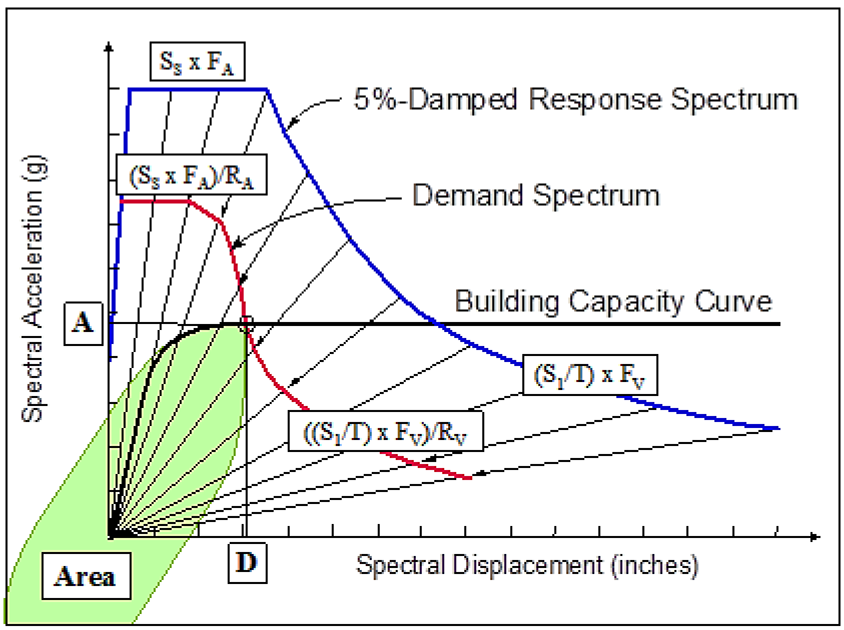


Figure 4-4 Example calculation of demand spectrum by reduction of 5%-damped response spectrum of ground motions.

The reduction factors, R_A and R_V, are a function of the effective damping, β_{eff}, due to the combined effects of elastic damping, β_E, and hysteretic damping, β_H, associated with the non-degraded portion of the area of the hysteresis loop shown in green in Figure 4-4. The values of reduction factors, R_A and R_V, are given in the following equations:

$$R_A = \frac{2.12}{3.21 - 0.68\ln(\beta_{eff})} \quad (4\text{-}6)$$

$$R_V = \frac{1.65}{2.31 - 0.41\ln(\beta_{eff})} \tag{4-7}$$

where the value of effective damping, β_{eff}, is given by the following equation:

$$\beta_{eff} = \beta_E + \beta_H = \beta_E + \kappa \frac{Area}{2\pi D A} \tag{4-8}$$

In Equation 4-8, the degradation factor, κ, describes the non-degraded fraction of the area of the hysteresis loop, and is function of the duration of earthquake shaking (i.e., the longer the shaking duration, the greater the degradation). Since the area of the hysteresis loop increases as (post-yield) response increases, values of reduction factors, R_A and R_V, are inherently amplitude dependent.

In certain cases where the effects of degradation are modest (e.g., larger values of κ), post-yield (inelastic) displacements of demand spectrum calculated using the HAZUS reduction factors, R_A and R_V, as defined by Equations 4-6 and 4-7, can be somewhat less than the elastic displacement, D_e, the value of capacity spectrum at the elastic period, T_e. Conceptually, inelastic displacements should not be less than the elastic displacement (i.e., based on the "equal displacement" rule attributed to Newmark). For development of Basic Scores (and Score Modifiers), the displacement D of the demand spectrum is, in all cases, taken as not less than the elastic displacement, D_e.

4.4.2.2 Part 2: Probability of Complete Damage State

HAZUS building fragility curves are lognormal probability functions that describe the likelihood of reaching, or exceeding, discrete states of structural and nonstructural damage, given an estimate of peak building response (e.g., the spectral displacement calculated in Section 4.4.2.1). The fragility curves take into account the variability and uncertainty associated with capacity curve properties, damage states, and ground shaking.

Development of Basic Scores and Score Modifiers only requires the fragility curve for the Complete damage state. Complete damage indicates that the structure is in imminent danger of collapse or has collapsed.

Figure 4-5 provides an example of HAZUS fragility curves for Slight, Moderate, Extensive, and Complete structural damage states, respectively, and illustrates differences in damage state probabilities for three levels of spectral response corresponding to weak, medium, and strong earthquake ground shaking, respectively. The terms "weak," "medium," and "strong" are used here for simplicity, but may be thought of representing different intensities of MCE_R ground motions.

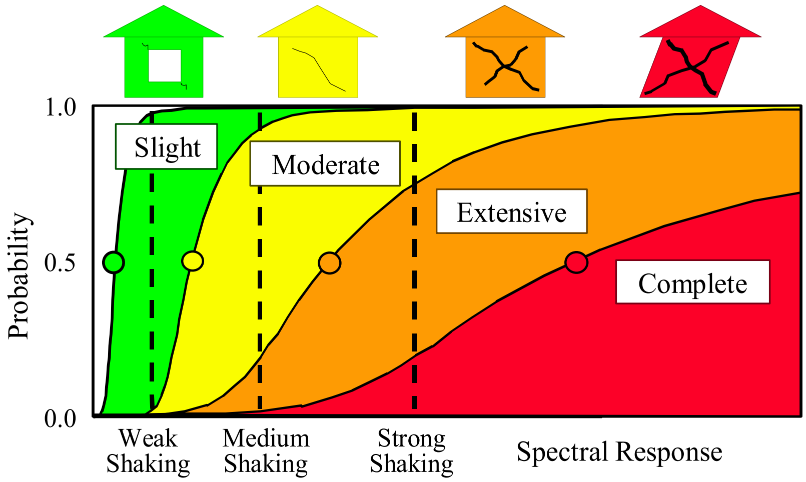


Figure 4-5 Example fragility curves for Slight, Moderate, Extensive and Complete structural damage.

Each fragility curve is defined by a median value of the demand parameter that corresponds to the threshold of that damage state and by the total variability associated with that damage state. The demand parameter is spectral displacement, $S_{d,ds}$, for the structure, and is the product of the story drift ratio, Δ_{ds}, associated with the damage state of interest, building height, H_R (in inches), and the ratio of modal parameters, α_2/α_3, where α_2 is the modal height factor and α_3 is the modal shape factor relating maximum-story drift and roof drift. Median values of fragility curves are based on observations of damage in past earthquakes, laboratory tests of structural components and systems, and engineering judgment.

The median value of spectral displacement, S_d, of the Complete structural damage state is given by the following equation:

$$S_{d,C} = \Delta_C H_R (\alpha_2 / \alpha_3) \qquad (4\text{-}9)$$

Lognormal standard deviation values, $\beta_{S,ds}$, describe the total variability of fragility-curve damage states. Three primary sources contribute to the total variability of any given state, namely, the variability associated with the capacity curve, the variability associated with the demand spectrum, and the variability associated with threshold of the damage state. Uncertainty due to damage-state threshold is assumed to be independent of other sources of uncertainty. However, demand and capacity curve uncertainties are not independent for the structure and their combined effect on total damage-state variability is a function of response, in particular post-yield response.

The beta values given in HAZUS TM are intended primarily for use with deterministic (scenario earthquake) ground motions. As such, the variability associated with the demand spectrum includes so-called record-to-record variability not included in the calculation of deterministic ground motions.

Using the values of $S_{d,C}$ and $\beta_{S,C}$ provided in HAZUS TM and the peak response, D, determined in Section 4.4.2.1, the probability of complete damage is calculated as:

$$P\left[Complete\,Damage\right] = \varphi\left[\frac{1}{\beta_{S,C}}\ln\left(\frac{D}{S_{d,C}}\right)\right] \qquad (4\text{-}10)$$

4.4.2.3 Part 3: Probability of Collapse

Once the probability of complete damage has been determined, the probability of collapse can be calculated by applying a collapse factor.

$$P\left[COL\right] = P\left[COL|Complete\,Damage\right] \times P[Complete\,Damage] \qquad (4\text{-}11)$$

where:

$$P\left[COL|Complete\,Damage\right] = Collapse\,Factor$$

HAZUS TM provides collapse factors for each Model Building Type. The collapse factor is small for light wood frame single or multiple-family dwellings (W1) (3%) and larger for Model Building Types more prone to collapse, such as unreinforced masonry bearing-wall buildings (URM) (15%).

4.4.3 History and Purpose of the OSHPD HAZUS Procedure

Tokas and Lobo (2009) summarize the history and purpose of the procedure developed by OSHPD for risk-based seismic evaluation of pre-1973 hospital building using the HAZUS methodology. The procedure was developed when pre-1973 hospital buildings were evaluated using conventional seismic evaluation procedures according to the California State Senate Bill 1953 regulations and over 90% of them were found to not meet the minimum life-safety standard. In response, OSHPD looked for a possible alternative to reclassify some of these buildings with the goal of ranking the risk of the failing hospitals so that, given limited resources, a "worst first" strategy could be applied to upgrading the hospital stock. OSHPD used HAZUS to determine probability of collapse (considering building type, age, and height), but modified the procedure so that the results also take into account a variety of deficiencies. The details of the procedure have since been codified within the *California Administrative Code, California Code of Regulations*, Title 24, Part 1, Chapter 6. The procedure is referred to in this document as the "OSHPD HAZUS" procedure.

4.4.4 Calculating Collapse Probability with the OSHPD HAZUS Procedure

As in HAZUS, probability of collapse is calculated with OSHPD HAZUS using the same three step process of calculating peak displacement, probability of complete damage, and, finally, the probability of collapse. Properties are provided for 16 different building types, known within OSHPD HAZUS as "Model Building Types" or MBTs. The significant difference between HAZUS and OSHPD HAZUS is that the assumed properties of the building (capacity, response, fragility, and collapse rate) vary based on the presence of deficiencies in OSHPD HAZUS, but not in HAZUS.

Deficiencies can affect the probability of collapse in a number of different ways. The deficiency may reduce the building's ultimate capacity; it may reduce the roof drift associated with the Complete damage state; it may increase the probability of collapse given the Complete damage state; or some combination of these effects may be triggered. In the case of a soft story, for example, a significant portion of the roof drift is assumed to be concentrated within a single story. The roof drift corresponding to the Complete damage state is reduced since it becomes more akin to the story drift associated with the Complete damage state. Vertical elements at that story experience higher drifts, leading to greater damage and a higher probability of collapse. Therefore, the collapse factor is increased. For example, a steel building with a soft story is assigned a 15% chance of collapsing given it reaching the complete damage state versus only an 8% chance of collapse for a similar building without a soft story.

When no deficiencies are present, the probability of collapse is calculated assuming "Baseline" performance properties. When deficiencies are present, Sub-Baseline (SubBase) or Ultra-Sub-Baseline (USB) performance properties are used as specified in OSHPD HAZUS Table A6-1 (reproduced below in Table 4-1). Deficiencies that moderately degrade the building performance, such as the presence of a weak story, result in the use of SubBase performance properties. Deficiencies (or certain combinations of deficiencies) that seriously degrade performance, such as the combination of weak story with torsional irregularity, result in the use of USB performance properties. When SubBase properties are used, the collapse probability increases. When USB properties are used, the collapse probabilities are increased even further.

Table 4-1 OSHPD HAZUS Significant Structural Deficiency Matrix

Significant Structural Deficiency/Condition[1]	Capacity		Response		Structural Damage - Complete Damage State						Collapse	
	Overstrength		Duration		Fragility Curve Median[4]				Fragility Curve Variability - Beta Factor (β_c)		Collapse Factor (P[COL|STR_5])	
	γ and λ Factors		Degradation, κ, Factor		Maximum Story Drift Ratio, Δ_c		Mode Shape, α_3 Factor					
	SubBase	USB	SubBase	USB[5]	SubBase	USB	SubBase	USB[6]	SubBase	USB[5]	SubBase	USB[6]
Age (Pre-1933 buildings)	X	X[7]										
Materials Testing (None)	X								X			
No Redundancy									X		X	X[6]
Weak Story Irregularity					X		X	X[6]			X	X[6]
Soft Story Irregularity					X		X	X[6]			X	X[6]
Mass Irregularity					X							
Vertical Discontinuity	X				X							
Torsional Irregularity						X					X	X[6]
Deflection Incompatibility[2]					X				X		X	X[6]
Short Column[3]	X					X						
Wood Deterioration		X	X									
Steel Deterioration		X	X									
Concrete Deterioration		X	X									
Weak Column-Steel	X				X							
Weak Column-	X		X		X							
No Cripple Wall Bracing					X		X	X[6]			X	X[6]
Topping Slab	X		X						X		X	X[6]
Inadequate Wall Anchorage		X							X			
Load Path/Diaphragm Openings									X		X	X[6]

[1] Sub-Baseline (SubBase) and Ultra-Sub-Baseline (USB) properties are based on one, or more, significant structural deficiencies.
[2] The deflection incompatibility structural deficiency applies only to concrete systems (C1, C2, and C3).
[3] The short column structural deficiency applies only to concrete and masonry systems (C1, C2, C3, RM1, and RM2).
[4] Effects of deficiencies related to drift and mode shape are limited to a combined factor of five reduction in Complete median (of HAZUS default value).
[5] Grey shading indicates USB performance is not defined/used for deficiencies related to degradation (kappa) and fragility curve (beta) factors.
[6] USB performance required for systems with multiple, SubBase deficiencies related to either the mode shape (α_3) factor or the collapse rate.
[7] USB performance required for pre-1933 buildings with other over-strength-related deficiencies (else use SubBase performance for pre-1933 buildings).

OSHPD HAZUS provides Equations A6-2 through A6-5 (reproduced below as Equations 4-12 through 4-15) to define building capacity:

$$A_y = C_s \gamma / \alpha_1 \tag{4-12}$$

$$D_y = 9.8 A_y T_e^2 \tag{4-13}$$

$$A_u = \lambda A_y \tag{4-14}$$

$$D_u = \lambda \mu D_y \tag{4-15}$$

where:

C_s = seismic design coefficient – values of C_S are given in OSHPD HAZUS Tables A6-2a and A6-2b. OSHPD HAZUS Table A6-2a provides values of C_S for the various Model Building Types and for varying number of stories considering buildings built post-or pre-1961 located in UBC Seismic Zone 4. OSHPD HAZUS Table A6-2b provides values of C_S for the various Model Building Types and for varying number of stories considering post-1961 or pre-1961 buildings located in UBC Seismic Zone 3.

γ = yield strength factor – values of γ are given in OSHPD HAZUS Table A6-5 for varying number of stories.

α_1 = modal weight factor – values of α_1 are given in OSHPD HAZUS Table A6-4 for the various Model Building Types and for varying number of stories.

T_e = elastic period, in seconds – values of T_e are given in OSHPD HAZUS Table A6-3 for the various Model Building Types and for varying number of stories.

λ = overstrength factor – values of λ are given in OSHPD HAZUS Table A6-5 for the various Model Building Types and for varying number of stories. This factor varies for Baseline, SubBase, and USB performance.

μ = ductility factor – values of μ are given in OSHPD HAZUS Table A6-6 for varying number of stories.

OSHPD HAZUS then provides variables β_E and κ to define building response where:

β_E = elastic damping – values of β_E are given in OSHPD HAZUS Table A6-7 for the various Model Building Types.

κ = degradation factor – values of κ are given in OSHPD HAZUS Table A6-8 for varying scenario earthquakes. The degradation factor also varies for Baseline and SubBase performance.

Based on the building capacity and the building response defined above, the user calculates the peak response of the building using the methods described in the HAZUS discussion above.

OSHPD HAZUS then provides equations and variables to create fragility curves for the building in the form:

$$S_{d,C} = \Delta_C H_R \alpha_2 / \alpha_3 \qquad (4\text{-}16)$$

where:

Δ_C = story drift ratio at the threshold of Complete Structural Damage - values of Δ_C are given in OSHPD HAZUS Table A6-9 for the various Model Building Types considering post-1961 or pre-1961. Δ_C varies for Baseline, SubBase, or USB performance.

H_R = height of building at the roof level – default values of H_R are given in OSHPD HAZUS Table A6-3 for the various Model Building Types and for varying number of stories.

α_2 = modal height factor – values of α_2 are given in OSHPD HAZUS Table A6-4 for the various Model Building Types and for varying number of stories.

α_3 = modal shape factor relating maximum-story drift and roof drift – values of α_3 are given in OSHPD HAZUS Table A6-10 for varying number of stories and for Baseline, SubBase, and USB performance.

Lognormal standard deviation values for complete damage, β_C, are provided in OSHPD HAZUS Table A6-11. These values consider post-1961 or pre-1961 designations, and vary for number of stories and for Baseline or SubBase performance. These are referred to in HAZUS TM as $\beta_{S,C}$.

Appendix A presents tables that have been developed to document the values of all variables used to develop the *Third Edition* Basic Scores. These tables include values from OSHPD HAZUS, values from OSHPD HAZUS adjusted for use in calculation of *Third Edition* Score Modifiers, and values derived for FEMA Building Types not included in OSHPD HAZUS. Section 5.2.4 presents a detailed list of Appendix A tables, Chapter 5 details how to use the tables.

Using the peak response and the fragility parameters $S_{d,C}$ and β_C, the user determines the probability of complete damage using the methods described in the HAZUS discussion above.

Finally, the OSHPD HAZUS procedure defines the probability of collapse, P[COL], as follows:

$$P[COL] = P[COL \mid STR_5] \times P[STR_5] \tag{4-17}$$

where the term STR_5 designates the Complete structural damage state and $P[COL|STR_5]$ is the collapse factor. Values of the collapse factor are given in OSHPD HAZUS Table A6-12 for the various Model Building Types and vary for Baseline, SubBase, and USB performance.

4.4.5 Use of the OSHPD HAZUS Procedure for FEMA P-154

Basic Scores were developed using properties that correspond to Baseline building performance. Score Modifiers were developed by varying assumptions of pre-1961 or post-1961, building height, and SubBase and USB performance. Specific mapping of OSHPD HAZUS tables to FEMA P -154 input is described in Chapter 5.

One significant difference between the OSHPD HAZUS procedure and the modified procedure for FEMA P-154 is the adjustment of the beta values. Another difference is in calculating Post-Benchmark Score Modifiers.

4.4.5.1 Adjustment of Beta Values

Like HAZUS, the beta values provided in OSHPD HAZUS are deterministic. When used with probabilistic ground motions (e.g., MCE_R ground motions other than certain sites of very high seismicity), these so-called deterministic betas should be reduced to avoid double counting the variability associated with demand, since the calculation of probabilistic ground motions includes record-to-record variability. The amount of reduction is a function of the degree of inelastic response. Incremental dynamic analysis results (e.g., studies in FEMA P-695 (FEMA, 2009b) have shown that the responses of a highly yielded nonlinear system exhibit significant record-to-record variability for a set of earthquake records scaled to have no variability in linear elastic response (i.e., records scaled to the same spectral acceleration at elastic period).

Considering the above discussion, probabilistic betas are derived from the deterministic betas of OSHPD HAZUS by removing a modest amount of demand (record-to-record) variability when the building is responding elastically, and by removing less demand variability when the building is responding inelastically, in proportion to the degree of inelastic response. Accordingly, values of probabilistic betas, $\beta_{C,P}$, are derived from deterministic betas, $\beta_{C,D}$, for the Complete damage state using the following equation:

$$\beta_{C,P} = \sqrt{\frac{\beta_{C,D}^2 - (\beta_{CAP}^2 + \beta_{T,C}^2)}{X\left(1 + \frac{D}{D_e}\right)} + (\beta_{CAP}^2 + \beta_{T,C}^2)} \quad (4\text{-}18)$$

Values of $\beta_{C,D}$ are derived from OSHPD HAZUS values of β_c, which vary by number of stories, performance level, and age. Values of β_{CAP} (variability associated with the capacity curve) and $\beta_{T,C}$ (variability associated with the threshold of the damage state) are selected from the *Multi-hazard Loss Estimation Methodology, Earthquake Model, HAZUS-MH MR1, Advanced Engineering Building Module, Technical and User's Manual* (FEMA, 2003). The HAZUS Advanced Engineering Building Module (AEBM) procedures are an extension of the more general methods of HAZUS. While HAZUS provides damage and loss functions for generic Model Building Types, the AEBM can be used to develop building-specific damage and loss functions. The elastic displacement, D_e, is defined as the value of demand spectrum at the elastic period, T_e. As previously established, D is always greater than or equal to, D_e.

The factor X in Equation 4-18 affects the amount of beta reduction. When X is equal to zero, the calculation is set so that the probabilistic betas come out the same as the deterministic betas. When X is large (e.g., 100), the probabilistic betas include only uncertainties associated with capacity and threshold of Complete damage. When X is small (e.g., around one), the probabilistic betas reflect reasonable amounts of ground motion uncertainty.

4.4.5.2 Post-Benchmark Score Modifiers

The OSHPD HAZUS procedure was designed to evaluate pre-1971 hospital buildings. It does not, therefore, provide parameters for newer buildings. In order to determine Post-Benchmark Score Modifiers, the approach used for post-benchmark buildings in HAZUS was adapted for the FEMA P-154 procedure.

In the *Second Edition*, Basic Scores for High, Moderate, and Low seismicity were based on HAZUS values for Moderate-Code, Low-Code, and Pre-Code, respectively. Post-Benchmark Score Modifiers for High, Moderate, and Low seismicity were based on HAZUS values for High-Code, Moderate-Code, and Low-Code, respectively.

The change from one code level to another (for example, from Low-Code to Moderate-Code for Post-Benchmark Score Modifiers in Moderate seismicity) triggered an increase in values for C_S, μ, $S_{d,C}$, and κ, and a decrease in beta values. Values of C_S typically doubled when going from Moderate-Code (basis of High seismicity Basic Score) to High-Code (basis of High seismicity Post-Benchmark Score Modifier). Other parameters had similar trends with varying ratios of the associated Post-Benchmark value to Basic Score value.

Ratios for calculating Post-Benchmark Score Modifiers using the OSHPD HAZUS values are based on the ratios given in HAZUS. In order to obtain meaningful Post-Benchmark Score Modifier values in Very High and High seismicity regions, ratios based on HAZUS's Special High-Code were used.

Chapter 5

Development of *Third Edition* Basic Scores and Score Modifiers

5.1 Introduction

An important part of the *Third Edition* update of FEMA P-154 is the development of new and improved Basic Scores and Score Modifiers. In addition to discussing the impetus for updating the *Second Edition* scores, Chapter 4 describes the theory behind the calculation of Basic Scores and Modifiers. Specifically, Chapter 4 describes the methodology documented in *Multi-hazard Loss Estimation Methodology, Earthquake Model, HAZUS-MH MR4 Technical Manual* (FEMA, 2009a), referred to in this document as "HAZUS methodology," as well as the procedure developed by the California Office of Statewide Health Planning and Development (OSHPD), referred to in this document as the "OSHPD HAZUS methodology" (CAC, 2010). It introduces how the HAZUS and OSHPD HAZUS methodologies were combined to create a unique FEMA P-154 procedure for calculating *Third Edition* scores. This chapter provides a comprehensive description of the steps and assumptions used to develop the *Third Edition* scores, and it provides the results.

5.2 Development of *Third Edition* Basic Scores

Basic Scores were calculated for five unique seismicity regions and the 17 FEMA Building Types considered in the *Third Edition*. All Basic Scores were calculated considering low-rise buildings on Soil Type CD.

5.2.1 Seismicity Regions

Five seismicity regions are considered: Low, Moderate, Moderately High, High, and Very High. These seismicity regions are demarcated by ranges of spectral response acceleration parameters. The ranges are defined in Table 5-1 for S_s, spectral response acceleration parameter for 5%-damped maximum considered earthquake (MCE_R) at a period of 0.2 seconds, and S_1, spectral response acceleration parameter for 5%-damped MCE_R at a period of 1 second, assuming Soil Type B (also referred to as Site Class). The colors in the table correspond to the maps provided in Appendix A of FEMA P-154.

Table 5-1 Range and Median MCE_R Spectral Response Acceleration Values in Each Seismicity Region

Seismicity Region	Range of Response Values for Each Region		Median Response Values for Each Region	
	S_S (g)	S_1 (g)	$S_{S,avg}$ (g)	$S_{1,avg}$ (g)
Low (L)	$S_S < 0.250g$	$S_1 < 0.100g$	0.20	0.08
Moderate (M)	$0.250g \leq S_S < 0.500g$	$0.100g \leq S_1 < 0.200g$	0.40	0.16
Moderately High (MH)	$0.500g \leq S_S < 1.000g$	$0.200g \leq S_1 < 0.400g$	0.80	0.32
High (H)	$1.000g \leq S_S < 1.500g$	$0.400g \leq S_1 < 0.600g$	1.20	0.48
Very High (VH)	$S_S \geq 1.500g$	$S_1 \geq 0.600g$	2.25	0.90

Table 5-1 also shows the median values of S_s and S_1 for each region. These median values approximate the average seismicity in the region and are used as the basis of the scores for that region. The maximum seismicity (at the extreme end of the Very High seismicity region) is considered to be S_S = 3.8g and S_1 = 1.5g.

Table 5-2 presents S_S and S_1 values and the resulting seismicity region for 35 selected cities throughout the United States. The S_S and S_1 values were obtained from the *U.S. Seismic Design Maps* web application on the USGS website (http://earthquake.usgs.gov/designmaps/us/application.php) using the latitude and longitude shown corresponding to a point within each city. The point used does not necessarily correspond to the location of maximum ground motion within the city. Hence, some locations within some cities may fall within a higher seismicity region than noted. The reported values are for BSE-2N (i.e., MCE_R) ground motion criteria, as defined in ASCE/SEI 41-13, *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE, 2014), and Site Class B soil. The seismicity region designation from each city according to the *Second Edition* is also included for comparison.

Spectral acceleration response parameters are adjusted for different soil types by multiplying S_S by F_a and S_1 by F_v, where F_a and F_v, are the short-period and one-second period site coefficients, respectively. Site coefficients for Soil Types B, C, D, and E are provided in ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE, 2010, Tables 11.4-1 and 11.4-2) and repeated in Table 5-3. Note that the coefficient for Soil Type B is equal to unity.

Table 5-2 Seismicity Region for 35 Selected Cities in the United States

City	Latitude	Longitude	MCE$_R$ Response Values S_S (g)	S_1 (g)	*Third Edition* Seismicity Region	*Second Edition* Seismicity Region
Southern California						
Los Angeles	34.05	-118.25	2.402	0.843	Very High	High
Century City	34.05	-118.4	2.165	0.804	Very High	High
Northridge	34.2	-118.55	1.69	0.6	Very High	High
Long Beach	33.8	-118.2	1.643	0.617	Very High	High
Irvine	33.65	-117.8	1.55	0.571	Very High	High
Riverside	33.95	-117.4	1.5	0.6	Very High	High
San Bernardino	34.1	-117.3	2.367	1.083	Very High	High
San Luis Obispo	35.3	-120.65	1.116	0.426	High	High
San Diego	32.7	-117.15	1.254	0.484	High	High
Santa Barbara	34.45	-119.7	2.828	0.993	Very High	High
Ventura	34.3	-119.3	2.381	0.9	Very High	High
Northern California						
Oakland	37.8	-122.25	1.861	0.747	Very High	High
Concord	37.95	-122.0	2.075	0.735	Very High	High
Monterey	36.6	-121.9	1.526	0.56	Very High	High
Sacramento	38.6	-121.5	0.672	0.293	Moderately High	High
San Francisco	37.75	-122.4	1.5	0.642	Very High	High
San Mateo	37.55	-122.3	1.849	0.86	Very High	High
San Jose	37.35	-121.9	1.5	0.6	Very High	High
Santa Cruz	36.95	-122.05	1.517	0.6	Very High	High
Vallejo	38.1	-122.25	1.5	0.6	Very High	High
Santa Rosa	38.45	-122.7	2.509	1.036	Very High	High
Oregon and Washington						
Seattle	47.6	-122.3	1.365	0.528	High	High
Tacoma	47.25	-122.45	1.297	0.506	High	High
Everett	48	-122.2	1.269	0.482	High	High
Portland	45.5	-122.65	0.982	0.421	High	High
Idaho, Utah, and Nevada						
Salt Lake City	40.75	-111.9	1.539	0.557	Very High	High
Boise	43.6	-116.2	0.309	0.105	Moderate	Moderate
Reno	39.55	-119.8	1.5	0.517	Very High	High
Las Vegas	36.2	-115.15	0.495	0.166	Moderate	Moderate

Table 5-2 Seismicity Region for 35 Selected Cities in the United States (Continued)

City	Latitude	Longitude	MCE_R Response Values S_S (g)	S_1 (g)	*Third Edition* Seismicity Region	*Second Edition* Seismicity Region
Missouri, Tennessee, South Carolina, Illinois, New York, Massachusetts						
St. Louis	38.6	-90.2	0.438	0.168	Moderate	Moderate
Memphis	35.15	-90.05	1.011	0.351	High	High
Charleston	32.8	-79.95	1.149	0.366	High	High
Chicago	41.85	-87.65	0.135	0.062	Low	Low
New York	40.75	-74	0.28	0.072	Moderate	Moderate
Boston	42.36	-71.06	0.217	0.069	Low	Low

Table 5-3 Site Coefficients for Soil Types B, C, D, and E

Spectral Acceleration on Site Class B	Site Class B	C	D	E
Short-Period, S_S (g)	**Short-Period Amplification Factor, F_A**			
$\leq$ 0.25	1.0	1.2	1.6	2.5
0.50	1.0	1.2	1.4	1.7
0.75	1.0	1.1	1.2	1.2
1.0	1.0	1.0	1.1	0.9
$\geq$ 1.25	1.0	1.0	1.0	0.9
1-second Period, S_1 (g)	**1.0-second Period Amplification Factor, F_V**			
$\leq$ 0.1	1.0	1.7	2.4	3.5
0.2	1.0	1.6	2.0	3.2
0.3	1.0	1.5	1.8	2.8
0.4	1.0	1.4	1.6	2.4
$\geq$ 0.5	1.0	1.3	1.5	2.4

To calculate Basic Scores, the median spectral acceleration values for each of the five seismicity regions from Table 5-1 (assumed to be based on Soil Type B) were multiplied by site coefficients for Soil Type CD. The site coefficients for Soil Type CD were determined by averaging the site coefficients for Soil Type C and Soil Type D. The resulting values, F_aS_S and F_VS_1, for Soil Type CD were used to develop an initial demand spectrum and are shown in Table 5-4. In addition to calculating Basic Scores for the median in each of the five seismicity regions, calculations were also performed at the extreme end of the Very High seismicity region (VH_{max}). S_S and S_1 are taken as 3.8g and 1.5g, respectively, approximating the maximum seismicity in the United States. The scores that were calculated at the maximum seismicity are not presented on any Data Collection Form.

Table 5-4 Median Spectral Acceleration Values in Each Seismicity Region Adjusted for Soil Type CD

	Site B 5% MCE_R		Site Class C Factors		Site Class D Factors		Site Class CD Factors		Basis of Basic Scores	
Region	S_S (g)	S_1 (g)	F_a	F_v	F_a	F_v	F_a	F_v	F_aS_S (g)	F_vS_1 (g)
L	0.20	0.08	1.20	1.70	1.60	2.40	1.40	2.05	0.28	0.16
M	0.40	0.16	1.20	1.64	1.48	2.16	1.34	1.90	0.54	0.30
MH	0.80	0.32	1.08	1.48	1.16	1.76	1.12	1.62	0.90	0.52
H	1.20	0.48	1.00	1.32	1.02	1.52	1.01	1.42	1.21	0.68
VH	2.25	0.90	1.00	1.30	1.00	1.50	1.00	1.40	2.25	1.26
VH_{max}	3.80	1.50	1.00	1.30	1.00	1.50	1.00	1.40	3.80	2.10

They are, however, provided to users of the electronic scoring methodology to allow for interpolation of scores at locations where the seismicity is greater than the median of Very High. See Chapter 6 for additional discussion of interpolating scores with electronic scoring.

The seismicity regions of FEMA P-154 can be compared with the Seismic Design Categories (SDC) in ASCE/SEI 7-10 and the "levels of seismicity" defined in ASCE/SEI 41-13. Similar to the seismicity regions of FEMA P-154, the ASCE/SEI 7-10 Seismic Design Categories and the ASCE/SEI 41-13 levels of seismicity are also used to describe the severity of earthquake ground motions at a given site. The ASCE/SEI 7-10 Seismic Design Categories range from SDC A (low seismicity) to SDC E (high seismicity). Seismic design requirements are less stringent for SDC A buildings and more stringent for SDC E buildings. ASCE/SEI 41-13 levels of seismicity include Very Low, Low, Moderate, and High.

Unlike the FEMA P-154 seismicity regions, Seismic Design Category and level of seismicity designations take into account site-specific soil conditions. It should not be assumed that all buildings in FEMA P-154 Low seismicity correspond to SDC A or B; some may be SDC C, or even SDC D in limited cases. For example, a building in FEMA P-154 Low seismicity region on Soil Type B may correspond to SDC A according to ASCE/SEI 7-10 and the Very Low level of seismicity according to ASCE/SEI 41-13, while a building in FEMA P-154 Low seismicity on Soil Type E may correspond to SDC C and the Moderate level of seismicity.

5.2.2 FEMA Building Types

The FEMA P-154 procedure considers 17 FEMA Building Types. Basic Scores for 15 of these (W1, W2, S1, S2, S3, S4, S5, C1, C2, C3, PC1, PC2, RM1, RM2, and URM) were calculated considering the W1, W2, S1, S2, S3,

S4, S5, C1, C2, C3, PC1, PC2, RM1, RM2, and URM Model Building Types (MBTs) included in OSHPD HAZUS. OSHPD HAZUS does not include W1A and has limited consideration of MH. Basic Scores for W1A were developed using engineering judgment to equal the average of the Basic Scores for W1 and W2. The OSHPD HAZUS procedure was used to develop the Basic Score for MH using values for capacity and fragility parameters as defined in the *HAZUS-MH MR4 Technical Manual* (HAZUS TM).

5.2.3 Using OSHPD HAZUS Values

OSHPD HAZUS provides values of all the parameters needed to calculate probability of collapse; they are also defined in Chapter 4. Guidance was needed to select the appropriate values from the OSHPD HAZUS tables to use for the Basic Score calculations for each FEMA Building Type in each seismicity region.

OSHPD HAZUS values for elastic damping, β_E, vary only by building type. Therefore, determining the appropriate value of β_E to use to calculate the Basic Score for any given FEMA Building Type was straightforward.

More often, values from the OSHPD HAZUS tables vary by building type and number of stories. This is true for default building height, H_R, elastic period, T_e, α_1, α_2, γ, and μ (the last of which is constant across building types and varies only by number of stories). Because T_e, α_1, α_2, and μ vary depending on number of stories, the probability of collapse of a given building type varies depending on the number of stories. The Basic Score is meant to represent the probability of collapse of a low-rise building (i.e., one that is one-story, two-story, or three-story). Therefore, calculations were run for a one-story building, a two-story building, and a three-story building. The Basic Score was then determined considering the average of the probability of collapse of the three different buildings. In some cases, such as for MH, a three-story structure does not exist and is not considered.

Values for λ, α_3, and collapse factor (P[$COL|STR_5$]) can vary depending on both number of stories and performance level. As described in Chapter 4, OSHPD HAZUS considers three performance levels: Baseline, Sub-Baseline (or SubBase), and Ultra-Sub-Baseline (or USB). Buildings without deficiencies were evaluated considering Baseline performance. When deficiencies are present, select parameters were adjusted for SubBase or USB performance. Values of λ, α_3, and P[$COL|STR_5$] vary depending on performance levels and are provided for Baseline, SubBase, or USB performance. For these parameters, number of stories were varied (as above), and Basic Scores were determined assuming Baseline values.

The remaining parameters vary by age (in addition to varying by number of stories and performance level). Values are provided for pre-1961 buildings and post-1961 buildings. Basic Scores were typically calculated using pre-1961 values. The following guidelines were used. See Chapter 4 for a description of the parameters.

- C_S: Varies by building type, age, number of stories, and *Uniform Building Code* (UBC) Seismic Zone. The UBC Seismic Zone categorization is relevant in the OSHPD HAZUS methodology which was developed to address older California buildings that were subject to UBC. For FEMA P-154, mapping to the various seismicity regions was needed. For Low and Moderate seismicity regions, Basic Scores were calculated using Zone 3, pre-1961 values. For High and Very High seismicity, Basic Scores were calculated using Zone 4, pre-1961 values. For Moderately High seismicity, an average of the Zone 3 and Zone 4 pre-1961 values was used.
- κ: Varies by scenario earthquake, age, and performance level. The scenario earthquake is defined by both magnitude of the earthquake and distance of the building from the fault. In a Low seismicity region, the scenario earthquake was considered to be greater than 50km from the site. For all other seismicity regions, the scenario earthquake was considered to be 10km to 25km from the site with a magnitude greater than 7.0. Baseline performance and pre-1961 values were considered.
- Δ_C: Varies by building type, age, and performance level. In Low and Moderate seismicity regions, Basic Scores were calculated assuming pre-1961 values. In High and Very High seismicity regions, Basic Scores were calculated assuming post-1961 values. In Moderately High seismicity regions, an average of the pre- and post-1961 values was used. All Basic Scores were calculated assuming Baseline performance.
- $\beta_{C,D}$: Values of $\beta_{C,D}$ are derived from OSHPD HAZUS values of β_C, which vary by number of stories, performance level, and age. Basic Scores were calculated using post-1961 SubBase values. (OSHPD HAZUS Table A6-1 indicates that if material data are not present, SubBase values of β_C shall be used.)

5.2.3.1 Exceptions

After reviewing preliminary results from the scoring update study, some selected revisions were made in the input parameters as follows:

- Based on engineering judgment, typical W1 buildings are expected to have strength comparable to the larger C_S values provided in the HAZUS TM. Use of the OSHPD HAZUS values would underestimate the strength of these buildings. Hence, C_S values for W1 buildings were taken from the HAZUS TM.
- For S3 buildings, the strength, C_s, values use the W1 values from HAZUS TM because S3 buildings are light and are designed for wind loading, and thus are expected to have strength comparable to W1 buildings. The lambda factor, λ, for S3 was taken as 2.0 to match the value used for W1.
- Basic Scores for MH were calculated using values from HAZUS TM because values for MH are not provided in OSHPD HAZUS.
- For S5 buildings, α_1 values are not provided in OSHPD HAZUS. The values were taken from the column for "W1, W2, S2, S3, S4, C2, C3, PC2, RM1 and RM2" in OSHPD HAZUS Table A6-4.
- Values of elastic damping are not provided in OSHPD HAZUS for URMs. An elastic damping of 7% was used, which matches the elastic damping that OSHPD HAZUS provides for URM infill buildings (C3 and S5).
- For URM, S5, and C3 buildings, C_S values were using Zone 3, pre-1961 values for all seismicity regions because these buildings pre-date seismic codes, even when located in High seismicity regions (Zone 4).
- Values of Δ_C for C1 and PC2 buildings were taken from the row for "S5, C3 and URM" in OSHPD HAZUS Table A6-9, rather than the row for "S3, S4, PC1, PC2, RM1 and RM2" because the FEMA P-154 project team believed C1 and PC2 buildings have lower story drift capacities and thus the Basic Scores for C1 and PC2 buildings should be lower to achieve the desired ranking order of the FEMA Building Types. For S5 buildings, values of Δ_C were taken from the row for "S1, C1, S2 and C2" in OSHPD HAZUS Table A6-9, rather than the row for "S5, C3, and URM" because the FEMA P-154 project team noted that steel frame infill buildings have a much better history of performance than concrete frame infill buildings and URM bearing wall buildings. By increasing the Δ_C value, the S5 Basic Score was raised and achieved the desired ranking order for the FEMA Building Types.

5.2.4 Values for Calculation of Basic Scores

Tables have been developed to document the values of all variables used to develop the *Third Edition* Basic Scores. These tables are presented in

Appendix A. Some of the tables include adjusted values for use in calculating Pre-code and Post-Benchmark Score Modifiers and Plan and Vertical Irregularity Score Modifiers. A discussion of how these values were adjusted for calculating Score Modifiers is provided in Section 5.2.

Table A1: Default building height, H_R, and elastic period, T_e; values vary by FEMA Building Type and number of stories.

Table A2a-c: Seismic design coefficient, C_S; values vary by FEMA Building Type, number of stories, and seismicity region. Table A2a provides values for calculating Basic Scores. Table A2b provides values for calculating Pre-Code Score Modifiers. Table A2c provides values for calculating Post-Benchmark Score Modifiers.

Table A3: γ and λ, factors; values vary by FEMA Building Type and number of stories. (Values are also provided for calculating Pre-Code Score Modifiers.)

Table A4: Ductility factor, μ; values vary by number of stories. (Values are also provided for calculating Post-Benchmark Score Modifiers.)

Table A5: Modal factors, α_1 and α_2; values vary by FEMA Building Type and number of stories.

Table A6: Modal factor, α_3; values vary by number of stories. (Values are also provided for calculating Vertical Irregularity Score Modifiers.)

Table A7: Elastic damping, β_E; values vary by FEMA Building Type.

Table A8: Degradation factor, κ; values vary by seismicity region. (Values are also provided for calculating Pre-Code and Post-Benchmark Score Modifiers.)

Table A9: Story drift ratio, Δ_C; values vary by FEMA Building Type and seismicity region. (Values are also provided for calculating Plan and Vertical Irregularity Score Modifiers and Pre-Code and Post-Benchmark Score Modifiers.)

Table A10: Lognormal standard deviation values, $\beta_{C,D}$; values vary by number of stories. (Values are also provided for calculating Pre-Code and Post-Benchmark Score Modifiers.)

Table A11: Collapse factor (P[$COL|STR_5$]); values vary by FEMA Building Type. (Values are also provided for calculating Plan and Vertical Irregularity Score Modifiers.)

5.2.5 Adjustment of Betas

As noted in Chapter 4, the deterministic beta values provided in the OSHPD HAZUS procedure were reduced when calculating Basic Scores for FEMA P-154 to avoid "double counting" the variability associated with demand. Probabilistic betas, $\beta_{C,P}$, were derived from deterministic betas, $\beta_{C,D}$, using Equation 4-18, repeated below:

$$\beta_{C,P} = \sqrt{\frac{\beta_{C,D}^2 - (\beta_{CAP}^2 + \beta_{T,C}^2)}{X\left(1 + \frac{D}{D_e}\right)} + (\beta_{CAP}^2 + \beta_{T,C}^2)}$$

where β_{CAP} is set equal to 0.3 and $\beta_{T,C}$ is set equal to 0.4, such that the square root of $(\beta_{CAP}^2 + \beta_{T,C}^2)$ is 0.5.

The value of X, which determines the magnitude of beta reduction, was set equal to 0.75. This value of X was selected to best align the *Third Edition* scores with observed damage from past earthquakes and the *Second Edition* scores.

5.3 Sample Calculation of a Basic Score

This section presents a sample calculation of the Basic Score for FEMA Building Type S2 in the High seismicity region.

5.3.1 Step 1: Development of the Capacity Curve

As described in Chapter 4, the capacity curve is defined by the yield capacity and ultimate capacity points, (D_y, A_y) and (D_u, A_u):

$$A_y = C_S \gamma / \alpha_1 = 0.109 \times 2.70 / 0.80 = 0.368\text{g}$$

$$D_y = 9.8\, A_y\, T_e^2 = 9.8 \times 0.368 \times 0.40^2 = 0.577 \text{ in}$$

$$A_u = \lambda\, A_y = 1.67 \times 0.368 = 0.613\text{g}$$

$$D_u = \lambda\, \mu\, D_y = 1.67 \times 6.0 \times 0.577 = 5.77 \text{ in}$$

where values of C_S, γ, α_1, T_e, λ, and μ are obtained from Appendix A Tables A-1 through A-5 for a one-story S2 building in the High seismicity region.

The building capacity curve is assumed to be linear when the spectral displacement is less than the yield displacement and is assumed to remain plastic past the ultimate point. The transition from yield point to ultimate point of the capacity curve is assumed to be elliptical with the following form (from Equation 4-2):

$$\frac{(D-D_u)^2}{a^2}+\frac{(A-k)^2}{b^2}=1$$

where a, b, and k are constants with the following values from Equations 4-3 through 4-5:

$$a=\sqrt{\frac{D_y}{A_y}b^2\frac{(D_u-D_y)}{(A_y-k)}}=5.206$$

$$b=A_u-k=0.266$$

$$k=\frac{A_u^2-A_y^2+\frac{A_y^2}{D_y}(D_y-D_u)}{2(A_u-A_y)+\frac{A_y}{D_y}(D_y-D_u)}=0.347$$

Figure 5-1 shows the building capacity curve of a one-story S2 in the High seismicity region.

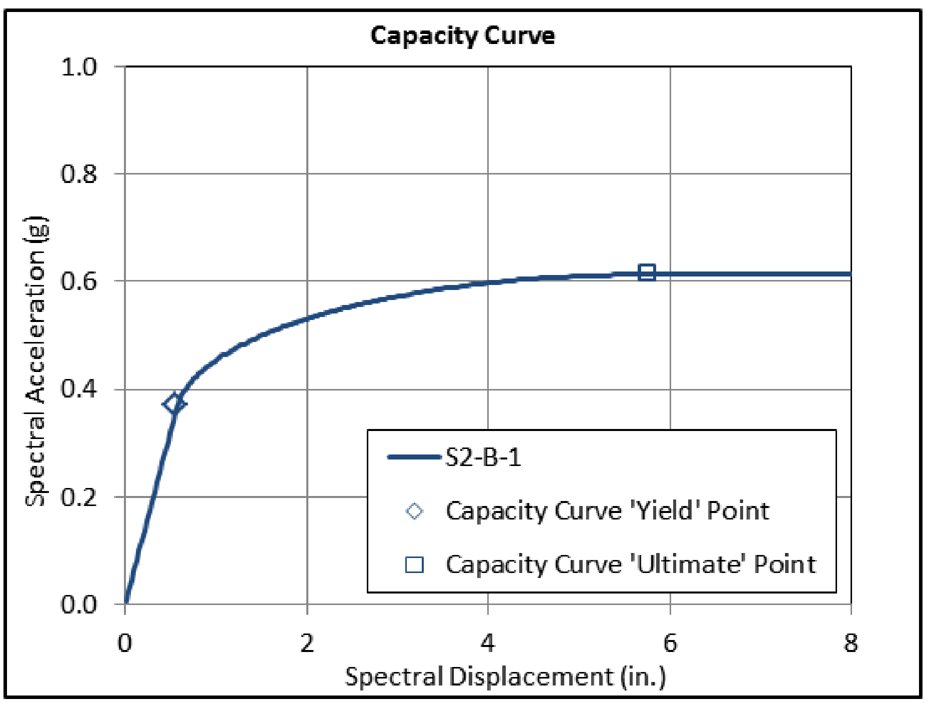


Figure 5-1 Building capacity curve for a one-story S2 in High seismicity.

This step is repeated for two- and three-story buildings, resulting in two additional capacity curves.

5.3.2 Step 2: Determination of Input Spectral Acceleration Response Values

Per Table 5-1, the median short-period spectral acceleration response, S_S, and the median one-second period spectral acceleration response, S_1, in a High seismicity region are 1.20g and 0.48g, respectively.

5.3.3 Step 3: Computation of Modified Input Spectral Acceleration Response Values, S_{MS} and S_{M1}

Values of S_S and S_1 are adjusted for Soil Type CD using site coefficients given in Table 5-4, $S_{MS} = F_a S_S = 1.21$g and $S_{M1} = F_v S_1 = 0.68$g.

5.3.4 Step 4: Development of a 5%-Damped Demand Response Spectrum

The demand response spectrum, formatted with spectral displacement response as the x-axis and spectral acceleration response as the y-axis, is developed through the use of the following equations, as taken from HAZUS TM:

At short periods (acceleration domain), $0 < T \leq T_S$:

$$S_A(T) = S_{MS}/R_A$$

At long periods (velocity domain), $T_S < T \leq T_{VD}$:

$$S_A(T) = (S_{M1}/T)/R_V$$

$$S_D(T) = 9.8 \times S_A \times T^2$$

where:

$S_A(T)$ = spectral acceleration response in g at period, T;

$S_D(T)$ = spectral displacement response in inches at period, T;

T_s = the transition period between the constant acceleration and the constant velocity regions of the response spectrum

= $(S_{M1}/S_{MS}) \times (R_A/R_V)$;

R_A = reduction factor in acceleration domain (Equation 4-6)

= $2.12/(3.21 - 0.68\ln(\beta_{eff}))$;

R_V = reduction factor in velocity domain (Equation 4-7)

= $1.65/(2.31 - 0.41\ln(\beta_{eff}))$;

β_{eff} = effective damping (Equation 4-8), which is the sum of the elastic damping, β_E, and hysteretic damping, β_H;

β_H = hysteretic damping, which is dependent on the amplitude of response, and is based on the area enclosed by the hysteresis loop, considering the potential degradation of energy-absorption capacity of the structure during cyclic earthquake loading

= $\kappa \times (Area / 2\pi DA)$

where:

Area = area enclosed by the hysteresis loop, as defined by the symmetric building capacity curve between peak positive and negative displacement, $\pm D$

D = peak displacement response

A = peak acceleration response at the peak displacement, D.

κ = degradation factor from Table A-8.

Thus, the 5%-damped spectrum for the High seismicity region is developed as follows and summarized in Table 5-5:

S_{MS} = 1.21g

S_{M1} = 0.68g

β_{eff} = 5%

$$R_A = \frac{2.12}{3.21 - 0.68\ln(\beta_{eff})} = \frac{2.12}{3.21 - 0.68\ln(5)} = 1.00$$

$$R_V = \frac{1.65}{2.31 - 0.41\ln(\beta_{eff})} = \frac{1.65}{2.31 - 0.41\ln(5)} = 1.00$$

$$T_S = \frac{F_v S_1}{F_a S_s} \times \frac{R_A}{R_V} = \frac{0.68}{1.21} \times \frac{1.00}{1.00} = 0.56$$

Table 5-5 5%-Damped Response Spectrum for Soil Type CD in High Seismicity Region

T (seconds)	S_A (5%) (g)	S_D (5%) (g)
0	1.21	0
0.56	1.21	3.72
1	0.68	6.66
2	0.34	13.3
4	0.17	26.7
8	0.085	53.3

The 5%-damped demand spectrum is shown in Figure 5-2.

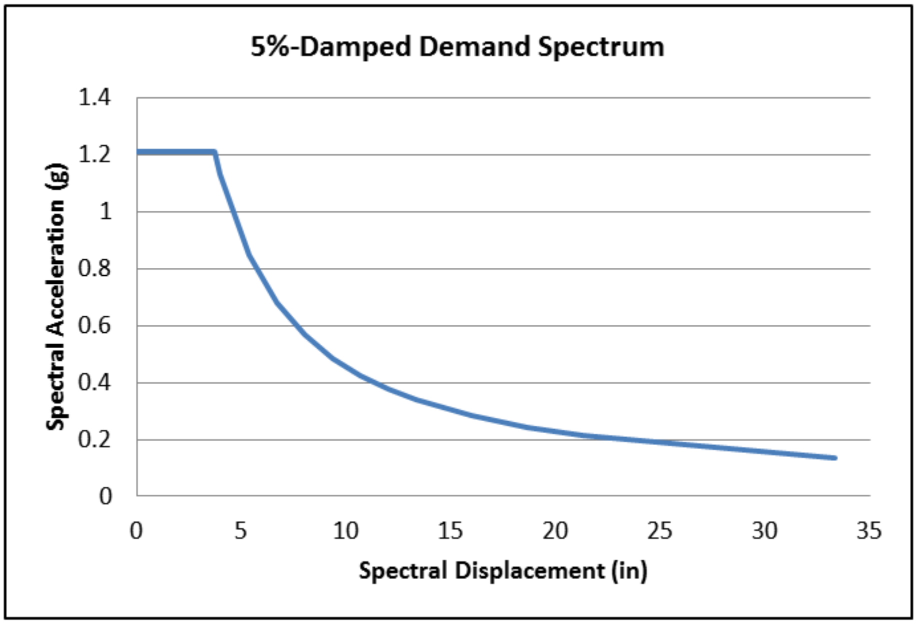


Figure 5-2 5%-Damped demand spectrum for high seismicity region.

5.3.5 *Step 5: Development of Damped Response Spectrum*

The demand spectrum developed in the previous step assumes 5% damping. As the spectral displacement of the building increases, the area under the hysteresis loop increases, thereby increasing β_H and β_{eff}. As β_{eff} increases, the demand curve decreases (via reduction factors R_A and R_V). Hence, the demand spectrum is dependent on the peak response. An iterative method is therefore required to determine the peak response, i.e., the intersection of the demand and capacity curves. Several methods exist to perform this calculation.

The peak response is calculated by developing what is termed a "β_{eff}-damped locus demand spectrum." This spectrum is developed by calculating the period and effective damping at each possible displacement, *D*, and then plotting spectral displacement versus spectral acceleration for each value of D as effective damping and period vary.

The process uses the following steps:

- Start at a displacement value, D, of $D_u/500$. At this very small displacement (D is approximately zero), the period, T, is equal to the elastic period, T_e, and the effective damping, β_{eff}, is equal to the elastic damping, β_E.
- Increment the value of D by a fraction of D_u, then for each value of D:
    - Compute the acceleration value, A, on the capacity curve
    - Compute the period, T, from D and A
    - Compute the area enclosed by the hysteresis loop up to the given (D, A) point
    - Compute effective damping, β_{eff}, based on the area
    - Compute R_A and R_V based on β_{eff}
    - Compute the demand curve point (S_D, S_A) reduced according to R_A and R_V. When S_D is less than the elastic displacement D_e associated with T_e, use D_e in lieu of the calculated S_D.
- Overlay the capacity curve on the β_{eff}-damped locus demand spectrum and take the intersection as the peak response.

For the specific case of the one-story S2 building in the High seismicity region, calculations were performed to determine more than 1,500 points on the β_{eff}-damped locus demand spectrum. Sample calculations are presented here for four of those points.

Recall, from Section 5.3.1:

Yield point: $D_y = 0.58$ in, $A_y = 0.37$g

Capacity point: $D_u = 5.77$ in, $A_u = 0.61$g

For elliptical portion of capacity curve, $k = 0.347$, $b = 0.266$, $a = 5.206$

Demand: $S_{MS} = 1.21$g, $S_{M1} = 0.68$g

Point 1: At start of capacity curve

$$D = D_u/500 = 5.77/500 = 0.012 \text{ in}$$

$$A = (D/D_y) \times A_y = (0.012/0.58) \times 0.37 = 0.007\text{g}$$

T = $(D/9.8A)^{1/2}$ = $(0.012/9.8/0.007)^{1/2}$ = 0.40 sec

Area = 0 (still on elastic portion of demand curve)

β_H = 0

β_{eff} = 5.0%

R_A = 2.12/(3.21 - 0.68 ln(5)) = 1.0

R_V = 1.65/(2.31 - 0.41 ln(5)) = 1.0

$\boldsymbol{S_A}$ **=** $\boldsymbol{S_{DS}/R_A}$ **= 1.21/1.0 = 1.21g**

$\boldsymbol{S_D}$ **=** $\boldsymbol{9.8\, S_A\, T^2}$ **= 9.8 × 1.21 × 0.4² = 1.90 in**

Repeat at small increments of D until,

Point 21: At yield point on capacity curve

D = D_y = 0.58 in

A = A_y = 0.37 g

T = $(D/9.8A)^{1/2}$ = $(0.58/9.8/0.37)^{1/2}$ = 0.40 sec (note that the period has not changed because it is still on the elastic portion of the capacity curve)

Area = 0 (still on elastic portion of capacity curve)

β_H = 0

β_{eff} = 5.0%

R_A = 2.12/(3.21 - 0.68 ln(5)) = 1.0

R_V = 1.65/(2.31 - 0.41 ln(5)) = 1.0

$\boldsymbol{S_A}$ **=** $\boldsymbol{S_{MS}/R_A}$ **= 1.21/1.0 = 1.21g**

$\boldsymbol{S_D}$ **=** $\boldsymbol{9.8\, S_A\, T^2}$ **= 9.8 × 1.21 × 0.4² = 1.90 in**

Points 1 through 21 all occur within the elastic portion of the capacity curve. In this range, the period, T, is always equal to the elastic period, T_e, and the effective damping, β_{eff}, is always equal to the elastic damping, β_E. Hence, these points all occur at $S_A = S_{DS}$ = 1.21g and $S_D = 9.8\, S_A\, T_e^2$. Point 1 is equal to Point 21. While the generic 5%-damped demand spectrum shown in Figure 5-2 starts at a spectral displacement of zero, the building-specific β_{eff}-damped locus demand spectrum begins at a point on the elastic period line.

Repeat at small increments of D until,

Point 101: At halfway point to D_u; on elliptical portion of capacity curve

$D \quad = \quad D_u/2 \; = \; 5.77/2 \; = \; 2.88$ in

$A \quad = \quad b[1-((D - D_u)/a)^2]^{1/2} + k$

$\quad = \quad 0.266[1- ((2.88 - 5.77)/5.206)^2]^{1/2} + 0.347 \; = \; 0.57g$

$T \quad = \quad (D/9.8A)^{1/2} \; = \; (2.88/9.8/0.57)^{1/2} \; = \; 0.72$ sec

Area = 4.66 (solved by numerical integration; see Tokas and Lobo [2009] for further details)

$\beta_H \quad = \quad \kappa\,(Area/2\pi DA) \; = \; 0.4 \cdot 4.66 / (2\pi \times 2.88 \times 0.57) \; = \; 18.1\%$

$\beta_{eff} \quad = \quad \beta_E + \beta_H \; = \; 5\% + 18.1\% \; = \; 23.1\%$

$R_A \quad = \quad 2.12/(3.21 - 0.68 \ln(23.1)) \; = \; 1.97$

$R_V \quad = \quad 1.65/(2.31 - 0.41 \ln(23.1)) \; = \; 1.61$

$\mathbf{S_A \quad = \quad S_{M1}/T/R_V \; = \; 0.68/0.72/1.61 \; = \; 0.59g}$

$\mathbf{S_D \quad = \quad 9.8\, S_A\, T^2 \; = \; 9.8 \times 0.59 \times 0.72^2 \; = \; 2.97\ in}$

Repeat at small increments of D until,

Point 151: At ultimate point on capacity curve

$D \quad = \quad D_u \; = \; 5.77$ in

$A \quad = \quad A_u \; = \; 0.61g$

$T \quad = \quad (D/9.8A)^{1/2} \; = \; (5.77/9.8/0.61)^{1/2} \; = \; 0.98$ sec

Area = 11.6 (solved by numerical integration; see Tokas and Lobo [2009] for further details)

$\beta_H \quad = \quad \kappa\,(Area/2\pi DA) \; = \; 0.4 \cdot 11.6 / (2\pi \times 5.77 \times 0.61) \; = \; 20.9\%$

$\beta_{eff} \quad = \quad \beta_E + \beta_H \; = \; 5\% + 20.9\% \; = \; 25.9\%$

$R_A \quad = \quad 2.12/(3.21 - 0.68 \ln(25.9)) \; = \; 2.13$

$R_V \quad = \quad 1.65/(2.31 - 0.41 \ln(25.9)) \; = \; 1.69$

$\mathbf{S_A \quad = \quad S_{M1}/T/R_V \; = \; 0.68/0.98/1.69 \; = \; 0.41\ g}$

$\mathbf{S_D \quad = \quad 9.8 \times S_A \times T^2 \; = \; 9.8 \times 0.41 \times 0.98^2 \; = \; 3.86\ in}$

Continue to repeat for small increments of D.

The resulting β_{eff}-damped locus demand spectrum is plotted in Figure 5-3.

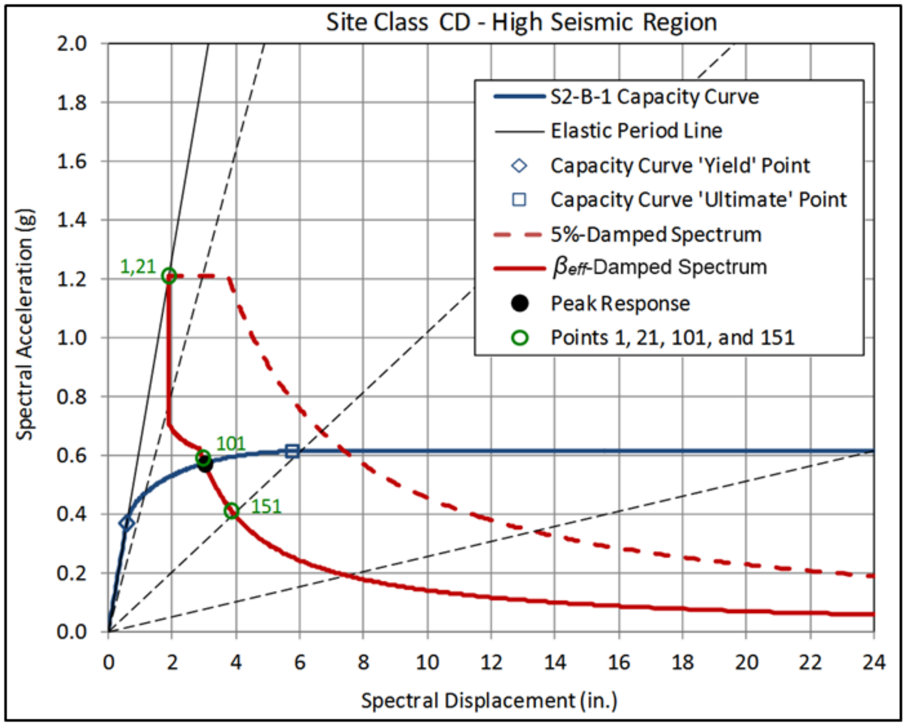


Figure 5-3 β_{eff}-Damped locus demand spectrum for one-story S2 in High seismicity region.

5.3.6 Step 6: Determination of Peak Response

The peak response is taken as the intersection between the capacity curve and the demand spectrum.

From the overlay of the capacity curve and demand spectrum shown in Figure 5-3, the peak response is taken as 3.04 in.

This is compared to the elastic displacement, D_e:

At the elastic period, $T_e = 0.4$ sec $< T_s = 0.56$ sec,

$$S_A = S_{MS}/R_A = 1.21 / 1.0 = 1.21\text{g}$$

$$S_D = 9.8 \times S_A \times T^2 = 9.8 \times 1.21 \times 0.4^2 = 1.89 \text{ in} = D_e$$

$$D/D_e = 3.04 / 1.89 = 1.61 > 1.0; \text{ use } D = 3.04 \text{ in.}$$

This step is repeated for the two- and three-story cases to determine the peak response for each case.

5.3.7 Step 7: Development of Fragility Curve

The median value of the Complete (C) structural damage state is (Equation 4-9):

$$S_{d,C} = \Delta_C \, H_R \, (\alpha_2 \, / \, \alpha_3)$$

Using the Appendix A tables, values are determined for Δ_C (Table A-9), H_R (Table A-1), α_2 (Table A-5), and α_3 (Table A-6). The median value of the Complete structural damage state for a one-story S2 building in the High seismicity region is:

$$S_{d,C} = \Delta_C \, H_R \, (\alpha_2 \, / \, \alpha_3) = 0.06 \times (14 \times 12) \times 0.75 \, / \, 1.00 = 7.6 \text{ in}$$

The lognormal standard deviation (beta) factor is (Equation 4-18):

$$\beta_{C,P} = \sqrt{\frac{\beta_{C,D}^2 - (\beta_{CAP}^2 + \beta_{T,C}^2)}{X\left(1 + \dfrac{D}{D_e}\right)} + (\beta_{CAP}^2 + \beta_{T,C}^2)}$$

$\beta_{C,D}$ is determined using Appendix A Table A-10. β_{CAP} is taken as 0.3 and $\beta_{T,C}$ is taken as 0.4. D and D_e were calculated above. X is taken as 0.75 for all FEMA P-154 calculations.

$$\beta_{C,P} = \sqrt{\frac{0.95^2 - (0.3^2 + 0.4^2)}{0.75\left(1 + \dfrac{3.04}{1.89}\right)} + (0.3^2 + 0.4^2)} = 0.89$$

The resulting fragility curve for a one-story S2 in High seismicity is defined by the following equation (Equation 4-10) and is shown in Figure 5-4:

$$P\left[Complete\,Damage\right] = \phi\left[\frac{1}{\beta_{C,P}} \ln\left(\frac{D}{S_{d,C}}\right)\right]$$

This step is repeated for the two-story and three-story cases, resulting in two additional fragility curves.

5.3.8 Step 8: Determination of Probability of Complete Damage

The probability of complete damage for a one-story S2 building in the High seismicity region is:

$$P\left[Complete\,Damage\right] = \varphi\left[\frac{1}{\beta_{C,P}} \ln\left(\frac{D}{S_{d,C}}\right)\right]$$

$$= \varphi\left[\frac{1}{0.89} \ln\left(\frac{3.04}{7.6}\right)\right] = 0.1526$$

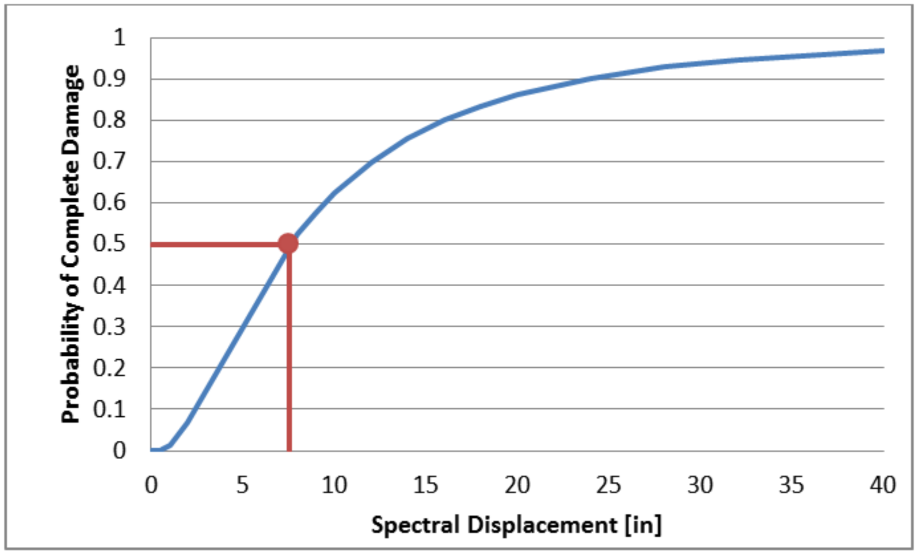


Figure 5-4 Fragility curve for one-story S2 in the High seismicity region. Note that the probability of complete damage at the mean spectral displacement of 7.6 inches is 50%.

This step is repeated for the two-story and three-story cases, resulting in two additional probabilities of complete damage.

5.3.9 Step 9: Determination of Probability of Collapse

Per Table A-11, the collapse rate P(*Collapse*) for S2 is 0.08.

The probability of collapse of the one-story S2 in High seismicity is therefore (Equation 4-17):

$$P(Collapse) = 0.08 \times 0.1526 = 0.0122.$$

This step is repeated for the two-story and three-story cases, resulting in two additional probabilities of collapse.

5.3.10 Step 10: Relate Probability of Collapse to an Associated Score

The associated score for the one-story S2 in High seismicity is

$$S = -\log_{10}(P(Collapse)) = -\log_{10}(0.0122) = 1.91$$

This step is repeated for the two-story and three-story cases, resulting in two additional scores. The associated scores for the two-story S2 and the three-story S2 are 2.05 and 2.13, respectively.

5.3.11 Step 11: Determine the Basic Score

The Basic Score for an S2 building in the High seismicity region is taken as the average of the one-story, two-story, and three-story results.

Basic Score = (1.91 + 2.05 + 2.13) / 3 = 2.03, approximated to 2.0.

5.4 Review of Basic Scores

Following the calculation of all the Basic Scores (for all FEMA Building Types and all seismicity regions), an extensive review of all of the scores was conducted, including a study of whether the relative ranking of the various FEMA Building Types was consistent with engineering judgment. As a result of this review, adjustments to the methodology, corrections to calculations, and modifications to some input parameters were made. The sample calculation provided above reflects the final methodology, calculations, and inputs used to develop the *Third Edition* Basic Scores.

Using engineering judgment and consideration of past performance, the Basic Scores for MH in Very High and High seismicity regions were adjusted from 1.4 and 1.8 to 1.1 and 1.5, respectively.

5.5 Development of Score Modifiers

Score Modifiers were determined by a three-step process:

1. Calculate the probability of collapse given the condition (e.g., plan irregularity, pre-code) under consideration: $P[COL|Condition]$
2. Convert the probability of collapse to an equivalent score: $S_{Condition} = -\log_{10}(P[COL|Condition]$
3. Calculate the modifier by subtracting the Basic Score from the equivalent score: Modifier = $S_{Condition}$ – Basic Score

Where the condition is beneficial to the building's seismic performance, there will be a decrease in the probability of collapse, $S_{Condition}$ will be greater than the Basic Score, and the modifier will be positive. Where the condition is detrimental, there will be an increase in the probability of collapse, $S_{Condition}$ will be less than the Basic Score, and the modifier will be negative.

5.5.1 Soil Type Modifiers

Modifiers for Soil Type B and Soil Type E were determined by varying the spectral demand. No revisions to assumptions about building properties were required.

The median spectral response acceleration parameters were adjusted for Soil Type B or Soil Type E by multiplying S_S and S_1 by the appropriate site coefficients, F_a and F_v, as defined in Table 5-3. For Soil Type B, F_a and F_v are equal to 1.0. For Soil Type E, they vary based on seismicity. The adjusted values are as shown in Table 5-6.

Table 5-6 Median MCER Response Values in Each Seismicity Region Adjusted for Soil Type B and E

Seismicity Region	Basis of Soil Type B Modifiers		Site Class E Factors		Basis of Soil Type E Modifiers	
	F_aS_S (g)	F_VS_1 (g)	F_a	F_v	F_aS_S (g)	F_vS_1 (g)
L	0.20	0.08	2.50	3.50	0.50	0.28
M	0.40	0.16	2.02	3.32	0.81	0.53
MH	0.80	0.32	1.10	2.72	0.88	0.87
H	1.20	0.48	0.90	2.40	1.08	1.15
VH	2.25	0.90	0.90	2.40	2.03	2.16
VH_{max}	3.80	1.50	0.90	2.40	3.42	3.60

Using these adjusted spectral demands, probability of collapse was calculated for each FEMA Building Type and each seismicity region.

Soil Type B Score Modifiers were calculated considering low-rise buildings; that is, the average Score Modifier for one-story, two-story, and three-story was used. Using engineering judgment and consideration of past performance, Soil Type B Score Modifiers for MH in Very High and High seismicity were adjusted from 0.2 and 0.5 to 0.1 and 0.3, respectively.

To capture the interaction that occurs between building height and soil type, separate modifiers are provided for low-rise buildings on Soil Type E (one to three stories) and taller buildings on Soil Type E (> 3 stories).

5.5.2 Vertical and Plan Irregularities

Vertical and Plan irregularity Score Modifiers were calculated for each FEMA Building Type at each seismicity level. The Vertical and Plan Irregularity Score Modifier calculations assume low-rise buildings and Soil Type CD.

The modifiers for severe vertical irregularities were calculated considering a building with both weak story plus soft story deficiencies. Per OSHPD HAZUS Table A6-1, the simultaneous presence of these two deficiencies triggers the use of USB values of α_3 and the collapse factor, as well as SubBase performance values of Δ_C.

The modifiers for moderate vertical irregularities were calculated considering a building with either a weak story or a soft story. Per OSHPD HAZUS Table A6-1, the presence of one of these deficiencies triggers the use of SubBase performance values of α_3, the collapse factor, and Δ_C.

The modifiers for plan irregularity were calculated considering a torsional irregularity. Per OSHPD HAZUS Table A6-1, the presence of a torsional irregularity triggers the use of USB values of Δ_C and SubBase performance values of the collapse factor.

Finally, modifiers were calculated considering both plan and vertical irregularity. For this condition, USB values were used for α_3, the collapse factor, and Δ_C.

Table 5-7 shows how the performance level considered for α_3, Δ_C, and collapse factor vary for each irregularity, and for combined plan plus vertical irregularity.

Table 5-7 Performance Level Considered for Various Irregularities

Parameter	Severe Vertical Irregularity	Moderate Vertical Irregularity	Plan Irregularity	Plan + Vertical Irregularity	Notes
	Performance Level				
α_3	USB	SubBase	Baseline	USB	See Table A-6
Δ_C	SubBase	SubBase	USB	USB	See Table A-9
$P[COL \mid STR_5]$	USB	SubBase	SubBase	USB	See Table A-11
	Weak + Soft Story	*Weak or Soft Story*	*Torsional Irregularity*	*NA*	*OSHPD HAZUS Deficiency*

Specifically, for all of the above irregularity cases, Score Modifiers were calculated assuming pre-1961 values of Δ_C for Low and Moderate seismicity and post-1961 values for High and Very High seismicity. Average values of Δ_C were used for the Moderately High seismicity region.

All of the adjustments described above are reflected in the Appendix A tables. For example, Table A-6 provides unique values of α_3 depending on the presence of Moderate or Severe Vertical Irregularity.

5.5.3 *Pre-Code*

Pre-Code Score Modifiers were calculated for each FEMA Building Type at each seismicity level. The modifier calculations assume low-rise buildings and Soil Type CD.

Pre-Code Score Modifiers were calculated considering USB values of λ. In lieu of the post-1961 SubBase values of $\beta_{C,D}$ that were used for the Basic

Score, pre-1961 SubBase values were used. For all seismicity regions, Zone 3 pre-1961 values of C_S were used.

Resulting Pre-Code Score Modifiers are provided on the Moderate, Moderately High, High, and Very High Data Collection Forms. In the case of Low seismicity, the Basic Scores were adjusted to include these modifiers before being reported on the Low seismicity form as Basic Scores. No Pre-Code Score Modifiers are provided on the Low seismicity form as it is expected that pre-benchmark buildings in Low seismicity were not designed for seismic codes.

5.5.4 Post-Benchmark

Post-Benchmark Score Modifiers were calculated for each FEMA Building Type at each seismicity level. The modifier calculations assume low-rise buildings and Soil Type CD.

Because OSHPD HAZUS was specifically developed to evaluate pre-1973 buildings, it does not provide capacity and fragility parameter values corresponding to the improved performance of post-benchmark buildings.

Within HAZUS, on the other hand, changes in code level trigger changes to capacity and fragility parameter values (C_S, μ, $S_{d,C}$, κ, and $\beta_{S,C}$) and subsequently the probability of collapse for five different code levels: Pre-Code, Low-Code, Moderate-Code, High-Code and Special High-Code. Values of T_e, γ, λ, α_1, α_2, α_3, b_e, and $P[COL|STR_5]$ do not vary by code level.

The mapping shown in Table 5-8 was used to develop Post-Benchmark Score Modifiers in the second edition of FEMA 154. Post-Benchmark Score Modifiers in the Low seismicity region reflected the relative difference in performance between Pre-Code and Low-Code. Similarly, Post-Benchmark Score Modifiers in the High seismicity region reflected the relative difference in performance between Moderate-Code and High-Code.

Table 5-8 Basis of *Second Edition* Post-Benchmark Score Modifiers

Seismicity Region	Code Considered for Developing Basic Scores	Code Considered for Developing Post Benchmark Score Modifiers
Low	Pre-Code	Low-Code
Moderate	Low-Code	Moderate-Code
High	Moderate-Code	High-Code

A slightly altered version of this mapping was used for *Third Edition* scoring, as shown in Table 5-9.

Table 5-9 Basis of *Third Edition* Post-Benchmark Score Modifiers

Seismicity Region	Code Considered for Developing Basic Scores	Code Considered for Developing Post Benchmark Score Modifiers
Low	Pre-Code	Low-Code
Moderate	Low-Code	Moderate-Code
Moderately High	Use average of Moderate and High, Very High values	
High, Very High	Moderate-Code	Special High-Code[1]

[1]Special High-Code was used rather than High-Code because using High-Code resulted in Post-Benchmark Score Modifiers that the project team deemed to be too small. Special High-Code values are taken from HAZUS TM Chapter 6.

To generate *Third Edition* Post-Benchmark modifiers, OSHPD HAZUS values of key parameters (C_S, μ, $S_{d,C}$, κ, and β_c) were multiplied by ratios that approximate the increases provided by HAZUS when changing code levels.

For example, HAZUS TM Table 5.4 shows that C_S for an S3 building is 0.05 for Pre-Code and Low-Code, 0.10 for Moderate-Code, 0.20 for High-Code, and 0.30 for Special High-Code (as back-calculated from values of A_y provided in HAZUS TM Table 6.3a). The Low-Code to Pre-Code ratio for C_S in HAZUS TM is 1.0; thus no adjustment to the value of C_S was made in the Low seismicity region. In the Moderate seismicity region, the value of C_S is doubled when calculating the Post-Benchmark Score Modifier because the Low-Code to Moderate-Code ratio in HAZUS TM is 2.0. In High and Very High seismicity regions, the value of C_S is tripled when calculating the Post-Benchmark Score Modifier because the Special High-Code to Moderate-Code ratio in HAZUS TM is 3.0. In the Moderately High seismicity region, an average ratio of 2.5 was used. Note that the ratios are slightly different for W1 and MH building types. This reflects the unique ratios of C_S for these building types as defined in the HAZUS TM. The calculated ratios are reflected in the post-benchmark values of C_S provided in Table A-2c.

Similar comparisons were made for parameters μ, $S_{d,c}$, κ, and β_C. For most building types, the Low seismicity ratio (Pre-Code to Low-Code) of μ is 1.0, the Moderate seismicity ratio (Low-Code to Moderate-Code) is 1.2, and the Very High and High seismicity ratio (Moderate-Code to Special High-Code) is 1.33. For Post-Benchmark calculations, the baseline values of μ were factored for simplicity by 1.33 for all seismicity regions and all building types to reflect the increased ductility of post-benchmark buildings. These ratios are reflected in Table A-4.

For κ the Low seismicity ratio (Pre-Code to Low-Code) is 1.5, the Moderate seismicity ratio (Low-Code to Moderate-Code) varies between 1.0 and 1.5, and the High and Very High seismicity ratio (Moderate-Code to Special High-Code) varies between 1.33 and 2.0, depending on the building type. For Post-Benchmark calculations for all building types, the baseline values of κ were factored by 1.5 for Low, Moderate, and Moderately High seismicity regions. A factor of 1.67 was used for High and Very High seismicity regions. These ratios are reflected in Table A-8.

For $S_{d,C}$, the ratios vary by building type. For each seismicity region, the ratios were averaged across building types and were applied as follows: 1.25 for Low and Moderate seismicity, 1.5 for Moderately High seismicity, and 1.67 for High and Very High seismicity. Table A-9 presents the values of Δ_C, which is a component of $S_{d,C}$, thus the ratios are evident in this table.

For $\beta_{C,D}$ the ratios again vary by building type. The average ratios resulted in similar post-benchmark values of β_C as using post-1961 Baseline performance values (per OSHPD HAZUS Table A6-11). Hence the OSHPD HAZUS post-1961 values were used for post-benchmark calculations as is reflected in Table A10. Values of β_C were reduced by engineering judgment for S1 buildings to account for the increased reliability expected from post-Northridge steel moment frames.

Finally, β_{CAP} was taken as 0.25 for post-benchmark calculations (versus 0.30 for Basic Score calculations). This reflects the HAZUS variation of β_{CAP} by code level as defined in the HAZUS TM Chapter 5.

The Post-Benchmark Score Modifier results compare favorably with engineering judgment. If a post-benchmark building has no other deficiencies, then it passes the 2.0 cut-off score for all FEMA Building Types in all seismicity regions except for MH buildings in Very High seismicity. When a post-benchmark building also has a severe vertical irregularity, the Post-Benchmark Score Modifier is sufficient such that the Final Score is above the 2.0 cut-off score for all FEMA Building Types from Low to High Seismicity except for MH. There are some building types in the Very High seismicity region that fall below the cut-off score in this case. Given the current value of the seismic demand in this region and the lack of use of near field factors for determining seismic design forces until only recently, this result was judged to be reasonable. MH buildings have a comparatively lower Post-Benchmark Score Modifier as post-benchmark status is not necessarily a guarantee that foundation bracing is fully addressed.

5.5.5 *Minimum Score*

For each FEMA Building Type and each seismicity region, a Minimum Score was calculated considering that all deficiencies exist simultaneously: Values of C_S, λ, α_3, and the collapse factor were selected from the tables in Appendix A considering a Pre-Code building with plan plus vertical irregularity and the worst case soil type.

By definition, the Minimum Score should always be greater than zero, since the probability of complete damage can never be greater than 100%, and the probability of collapse is only a fraction of the probability of complete damage.

For example, consider an S2 building. If the S2 building has a severe vertical irregularity, the collapse factor is 0.30 (per Table A-11). At very large demands and for capacity and fragility parameters related to Pre-Code properties, the probability of complete damage may approach 100%. The probability of collapse would then be 100% × 0.3 = 30%. The associated minimum score is $-\log_{10}(0.30) = 0.52$. Hence, the Minimum Score for S2 in high seismic zones is approximately 0.5. In lower seismicity zones, the Minimum Score increases.

Vertical and Plan Irregularity Score Modifiers are not used on the Data Collection Forms for MH buildings because MH buildings typically do not have these deficiencies in the superstructure. Minimum Scores for MH are set equal to the Basic Score plus the Soil Type E Score Modifier plus the Pre-Code Score Modifier.

5.6 Summary of *Third Edition* Scores

The resulting Basic Scores and Score Modifiers are shown on the Data Collection Forms of FEMA P-154 Appendix B and are shown below in Table 5-10.

5.7 Development of Level 2 Score Modifiers

Using engineering judgment, Level 2 Score Modifiers were anchored to the calculated Level 1 Score Modifiers.

On the Level 2 form, the screener is asked detailed questions about building characteristics that affect seismic performance. To develop the Level 2 Score Modifiers, each condition was associated with a comparable Level 1 condition (e.g., vertical irregularity, plan irregularity, or post-benchmark) and assigned a severity based on engineering judgment. For conditions that greatly influence seismic performance, the full Level 1 Score Modifier was

Table 5-10 *Third Edition* **Basic Scores and Score Modifiers**

Low Seismicity Region																	
FEMA Building Type	**W1**	**W1A**	**W2**	**S1**	**S2**	**S3**	**S4**	**S5**	**C1**	**C2**	**C3**	**PC1**	**PC2**	**RM1**	**RM2**	**URM**	**MH**
Basic Score	6.2	5.9	5.7	3.8	3.9	4.4	4.1	4.5	3.3	4.2	3.5	3.8	3.3	3.7	3.7	3.2	4.6
Severe Vert. Irreg.	-1.5	-1.5	-1.5	-1.4	-1.3	-1.6	-1.2	-1.3	-1.3	-1.2	-1.1	-1.3	-1.1	-1.1	-1.1	-1.2	NA
Moderate Vert. Irreg.	-1.0	-0.9	-0.9	-0.9	-0.8	-1.0	-0.7	-0.7	-0.7	-0.7	-0.6	-0.8	-0.6	-0.6	-0.6	-0.7	NA
Plan Irreg.	-1.6	-1.4	-1.3	-1.2	-1.1	-1.4	-1.0	-1.1	-1.0	-1.0	-0.9	-1.2	-0.9	-0.9	-0.9	-1.0	NA
Pre-Code	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Post-Benchmark	2.2	2.4	2.5	2.0	1.6	1.4	2.1	NA	2.3	2.2	NA	1.9	2.6	2.3	2.3	NA	1.8
Soil Type B	0.9	1.1	1.3	1.0	1.2	0.8	1.3	1.4	0.9	1.2	1.2	1.3	1.3	1.4	1.4	1.3	0.9
Soil Type E - Low-Rise	-1.2	-1.7	-2.3	-1.2	-1.4	-1.0	-1.7	-2.0	-1.4	-2.0	-1.6	-1.7	-1.6	-1.7	-1.7	-1.5	-2.1
Soil Type E - Mid/High-Rise	-1.7	-2.0	-2.2	-1.2	-1.4	NA	-1.7	-1.9	-1.3	-1.9	-1.6	NA	-1.6	-1.6	-1.7	-1.4	NA
Min. Score	2.7	2.1	1.5	0.9	0.8	1.2	0.8	0.9	0.5	0.6	0.5	0.6	0.4	0.6	0.5	0.4	2.5

Moderate Seismicity Region																	
FEMA Building Type	**W1**	**W1A**	**W2**	**S1**	**S2**	**S3**	**S4**	**S5**	**C1**	**C2**	**C3**	**PC1**	**PC2**	**RM1**	**RM2**	**URM**	**MH**
Basic Score	5.1	4.5	3.8	2.7	2.6	3.5	2.5	2.7	2.1	2.5	2.0	2.1	1.9	2.1	2.1	1.7	2.9
Severe Vert. Irreg.	-1.4	-1.4	-1.4	-1.2	-1.2	-1.4	-1.1	-1.2	-1.1	-1.2	-1.0	-1.1	-1.0	-1.1	-1.1	-1.0	NA
Moderate Vert. Irreg.	-0.9	-0.9	-0.9	-0.8	-0.7	-0.9	-0.7	-0.7	-0.7	-0.7	-0.6	-0.7	-0.6	-0.7	-0.7	-0.6	NA
Plan Irreg.	-1.4	-1.3	-1.2	-1.0	-0.9	-1.2	-0.9	-0.9	-0.8	-1.0	-0.8	-0.9	-0.8	-0.8	-0.8	-0.7	NA
Pre-Code	-0.3	-0.5	-0.6	-0.3	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.3	-0.2	-0.2	-0.2	-0.2	-0.1	-0.5
Post-Benchmark	1.4	2.0	2.5	1.5	1.5	0.8	2.1	NA	2.0	2.3	NA	2.1	2.5	2.3	2.3	NA	1.2
Soil Type B	0.7	1.2	1.8	1.1	1.4	0.6	1.5	1.6	1.1	1.5	1.3	1.6	1.3	1.4	1.4	1.3	1.6
Soil Type E - Low-Rise	-1.2	-1.3	-1.4	-0.9	-0.9	-1.0	-0.9	-0.9	-0.7	-1.0	-0.7	-0.8	-0.7	-0.8	-0.8	-0.6	-0.9
Soil Type E - Mid/High-Rise	-1.8	-1.6	-1.3	-0.9	-0.9	NA	-0.9	-1.0	-0.8	-1.0	-0.8	NA	-0.7	-0.7	-0.8	-0.6	NA
Min. Score	1.6	1.2	0.9	0.6	0.6	0.8	0.6	0.6	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.2	1.5

Table 5-10 *Third* Edition Basic Scores and Score Modifiers (Continued)

Moderately High Seismicity Region																	
FEMA Building Type	W1	W1A	W2	S1	S2	S3	S4	S5	C1	C2	C3	PC1	PC2	RM1	RM2	URM	MH
Basic Score	4.1	3.7	3.2	2.3	2.2	2.9	2.2	2.0	1.7	2.1	1.4	1.8	1.5	1.8	1.8	1.2	2.2
Severe Vert. Irreg.	-1.3	-1.3	-1.3	-1.1	-1.0	-1.2	-1.0	-0.9	-1.0	-1.1	-0.8	-1.0	-0.9	-1.0	-1.0	-0.8	NA
Moderate Vert. Irreg.	-0.8	-0.8	-0.8	-0.7	-0.6	-0.8	-0.6	-0.6	-0.6	-0.6	-0.5	-0.6	-0.6	-0.6	-0.6	-0.5	NA
Plan Irreg.	-1.3	-1.2	-1.1	-0.9	-0.8	-1.0	-0.8	-0.7	-0.7	-0.9	-0.6	-0.8	-0.7	-0.7	-0.7	-0.5	NA
Pre-Code	-0.8	-0.9	-0.9	-0.5	-0.5	-0.7	-0.6	-0.2	-0.4	-0.7	-0.1	-0.4	-0.3	-0.5	-0.5	-0.1	-0.3
Post-Benchmark	1.5	1.9	2.3	1.4	1.4	1.0	1.9	NA	1.9	2.1	NA	2.1	2.4	2.1	2.1	NA	1.2
Soil Type B	0.3	0.6	0.9	0.6	0.9	0.3	0.9	0.9	0.6	0.8	0.7	0.9	0.7	0.8	0.8	0.6	0.9
Soil Type E - Low-Rise	0.0	-0.1	-0.3	-0.4	-0.5	0.0	-0.4	-0.5	-0.2	-0.2	-0.4	-0.5	-0.3	-0.4	-0.4	-0.3	-0.5
Soil Type E - Mid/High-Rise	-0.5	-0.8	-1.2	-0.7	-0.7	NA	-0.7	-0.6	-0.6	-0.8	-0.4	NA	-0.5	-0.6	-0.7	-0.3	NA
Min. Score	1.6	1.2	0.8	0.5	0.5	0.9	0.5	0.5	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.2	1.4

High Seismicity Region																	
FEMA Building Type	W1	W1A	W2	S1	S2	S3	S4	S5	C1	C2	C3	PC1	PC2	RM1	RM2	URM	MH
Basic Score	3.6	3.2	2.9	2.1	2.0	2.6	2.0	1.7	1.5	2.0	1.2	1.6	1.4	1.7	1.7	1.0	1.5
Severe Vert. Irreg.	-1.2	-1.2	-1.2	-1.0	-1.0	-1.1	-1.0	-0.8	-0.9	-1.0	-0.7	-1.0	-0.9	-0.9	-0.9	-0.7	NA
Moderate Vert. Irreg.	-0.7	-0.7	-0.7	-0.6	-0.6	-0.7	-0.6	-0.5	-0.5	-0.6	-0.4	-0.6	-0.5	-0.5	-0.5	-0.4	NA
Plan Irreg.	-1.1	-1.0	-1.0	-0.8	-0.7	-0.9	-0.7	-0.6	-0.6	-0.8	-0.5	-0.7	-0.6	-0.7	-0.7	-0.4	NA
Pre-Code	-1.1	-1.0	-0.9	-0.6	-0.6	-0.8	-0.6	-0.2	-0.4	-0.7	-0.1	-0.5	-0.3	-0.5	-0.5	0.0	-0.1
Post-Benchmark	1.6	1.9	2.2	1.4	1.4	1.1	1.9	NA	1.9	2.1	NA	2.0	2.4	2.1	2.1	NA	1.2
Soil Type B	0.1	0.3	0.5	0.4	0.6	0.1	0.6	0.5	0.4	0.5	0.3	0.6	0.4	0.5	0.5	0.3	0.3
Soil Type E - Low-Rise	0.2	0.2	0.1	-0.2	-0.4	0.2	-0.1	-0.4	0.0	0.0	-0.2	-0.3	-0.1	-0.1	-0.1	-0.2	-0.4
Soil Type E - Mid/High-Rise	-0.3	-0.6	-0.9	-0.6	-0.6	NA	-0.6	-0.4	-0.5	-0.7	-0.3	NA	-0.4	-0.5	-0.6	-0.2	NA
Min. Score	1.1	0.9	0.7	0.5	0.5	0.6	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.2	1.0

Table 5-10 *Third Edition* **Basic Scores and Score Modifiers (continued)**

Very High Seismicity Region																	
FEMA Building Type	W1	W1A	W2	S1	S2	S3	S4	S5	C1	C2	C3	PC1	PC2	RM1	RM2	URM	MH
Basic Score	2.1	1.9	1.8	1.5	1.4	1.6	1.4	1.2	1.0	1.2	0.9	1.1	1.0	1.1	1.1	0.9	1.1
Severe Vert. Irreg.	-0.9	-0.9	-0.9	-0.8	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.6	-0.7	-0.7	-0.7	-0.7	-0.6	NA
Moderate Vert. Irreg.	-0.6	-0.5	-0.5	-0.4	-0.4	-0.5	-0.4	-0.3	-0.4	-0.4	-0.3	-0.4	-0.4	-0.4	-0.4	-0.3	NA
Plan Irreg.	-0.7	-0.7	-0.6	-0.5	-0.5	-0.6	-0.4	-0.4	-0.4	-0.5	-0.3	-0.5	-0.4	-0.4	-0.4	-0.3	NA
Pre-Code	-0.3	-0.3	-0.3	-0.3	-0.2	-0.3	-0.2	-0.1	-0.1	-0.2	0.0	-0.2	-0.1	-0.2	-0.2	0.0	0.0
Post-Benchmark	1.9	1.9	2.0	1.0	1.1	1.1	1.5	NA	1.4	1.7	NA	1.5	1.7	1.6	1.6	NA	0.5
Soil Type B	0.5	0.5	0.4	0.3	0.3	0.4	0.3	0.2	0.2	0.3	0.1	0.3	0.2	0.3	0.3	0.1	0.1
Soil Type E - Low-Rise	0.0	-0.2	-0.4	-0.3	-0.2	-0.2	-0.2	-0.1	-0.1	-0.2	0.0	-0.2	-0.1	-0.2	-0.2	0.0	-0.1
Soil Type E - Mid/High-Rise	-0.4	-0.4	-0.4	-0.3	-0.3	NA	-0.3	-0.1	-0.1	-0.3	-0.1	NA	-0.1	-0.2	-0.2	0.0	NA
Min. Score	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.2	1.0

Very High MAX (these values are used for electronic scoring only)																	
FEMA Building Type	W1	W1A	W2	S1	S2	S3	S4	S5	C1	C2	C3	PC1	PC2	RM1	RM2	URM	MH
Basic Score	1.6	1.5	1.5	1.2	1.2	1.3	1.2	1.1	0.9	1.0	0.9	0.9	0.8	0.9	0.9	0.8	1.0
Severe Vert. Irreg.	-0.8	-0.7	-0.7	-0.6	-0.6	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	NA
Moderate Vert. Irreg.	-0.4	-0.4	-0.4	-0.3	-0.3	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	NA
Plan Irreg.	-0.5	-0.5	-0.4	-0.3	-0.3	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	NA
Pre-Code	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Post-Benchmark	1.5	1.4	1.4	0.7	0.7	0.8	0.9	NA	0.9	1.0	NA	0.8	0.8	0.8	0.8	NA	0.2
Soil Type B	0.3	0.3	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.1	0.1	0.0	0.0
Soil Type E - Low-Rise	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soil Type E - Mid/High-Rise	-0.2	-0.2	-0.1	-0.1	-0.1	NA	-0.1	0.0	0.0	-0.1	0.0	NA	0.0	0.0	0.0	0.0	NA
Min. Score	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.2	1.0

used on Level 2. For less significant conditions, only a portion of the Level 1 Score Modifier was used.

5.7.1 Vertical Irregularity Score Modifiers

On the Level 2 form, the screener is asked detailed questions about different types of vertical irregularities. Each vertical irregularity was assigned a severity based on engineering judgment. For severe vertical irregularities, the full Level 1 Score Modifier, V_{L1}, was used on Level 2. For less severe irregularities, only a portion of V_{L1} was used on Level 2. The basis of the Level 2 Vertical Irregularity Score Modifiers is shown in Table 5-11. Based on the rules in Table 5-11, Score Modifiers are defined as shown in Table 5-12.

Where multiple vertical irregularities occur, V_{L2} is the sum of the applicable modifiers, but is subject to a cap. The cap corresponds to the maximum value of V_{L1} for the given seismicity range. These caps are noted on the Level 2 forms.

5.7.2 Plan Irregularity Score Modifiers

On the Level 2 form, the screener is asked detailed questions about different types of plan irregularities. Each plan irregularity was assigned a severity based on engineering judgment. Note that for W1A, W1A with an open front is excluded because the penalty has already been applied in the vertical irregularity section and need not be double counted. In comparison, a torsional irregularity was considered to have a more severe effect on the building's seismic performance than a large diaphragm opening. For severe plan irregularities, the full Level 1 Plan Irregularity Score Modifier, P_{L1}, is applied. For less severe irregularities, only a percentage of P_{L1} is applied. The basis of the Level 2 Plan Irregularity Score Modifiers is shown in Table 5-13. Based on the rules in Table 5-13, Score Modifiers are defined as shown in Table 5-14.

Where multiple plan irregularities occur, P_{L2} is the sum of the applicable modifiers, but is subject to a cap. The cap corresponds to the maximum value of P_{L1} for the given seismicity range. These caps are noted on the Level 2 forms.

Table 5-11 Basis of Level 2 Vertical Irregularity Score Modifiers

Level 2 Statement		Relative Severity of Condition	Basis of Level 2 Score Modifier
Sloping Site	*W1 building:* There is at least a full story grade change from one side of the building to the other.	High	100% of Level 1 Severe Vertical Irregularity Score Modifier for W1
	Non-W1 building: There is at least a full story grade change from one side of the building to the other.	Low	33% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types except W1, W1A, and W2
Weak and/or Soft Story	*W1 building cripple wall:* An unbraced cripple wall is visible in the crawl space.	Moderate	50% of Level 1 Severe Vertical Irregularity Score Modifier for W1
	W1 house over garage: Underneath an occupied story, there is a garage opening without a steel moment frame, and there is less than 8' of wall on the same line (for multiple occupied floors above, use 16' of wall minimum).	High	100% of Level 1 Severe Vertical Irregularity Score Modifier for W1
	W1A building open front: There are openings at the ground story (such as for parking) over at least 50% of the length of the building.	High	100% of Level 1 Severe Vertical Irregularity Score Modifier for W1A
	Non-W1 building: Length of lateral system at any story is less than 50% of that at story above or height of any story is more than 2.0 times the height of the story above.	High	100% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types except W1, W1A, and W2
	Non-W1 building: Length of lateral system at any story is between 50% and 75% of that at story above or height of any story is between 1.3 and 2.0 times the height of the story above.	Moderate	50% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types except W1, W1A, and W2
Setback	Vertical elements of the lateral system at an upper story are outboard of those at the story below causing the diaphragm to cantilever at the offset.	High	100% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
	Vertical elements of the lateral system at upper stories are inboard of those at lower stories.	Moderate	50% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
	There is an in-plane offset of the lateral elements that is greater than the length of the elements.	Low	33% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types

Table 5-11 Basis of Level 2 Vertical Irregularity Score Modifiers (Continued)

Level 2 Statement		Relative Severity of Conditio n	Basis of Level 2 Modifier
Short Column/ Pier	*C1,C2,C3,PC1,PC2,RM1,RM2:* At least 20% of columns (or piers) along a column line in the lateral system have height/depth ratios less than 50% of the nominal height/depth ratio at that level.	Moderat e	50% of average of Level 1 Severe Vertical Irregularity Score Modifiers for C1, C2, C3, PC1, PC2, RM1, and RM2
	C1,C2,C3,PC1,PC2,RM1,RM2: The column depth (or pier width) is less than one half of the depth of the spandrel, or there are infill walls or adjacent floors that shorten the column.	Moderat e	50% of average of Level 1 Severe Vertical Irregularity Score Modifiers for C1, C2, C3, PC1, PC2, RM1, and RM2
Split Level	There is a split level at one of the floor levels or at the roof.	Moderat e	50% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
Other Irregularity	There is another observable severe vertical irregularity that obviously affects the building's seismic performance.	High	100% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
	There is another observable moderate vertical irregularity that may affect the building's seismic performance.	Moderat e	50% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types

Table 5-12 Level 2 Vertical Irregularity Score Modifiers

Level 2 Statement		Level 2 Score Modifier (by Seismicity Region)				
		VH	H	MH	M	L
Sloping Site	*W1 building:* There is at least a full story grade change from one side of the building to the other.	-0.9	-1.2	-1.3	-1.4	-1.5
	Non-W1 building: There is at least a full story grade change from one side of the building to the other.	-0.2	-0.3	-0.3	-0.4	-0.4
Weak and/or Soft Story	*W1 building cripple wall:* An unbraced cripple wall is visible in the crawl space.	-0.5	-0.6	-0.6	-0.7	-0.7
	W1 house over garage: Underneath an occupied story, there is a garage opening without a steel moment frame, and there is less than 8′ of wall on the same line (for multiple occupied floors above, use 16′ of wall minimum).	-0.9	-1.2	-1.3	-1.4	-1.5
	W1A building open front: There are openings at the ground story (such as for parking) over at least 50% of the length of the building.	-0.9	-1.2	-1.3	-1.4	-1.5

Table 5-12 **Level 2 Vertical Irregularity Score Modifiers (continued)**

Level 2 Statement		Level 2 Score Modifier (by Seismicity Region) VH	H	MH	M	L
Weak and/or Soft Story (continued)	*Non-W1 building:* Length of lateral system at any story is less than 50% of that at story above or height of any story is more than 2.0 times the height of the story above.	-0.7	-0.9	-1.0	-1.1	-1.3
	Non-W1 building: Length of lateral system at any story is between 50% and 75% of that at story above or height of any story is between 1.3 and 2.0 times the height of the story above.	-0.4	-0.5	-0.5	-0.6	-0.6
Setback	Vertical elements of the lateral system at an upper story are outboard of those at the story below causing the diaphragm to cantilever at the offset.	-0.7	-1.0	-1.0	-1.2	-1.3
	Vertical elements of the lateral system at upper stories are inboard of those at lower stories.	-0.4	-0.5	-0.5	-0.6	-0.6
	There is an in-plane offset of the lateral elements that is greater than the length of the elements.	-0.2	-0.3	-0.3	-0.4	-0.4
Short Column/ Pier	*C1,C2,C3,PC1,PC2,RM1,RM2:* At least 20% of columns (or piers) along a column line in the lateral system have height/depth ratios less than 50% of the nominal height/depth ratio at that level.	-0.4	-0.5	-0.5	-0.5	-0.6
	C1,C2,C3,PC1,PC2,RM1,RM2: The column depth (or pier width) is less than one half of the depth of the spandrel, or there are infill walls or adjacent floors that shorten the column.	-0.4	-0.5	-0.5	-0.5	-0.6
Split Level	There is a split level at one of the floor levels or at the roof.	-0.4	-0.5	-0.5	-0.6	-0.6
Other Irregularity	There is another observable severe vertical irregularity that obviously affects the building's seismic performance.	-0.7	-1.0	-1.0	-1.2	-1.3
	There is another observable moderate vertical irregularity that may affect the building's seismic performance.	-0.4	-0.5	-0.5	-0.6	-0.6

Table 5-13 Basis of Level 2 Plan Irregularity Score Modifiers

	Level 2 Statement	Relative Severity of Condition	Basis of Level 2 Score Modifier
Plan Irregularity	*Torsional irregularity:* Lateral system does not appear relatively well distributed in plan in either or both directions. *(Do not include the W1A open front irregularity listed above.)*	High	100% of average of Level 1 Plan Irregularity Score Modifiers for all FEMA Building Types
	Non-parallel system: There are one or more major vertical elements of the lateral system that are not orthogonal to each other.	Moderate	50% of average of Level 1 Plan Irregularity Score Modifiers for all FEMA Building Types
	Reentrant corner: Both projections from an interior corner exceed 50% of the overall plan dimension in that direction.	Moderate	50% of average of Level 1 Plan Irregularity Score Modifiers for all FEMA Building Types
	Diaphragm opening: There is an opening in the diaphragm with a width over 50% of the total diaphragm width at that level.	Low	33% of average of Level 1 Plan Irregularity Score Modifiers for all FEMA Building Types
	C1, C2 building out-of-plane offset: The exterior beams do not align with the columns in plan.	Moderate	50% of average of Level 1 Plan Irregularity Score Modifiers for C1 and C2
	Other irregularity: There is another observable plan irregularity that obviously affects the building's seismic performance.	High	100% of average of Level 1 Plan Irregularity Score Modifiers for all FEMA Building Types

Table 5-14 Level 2 Plan Irregularity Score Modifiers

	Level 2 Statement	Level 2 Score Modifier (by Seismicity Region)				
		VH	H	MH	M	L
Plan Irregularity	*Torsional irregularity:* Lateral system does not appear relatively well distributed in plan in either or both directions. *(Do not include the W1A open front irregularity listed above.)*	-0.5	-0.7	-0.8	-1.0	-1.1
	Non-parallel system: There are one or more major vertical elements of the lateral system that are not orthogonal to each other.	-0.2	-0.4	-0.4	-0.5	-0.6
	Reentrant corner: Both projections from an interior corner exceed 50% of the overall plan dimension in that direction.	-0.2	-0.4	-0.4	-0.5	-0.6
	Diaphragm opening: There is an opening in the diaphragm with a width over 50% of the total diaphragm width at that level.	-0.2	-0.2	-0.3	-0.3	-0.4
	C1, C2 building out-of-plane offset: The exterior beams do not align with the columns in plan.	-0.2	-0.4	-0.4	-0.4	-0.5
	Other irregularity: There is another observable plan irregularity that obviously affects the building's seismic performance.	-0.5	-0.7	-0.8	-1.0	-1.1

5.7.3 Other Level 2 Score Modifiers

Other Level 2 modifiers, such as for pounding, retrofits, and building type-specific Level 2 statements, were determined using a similar combination of engineering judgment and Level 1 Score Modifier values. The basis of the other Level 2 Score Modifiers is shown in Table 5-15. Based on the rules in Table 5-15, Score Modifiers are defined as shown in Table 5-16.

Table 5-15 Basis of Other Level 2 Modifiers

Level 2 Statement		Relative Severity of Condition	Basis of Level 2 Score Modifier
Redundancy	The building has at least two bays of lateral elements on each side of the building in each direction.	Low (benefit)	Benefit of 33% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
Pounding	Building is separated from an adjacent structure by less than 1.5% of the height of the shorter of the building and adjacent structure and:The floors do not align vertically within 2 feet.	High	100% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
	One building is 2 or more stories taller than the other.	High	100% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
	The building is at the end of the block.	Moderate	50% of average of Level 1 Severe Vertical Irregularity Score Modifiers for all FEMA Building Types
S2 Building	"K" bracing geometry is visible.	High	100% of Level 1 Severe Vertical Irregularity Score Modifier for S2
C1 Building	Flat plate serves as the beam in the moment frame.	Moderate	50% of Level 1 Severe Vertical Irregularity Score Modifier for C1
PC1/RM1 Bldg	There are roof-to-wall ties that are visible or known from drawings that do not rely on cross-grain bending. *(Do not combine with post-benchmark or retrofit modifier.)*	Low (benefit)	33% of average of Level 1 Severe Vertical Irregularity Score Modifiers for PC1 and RM1
PC1/RM1 Bldg	The building has closely spaced interior walls (rather than an interior space with no walls such as in a warehouse or box store).	Low (benefit)	Benefit of 33% of average of Level 1 Severe Vertical Irregularity Score Modifiers for PC1 and RM1 (similar to redundancy benefit)
URM	Gable walls are present.	Moderate	50% of Level 1 Severe Vertical Irregularity Score Modifier for URM
MH	There is a supplemental seismic bracing system provided between the carriage and the ground.	High (benefit)	100% of Level 1 Post-Benchmark Score Modifier for MH
Retrofit	Comprehensive seismic retrofit is visible or known from drawings.	Moderately High (benefit)	Benefit of 75% of average of Level 1 Post-Benchmark Score Modifiers for all FEMA Building Types

Table 5-16 Other Level 2 Score Modifiers

Level 2 Statement		Level 2 Score Modifier (by Seismicity Region) VH	H	MH	M	L
Redundancy	The building has at least two bays of lateral elements on each side of the building in each direction.	0.2	0.3	0.3	0.4	0.4
Pounding	Building is separated from an adjacent structure by less than 1.5% of the height of the shorter of the building and adjacent structure and: The floors do not align vertically within 2 feet.	-0.7	-1.0	-1.0	-1.2	-1.3
	One building is 2 or more stories taller than the other.	-0.7	-1.0	-1.0	-1.2	-1.3
	The building is at the end of the block.	-0.4	-0.5	-0.5	-0.6	-0.6
S2 Building	"K" bracing geometry is visible.	-0.7	-1.0	-1.0	-1.2	-1.3
C1 Building	Flat plate serves as the beam in the moment frame.	-0.3	-0.4	-0.5	-0.5	-0.6
PC1/RM1 Bldg	There are roof-to-wall ties that are visible or known from drawings that do not rely on cross-grain bending. *(Do not combine with post-benchmark or retrofit modifier.)*	0.2	0.3	0.3	0.4	0.4
PC1/RM1 Bldg	The building has closely spaced interior walls (rather than an interior space with no walls such as in a warehouse or box store).	0.2	0.3	0.3	0.4	0.4
URM	Gable walls are present.	-0.3	-0.4	-0.4	-0.5	-0.6
MH	There is a supplemental seismic bracing system provided between the carriage and the ground.	0.5	1.2	1.2	1.2	1.8
Retrofit	Comprehensive seismic retrofit is visible or known from drawings.	1.2	1.4	1.4	1.4	1.6

Where multiple pounding conditions occur, the sum of the applicable Score Modifiers is used, subject to a cap. The cap for pounding is the same as the vertical irregularity cap. These caps are noted on the Level 2 forms.

Some comments on the rationale underlying the relative severity and basis for the modifiers in Table 5-16 are as follows.

- *Redundancy:* Design standards such as ASCE/SEI 7-10 penalize structural systems that do not meet certain criteria related to redundancy. In rapid visual screening, when redundancy is observed due to multiple bays of lateral elements on each side of the building, a benefit is considered warranted, but the benefit is considered relatively low compared to other structural attributes in the absence of calculations.
- *Pounding:* There are a variety of pounding configurations, as discussed in Chapter 6. The configurations where floors in adjacent buildings do not align or there is a significant difference in the number of stories between the two structures are considered to be somewhat similar to a severe vertical irregularity such as a soft story as they can clearly lead to the potential for increasing the risk of collapse. Buildings at the end of blocks have performed worse than those in the middle of blocks, but the increase in the risk of actual collapse is considered to be moderate.
- *S2 building with "K" bracing:* "K" bracing has been prohibited for use in resisting seismic loading in design standards such as ANSI/AISC 341-10 (AISC, 2010), due to the risk of column buckling after compression buckling of one of the braces intersecting the column. While the failure would be local, FEMA P-154 rapid visual screening is intended to address partial collapse as well as full collapse. Thus, K-bracing is considered similar to the full value of a severe vertical irregularity such as a soft story.
- *C1 building with a flat plate moment frame:* When a concrete moment frame lacks a dropped beam running through the column, the risk of a punching shear failure at the column is increased. This is viewed as a moderate deficiency in the absence of calculations.
- *PC1/RM1 building with roof-to-wall ties that do not rely on cross-grain bending:* Many PC1 or RM1 buildings will not have ceilings, and the connection at the roof-to-wall intersection may be visible during an interior visit. Historic detailing often relied on a connection with a ledger bolted to the wall and the wood roof nailed to the top of the ledger. The vertical eccentricity between these connection points during out-of-plane loading places the ledger in cross-grain bending, a particularly weak and brittle mode of behavior in wood that is no longer permitted. If modern tension ties and hardware are observed that do not rely on cross-grain bending, then a benefit is given. In the absence of calculations, it is considered a relatively low benefit.

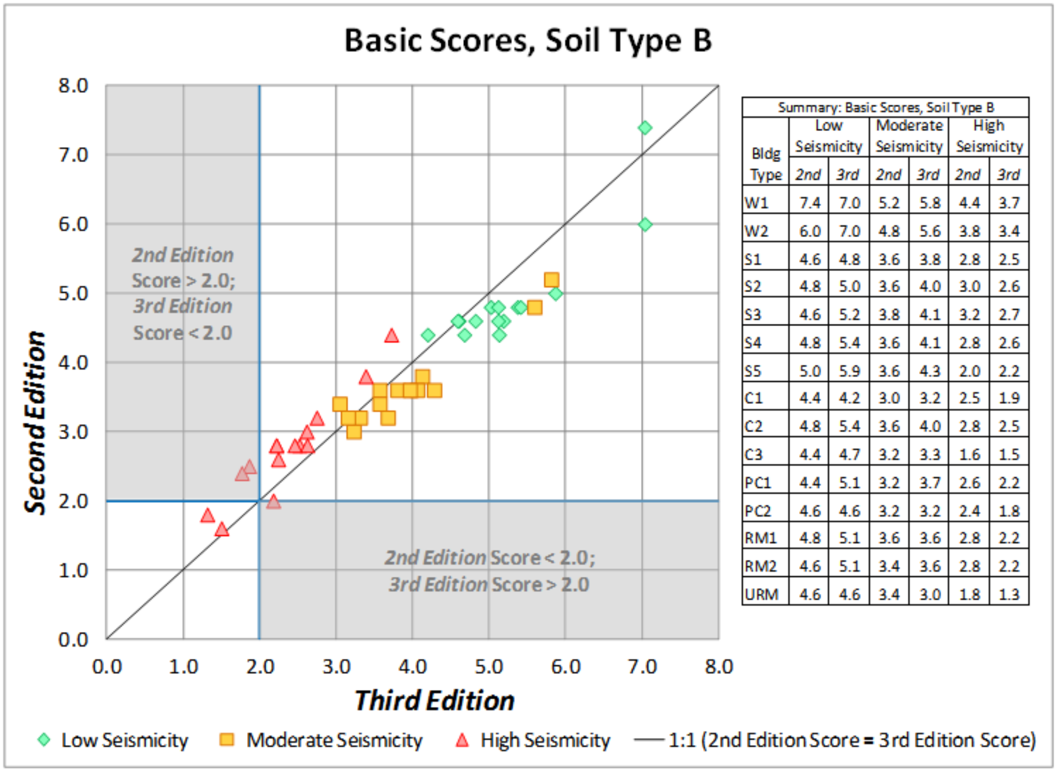
- *PC1/RM1 building with closely spaced walls:* Typical PC1 and RM1 buildings are assumed to be similar to warehouses and have limited if any interior partitions that can improve redundancy and provide additional damping. However, when the buildings are used for offices or some other uses, they may have relatively closely spaced partitions that can provide some redundancy for carrying gravity loads and additional damping. In the absence of calculations, this is considered a relatively low benefit.
- *URM with gable walls:* Gable walls have a poor history of performance. In some cases, an out-of-plane wall failure might lead to compromising gravity support for the roof above. This is considered a relatively moderate hazard as there are many buildings that have had out-of-plane gable failures, but have not necessarily had collapses.
- *MH with a supplemental seismic bracing system:* 100% of the post-benchmark modifier is assigned as lack of bracing under the carriage is the critical seismic issue with MH buildings, and a supplemental bracing system thus addresses the primary issue of concern.
- *Retrofit:* As noted in FEMA P-154, to qualify for the retrofit modifier, the retrofit needs to be known to be comprehensive. Many retrofit standards use 75% of current code level of forces when designing seismic force-resisting elements. As such, 75% of the average Post-Benchmark Score Modifier was considered to be a reasonable value for the Level 2 retrofit modifier.

5.8 Comparison of *Second Edition* and *Third Edition* Scores

The following two plots show comparisons of the *Second Edition* Basic Scores to the updated *Third Edition* Basic Scores. Figure 5-5 shows a comparison of the Basic Scores when the buildings are on Soil Type B, which was the default in the *Second Edition.*

Figure 5-6 shows a comparison of the Basic Scores when the buildings are on Soil Type CD, which is the default for the *Third Edition*. Data points above the diagonal 1:1 line indicate the *Second Edition* scores are higher; data points below the line indicate the *Third Edition* scores are higher. In general, scores fall relatively close to the 1:1 line.

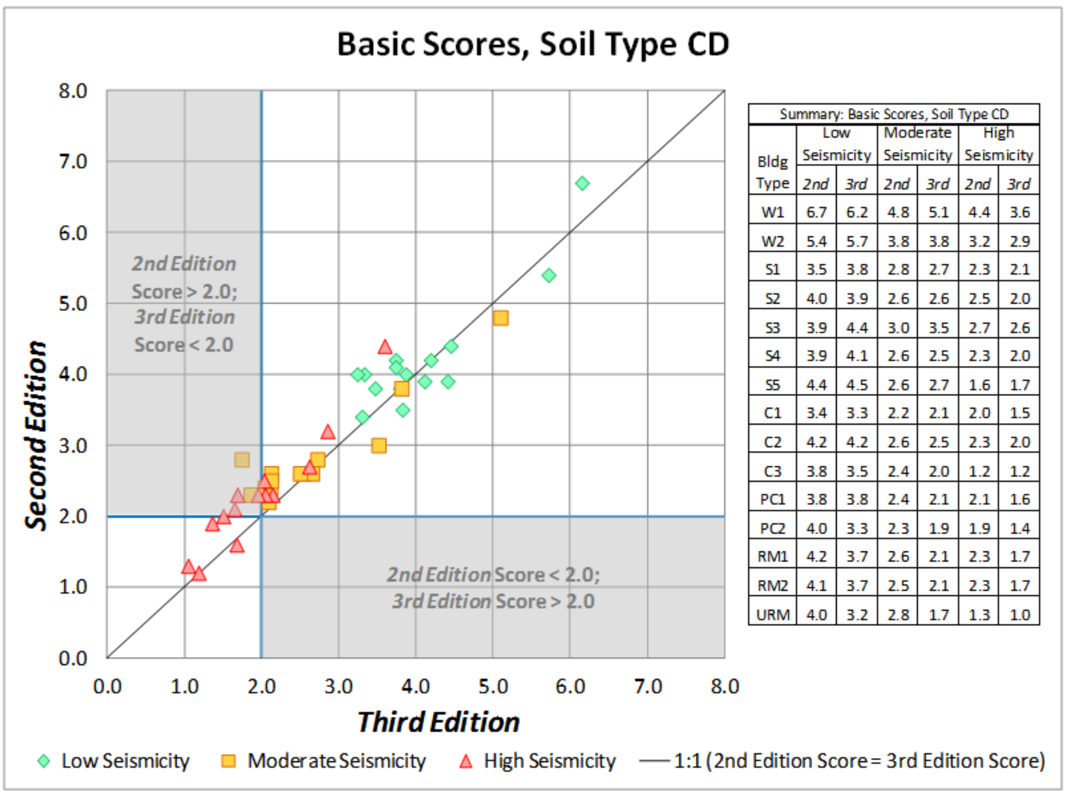
For Soil Type B, the *Third Edition* scores are somewhat lower in the High seismicity region, and a bit higher for Moderate and Low seismicity regions. For Soil Type CD, the scores straddle the 1:1 line more closely in all regions. The shaded zones represent areas where in one edition, the score is below 2.0



Summary: Basic Scores, Soil Type B

Bldg Type	Low Seismicity		Moderate Seismicity		High Seismicity	
	2nd	*3rd*	*2nd*	*3rd*	*2nd*	*3rd*
W1	7.4	7.0	5.2	5.8	4.4	3.7
W2	6.0	7.0	4.8	5.6	3.8	3.4
S1	4.6	4.8	3.6	3.8	2.8	2.5
S2	4.8	5.0	3.6	4.0	3.0	2.6
S3	4.6	5.2	3.8	4.1	3.2	2.7
S4	4.8	5.4	3.6	4.1	2.8	2.6
S5	5.0	5.9	3.6	4.3	2.0	2.2
C1	4.4	4.2	3.0	3.2	2.5	1.9
C2	4.8	5.4	3.6	4.0	2.8	2.5
C3	4.4	4.7	3.2	3.3	1.6	1.5
PC1	4.4	5.1	3.2	3.7	2.6	2.2
PC2	4.6	4.6	3.2	3.2	2.4	1.8
RM1	4.8	5.1	3.6	3.6	2.8	2.2
RM2	4.6	5.1	3.4	3.6	2.8	2.2
URM	4.6	4.6	3.4	3.0	1.8	1.3

Figure 5-5 Comparison of *Second Edition* and *Third Edition* Basic Scores on Soil Type B.



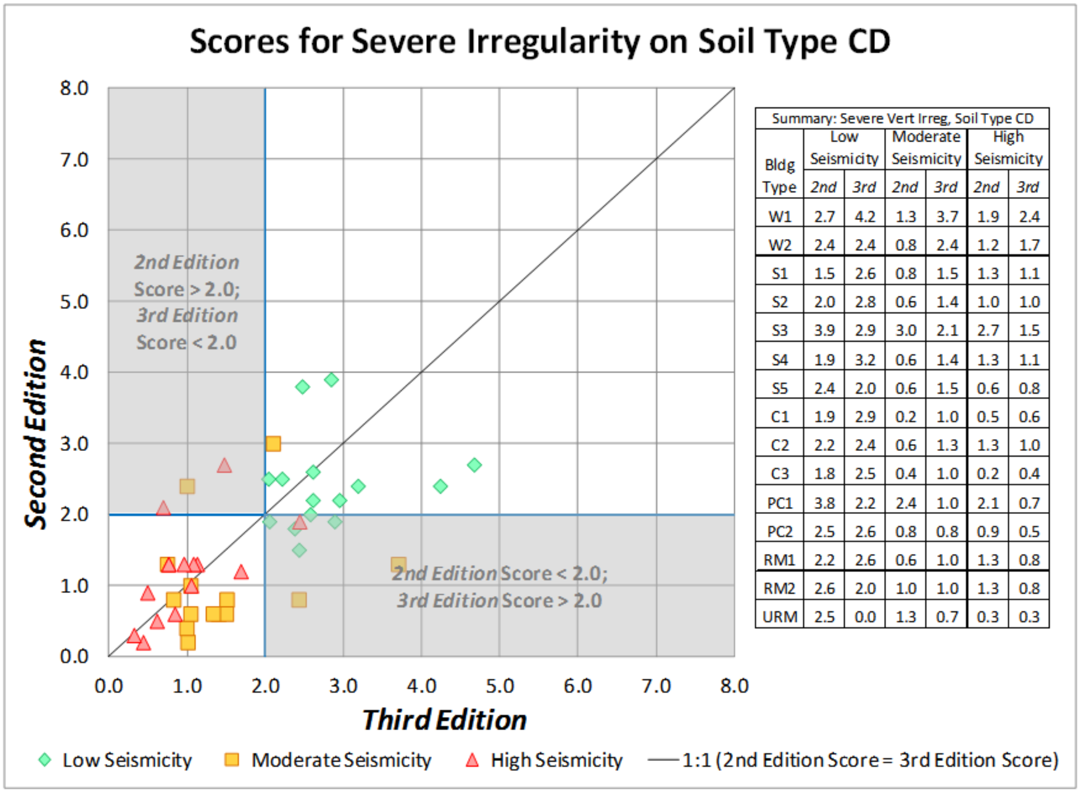
Summary: Basic Scores, Soil Type CD

Bldg Type	Low Seismicity		Moderate Seismicity		High Seismicity	
	2nd	*3rd*	*2nd*	*3rd*	*2nd*	*3rd*
W1	6.7	6.2	4.8	5.1	4.4	3.6
W2	5.4	5.7	3.8	3.8	3.2	2.9
S1	3.5	3.8	2.8	2.7	2.3	2.1
S2	4.0	3.9	2.6	2.6	2.5	2.0
S3	3.9	4.4	3.0	3.5	2.7	2.6
S4	3.9	4.1	2.6	2.5	2.3	2.0
S5	4.4	4.5	2.6	2.7	1.6	1.7
C1	3.4	3.3	2.2	2.1	2.0	1.5
C2	4.2	4.2	2.6	2.5	2.3	2.0
C3	3.8	3.5	2.4	2.0	1.2	1.2
PC1	3.8	3.8	2.4	2.1	2.1	1.6
PC2	4.0	3.3	2.3	1.9	1.9	1.4
RM1	4.2	3.7	2.6	2.1	2.3	1.7
RM2	4.1	3.7	2.5	2.1	2.3	1.7
URM	4.0	3.2	2.8	1.7	1.3	1.0

Figure 5-6 Comparison of *Second Edition* and *Third Edition* Basic Scores on Soil Type CD.

and in the other edition it is above 2.0. For example, in Soil Type B, a couple of building types are in the upper shaded zone, meaning they scored above 2.0 in the *Second Edition*, but would be just below 2.0 in the *Third Edition*. Thus, rescreening would be recommended. For Soil Type CD, there are building types also in the Moderate seismicity region that would fall in this category. There are no buildings in the lower shaded zone, meaning they scored below 2.0 in the *Second Edition*, but above in the *Third Edition*. Above comparisons are only for Basic Scores.

When Score Modifiers are considered, the results are more diverse. Figure 5-7 shows a comparison of the scores when the building is on Soil Type CD and has a Vertical Irregularity in the *Second Edition* (or a Severe Vertical Irregularity in the *Third Edition*).



Summary: Severe Vert Irreg, Soil Type CD						
Bldg Type	Low Seismicity		Moderate Seismicity		High Seismicity	
	2nd	*3rd*	*2nd*	*3rd*	*2nd*	*3rd*
W1	2.7	4.2	1.3	3.7	1.9	2.4
W2	2.4	2.4	0.8	2.4	1.2	1.7
S1	1.5	2.6	0.8	1.5	1.3	1.1
S2	2.0	2.8	0.6	1.4	1.0	1.0
S3	3.9	2.9	3.0	2.1	2.7	1.5
S4	1.9	3.2	0.6	1.4	1.3	1.1
S5	2.4	2.0	0.6	1.5	0.6	0.8
C1	1.9	2.9	0.2	1.0	0.5	0.6
C2	2.2	2.4	0.6	1.3	1.3	1.0
C3	1.8	2.5	0.4	1.0	0.2	0.4
PC1	3.8	2.2	2.4	1.0	2.1	0.7
PC2	2.5	2.6	0.8	0.8	0.9	0.5
RM1	2.2	2.6	0.6	1.0	1.3	0.8
RM2	2.6	2.0	1.0	1.0	1.3	0.8
URM	2.5	0.0	1.3	0.7	0.3	0.3

Figure 5-7 Comparison of *Second Edition* and *Third Edition* Scores with a Severe Vertical Irregularity on Soil Type CD.

As shown in Figure 5-7, in the Moderate seismicity region, the *Third Edition* score is 3.7, 2.4, and 2.1, for W1, W2, and S3 buildings, respectively, on Soil Type CD with a vertical irregularity. All the other buildings have scores below 2.0. In the High seismicity region, the W1 building has a score of 2.4, with the rest below 2.0. The W1 building with severe vertical irregularity falls in the lower shaded zone meaning that it scored below 2.0 in the *Second Edition*. If the Severe Vertical Irregularity Score Modifier in the *Third*

Edition were increased, then the points in the lower shaded zone would move to the left and be below the 2.0 cut-off, consistent with the *Second Edition* scores. For Soil Type B, there would be many more that would fall in this category, as the calculations for the *Third Edition* yield somewhat lower irregularity modifiers than those in the *Second Edition*.

Figure 5-8 shows a comparison of the *Second Edition* and *Third Edition* scores for post-benchmark buildings on Soil Type CD. The Post-Benchmark Score Modifier increases the scores such that nearly all FEMA Building Types are above the cut-off score. The *Third Edition* scores are somewhat smaller than the *Second Edition* scores.

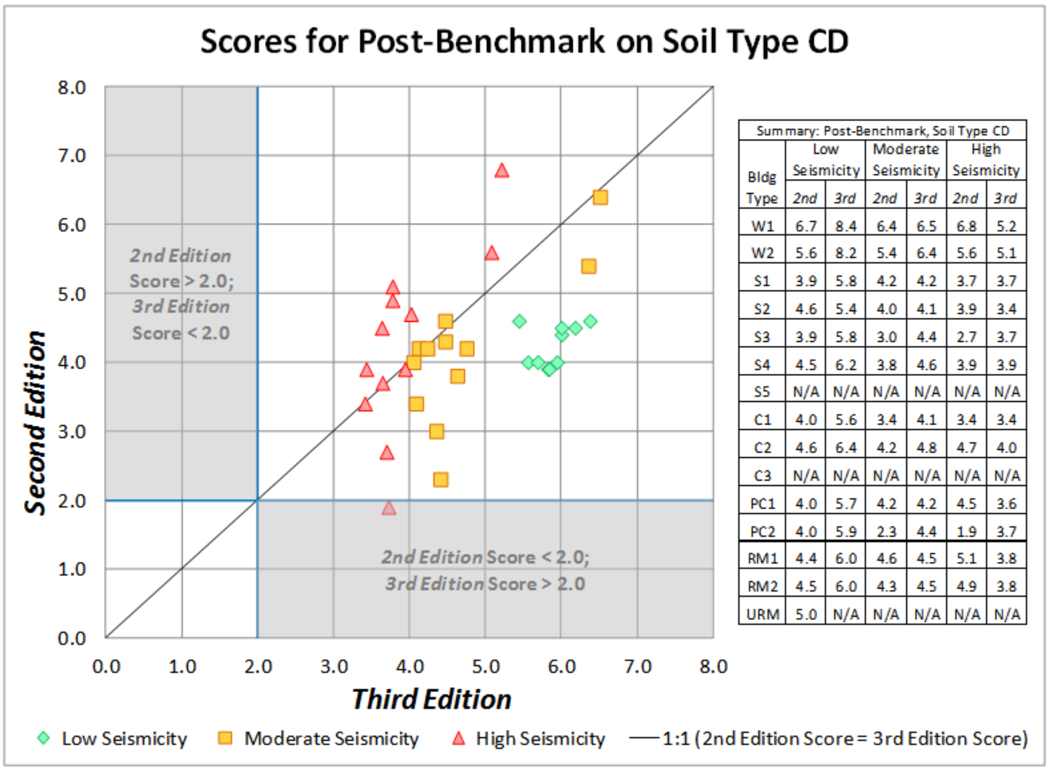


Figure 5-8 Comparison of *Second Edition* and *Third* Edition Scores on Soil Type CD with Post-Benchmark Score Modifiers.

Figure 5-9 shows a comparison of the *Second Edition* and *Third Edition* scores for high-rise buildings on Soil Type E. Because the high-rise benefit of the *Second Edition* is not provided in the *Third Edition*, many of the buildings fall in the upper shaded zone.

With the updated *Third Edition* Scores, the relative ranking of the different building types has changed. Consider, for example, the relative rankings for High seismicity. Table 5-17 shows a ranking of the building types of the *Second Edition* by Basic Score. Only three of the building types, C3, S5, and URM, had Basic Scores less than or equal to 2.0.

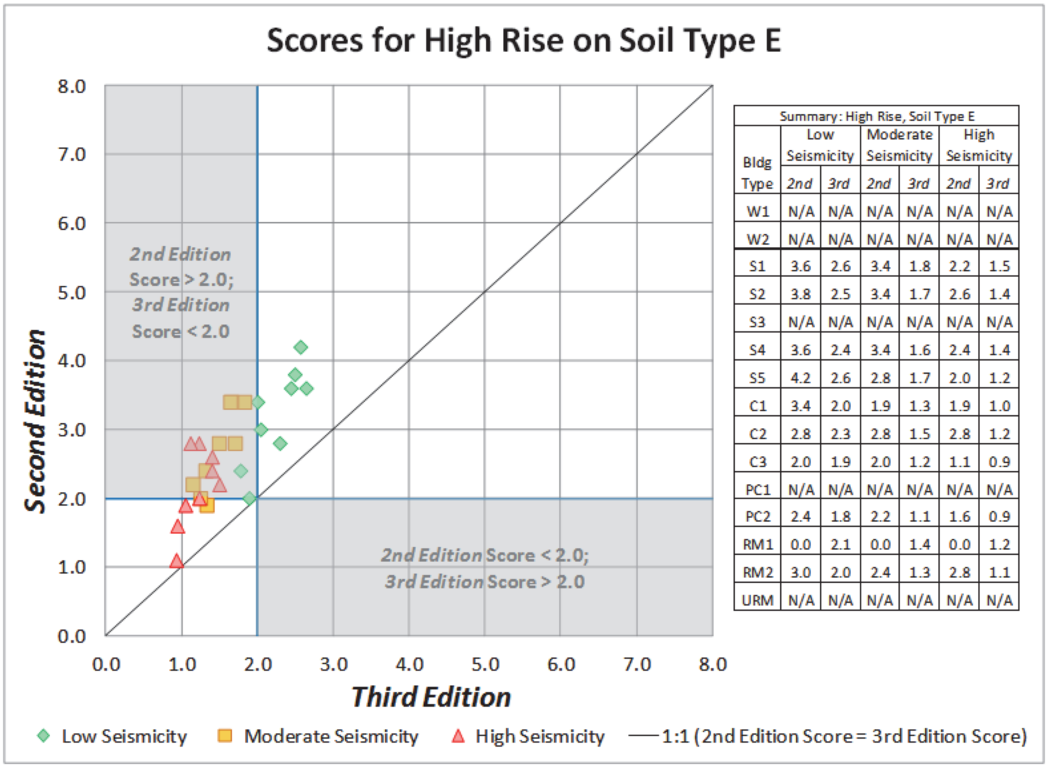


Figure 5-9 Comparison of *Second Edition* and *Third Edition* Scores on Soil Type E with more than seven stories.

Table 5-17 *Second Edition* Basic Scores and Rankings in High Seismicity (Using Soil Type B)

	C3	URM	S5	PC2	C1	PC1	S1	S4	C2	RM1	RM2	S2	S3	W2	W1
	1.6	1.8	2.0	2.4	2.5	2.6	2.8	2.8	2.8	2.8	2.8	3.0	3.2	3.8	4.4

Third Edition Basic Scores (adjusted for Soil Type B) result in the revised rankings shown in Table 5-18. Five of the building types, URM, C3, PC2, MH, and C1, have Basic Scores less than or equal to 2.0.

Table 5-18 *Third Edition* Basic Scores and Rankings in High Seismicity (Using Soil Type B)

	URM	C3	PC2	MH	C1	S5	RM2	RM1	PC1	C2	S1	S2	S4	S3	W2	W1A	W1
	1.3	1.5	1.8	1.8	1.9	2.2	2.2	2.2	2.2	2.5	2.5	2.6	2.6	2.7	3.4	3.6	3.7

The updated *Third Edition* scores for the Low seismicity region are generally comparable to the *Second Edition* values. Table 5-19 shows a comparison of the *Third Edition* Basic Scores (adjusted to Soil Type B) with the *Second Edition* Basic Scores. Also shown are the minimum possible scores with the *Third Edition* (using *Third Edition* calculated "Minimum Scores") and the

Second Edition (summing the Basic Score with the worst possible combination of modifiers).

Table 5-19 *Second Edition* and *Third Edition* Basic Scores (using Soil Type B) and Minimum Scores in Low Seismicity

Second Edition	W1	W1A	W2	S1	S2	S3	S4	S5	C1	C2	C3	PC1	PC2	RM1	RM2	URM	MH
Basic Score	7.4	NA	6.0	4.6	4.8	4.6	4.8	5.0	4.4	4.8	4.4	4.4	4.6	4.8	4.6	4.6	NA
Min. Score	0.8	NA	0.2	-0.2	0.0	1.8	-0.2	0.2	0.1	0.0	-0.4	1.8	0.3	0.6	0.7	0.9	NA
Third Edition																	
Basic Score (Soil Type B)	7.0	7.0	7.0	4.8	5.0	5.2	5.4	5.9	4.2	5.4	4.7	5.1	4.6	5.1	5.1	4.6	5.5
Min. Score	2.7	2.1	1.5	0.9	0.8	1.2	0.8	0.9	0.5	0.6	0.5	0.6	0.4	0.6	0.5	0.4	2.5

In the Low seismicity region, two building types will never fall below the cut-off score in the *Third Edition* (W1 and W1A), whereas in the *Second Edition*, it was possible for any building type to fall below the cut-off score.

The MH building type was not included in the *Second Edition* procedure; therefore, the *Second Edition* and *Third Edition* scores cannot be compared. Review of damage data to MH buildings after the 1994 Northridge earthquake helped confirm that the Basic Score of less than 2.0 for MH in High seismicity was appropriate. Considering the damage data, the Basic Scores and Soil Type B Score Modifiers for MH in High and Very High were reduced so that non-post-benchmark MH buildings on Soil Type B in these high seismicity regions will receive Level 1 scores less than 2.0.

Chapter 6

Pounding

6.1 Introduction

Consideration of pounding effects between adjacent buildings has been added to the rapid visual screening in the *Third Edition*. This chapter summarizes the research and literature that was considered, how it was synthesized into the criteria used in FEMA P-154, and the basis of the quantitative values in the criteria.

6.2 Overview and Background Research

Building pounding issues can arise when structures are built in close proximity. This becomes a particularly important factor when considering older existing buildings where setback requirements may not have been in force at the time of construction and developments maximized the use of the property.

Damage from adjacency and pounding has been observed in many different earthquakes and regions. Buildings have been subject to moderate to severe damage and collapse, causing concern that this type of effect needs to be better identified as a consideration during rapid visual evaluations.

A number of resources were used to help define and develop the criteria for pounding in the third edition of FEMA P-154. The literature available is relatively new and due to the complexity of the issue sometimes contradictory. There are, however, some basic parameters that can be used to identify potential problems caused by adjacent buildings pounding together, such as building separation, alignment of floor and roof levels, height differences, and end-of-row considerations.

The following is a brief review of selected resources used to develop the pounding criteria in the Level 1 and Level 2 screening forms.

6.2.1 Previous Editions of FEMA 154 and FEMA 155

The first edition of FEMA 155 (FEMA, 1988b) noted that certain site aspects, such as pounding, corner buildings, and adjacencies, had been used as identifying criteria in the prior survey methods, and might be useful for rapid visual screening procedure.

This set of attributes was reduced to a single consideration for pounding for FEMA 154 (FEMA, 1988a). The effect was used as a Score Modifier (-0.5) for S1, S2, S4, C1, and PC2 building types for the Low, Medium, and High NEHRP map areas. Presumably, this recognized the flexibility of certain building types as a key contributing factor in building pounding. The Score Modifier trigger occurred where there was inadequate seismic clearance between buildings and when adjacent building floor heights differed so that one building's floors would impact the neighboring building's columns at locations away from floor levels and thus weaken the columns.

This Score Modifier was subsequently dropped in the second edition of FEMA 154 (FEMA, 2002a) to facilitate the screening effort by shortening the effort necessary to complete the form.

6.2.2 Building Pounding State of Art: Identifying Structures Vulnerable to Pounding Damage

Building Pounding State of the Art: Identifying Structures Vulnerable to Pounding Damage (Cole et al., 2012) was created to help engineers using the New Zealand Initial Evaluation Procedure (IEP) in *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes including Corrigenda Nos. 1 and 2* (NZSEE, 2012) understand the background and basis of pounding. It describes fundamental concepts of building response under earthquake forces and categorizes pounding into two general cases: floor-to-floor and floor-to-column, as shown in Figure 6-1.

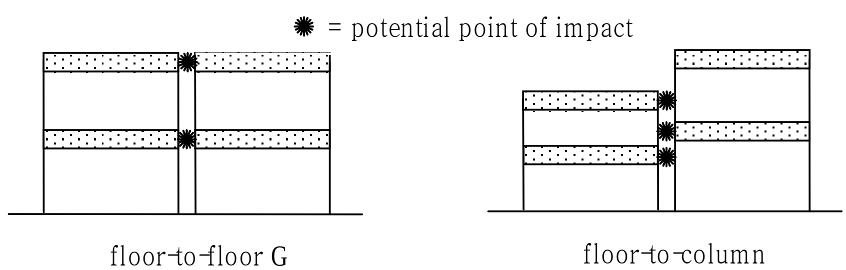


Figure 6-1 Pounding categorization (NZSEE, 2012).

Building Pounding State of the Art contains a review of the available literature on pounding and presents six critical building configurations vulnerable to pounding that could affect the likelihood of structural collapse taken from Jeng and Tzeng (2000). The six configurations are shown in Figure 6-2 and are as follows.

1. Floor-to-column
2. Adjacent buildings with greatly differing mass
3. Buildings with significantly different heights

4. External (end) buildings in a row
5. Buildings subject to horizontal plan torsion
6. Buildings made of brittle materials

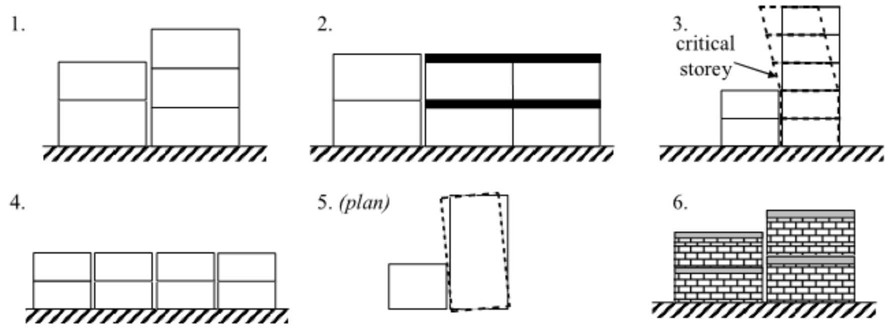


Figure 6-2 Critical pounding configurations (Jeng and Tzeng, 2000).

Cole, et al. (2012) observed that buildings subject to pounding, but without the above characteristics are less likely, to experience detrimental effects. It was also noted that very little consensus exists at this time regarding generic building performance, and criteria such as separation distances and building mass are difficult to assess.

For the third edition of FEMA P-154, three of the six building configurations above were deemed important to capture: floor-to-column, buildings with significantly different heights, and external (end) buildings in a row.

6.2.3 Assessment and Improvement of the Structural Performance of Buildings in Earthquakes

Assessment and Improvement of the Structural Performance of Buildings in Earthquakes was prepared at the request of the New Zealand Building Industry Authority to provide a consistent means for Territorial Authorities to use in assessing the earthquake performance of pre-1976 buildings. It establishes a method for identifying Earthquake Prone Buildings as described in The Building Act of 2004 as administered by the New Zealand Department of Building and Housing (now part of the Ministry of Business, Innovation, and Employment).

The guidelines cover a full range of topics including prioritization, initial evaluation, detailed assessment, and improvement measures. The Initial Evaluation Procedure (IEP) contains within it specific measures to identify and quantify the effects of building pounding. The process is similar to the rapid visual screening in FEMA P-154 in that a basic score is established and then modified by known building and site features that reduce seismic capacities.

There are two basic configurations considered – floor alignments and building height differences. These conditions, when met, generate factors D1 and D2 that are further graded according to the severity of the deficiency. The lesser of D1 or D2 is then used in the computation of the final grade and structural performance score.

The D1 and D2 factors assume the building has a frame structure and allows for reduction of these values if it is a stiff, or shear wall, structure. Figure 6-3 shows a page from the *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes* IEP screening form where pounding is addressed.

6.2.4 Adjacency Issues in Soft-Story Wood Frame Buildings

Adjacency Issues in Soft-Story Wood-Framed Buildings (Maison et al., 2011) was prepared for the Structural Engineers Association of Northern California to help characterize the damage observed to multi-story wood frame buildings during the 1989 Loma Prieta earthquake in San Francisco.

The study used computer modeling to simulate actual earthquake response and analyzed twenty-two hypothetical pounding situations for both as-built and retrofitted buildings. The findings revealed that for a typical pounding situation there was a 14% increase in the collapse rate for corner buildings at design earthquake intensities.

The study revealed that there were several factors that appeared to significantly increase the potential collapse rate including negligible building separations and multiple adjacent buildings having low effective damping and large mass. Conditions that appeared to have no discernible effect on collapse rate included effective periods common to adjacent buildings in a row and whether the adjacent buildings were modeled as rigid or flexible diaphragms.

6.2.5 ASCE/SEI 41-13 Seismic Evaluation of Existing Buildings

ASCE/SEI 41-13, *Seismic Evaluation of Existing Buildings* (ASCE, 2014), recognizes the influence of adjacent buildings in Commentary Section C3.2.5.1 on Building Pounding:

> *"Building pounding can alter the basic response of the building to ground motion and impart additional inertial loads and energy to the building from the adjacent structure. Of particular concern is the potential for extreme local damage to structural elements at the zones of impact, particularly where the floor and roof levels of adjacent building do not align in height."*

Building Name | **Ref.**
Location | **By**
Direction Considered: a) Longitudinal b) Transverse
(Choose worse case if clear at start. Complete IEP-1 and IEP-2 for each if in doubt) | **Date**

Step 3 - Assessment of Performance Achievement Ratio (PAR)
(Refer 3.4.3 - Section B3.2)

Critical Structural Weakness	Building Score	Effect on Structural Performance *(Choose a value - Do not interpolate)*		
3.1 Plan Irregularity *Effect on Structural Performance*		Severe	Significant	Insignificant
Comment	**Factor A**	0.4 max	0.7	1
3.2 Vertical Irregularity *Effect on Structural Performance*		Severe	Significant	Insignificant
Comment	**Factor B**	0.4 max	0.7	1
3.3 Short Columns *Effect on Structural Performance*		Severe	Significant	Insignificant
Comment	**Factor C**	0.4 max	0.7	1

3.4 Pounding Potential
(Estimate D1 and D2 and set D = the lower of the two, or =1.0 if no potential for pounding)

a) Factor D1: - Pounding Effect
Select appropriate value from Table

Note:
Values given assume the building has a frame structure. For stiff buildings (eg with shear walls), the effect of pounding may be reduced by taking the co-efficient to the right of the value applicable to frame buildings.

Factor D1

Table for Selection of Factor D1	Severe	Significant	Insignificant
Separation	0<Sep<.005H	.005<Sep<.01H	Sep>.01H
Alignment of Floors within 20% of Storey Height	0.7	0.8	1
Alignment of Floors not within 20% of Storey Height	0.4	0.7	0.8

b) Factor D2: - Height Difference Effect
Select appropriate value from Table

Factor D2

Table for Selection of Factor D2	Severe	Significant	Insignificant
	0<Sep<.005H	.005<Sep<.01H	Sep>.01H
Height Difference > 4 Storeys	0.4	0.7	1
Height Difference 2 to 4 Storeys	0.7	0.9	1
Height Difference < 2 Storeys	1	1	1

Factor D ***(Set D = lesser of D1 and D2 or.. set D = 1.0 if no prospect of pounding)***

3.5 Site Characteristics - *(Stability, landslide threat, liquefaction etc)*

Effect on Structural Performance	Severe	Significant	Insignificant
Factor E	0.5 max	0.7	1

3.6 Other Factors

Factor F

This factor is included to enable allowance for other characteristics of the building to be taken into account.
These may be beneficial or detrimental to the structural performance. For ≤ 4 storeys - Maximum value 2.0. No minimu
otherwise - Maximum value 1.5. No minimun

Record rationale for choice of Factor F

....

....

3.7 Performance Achievement Ratio (PAR)
(equals **A x B x C x D x E x F**)

Figure 6-3 Initial Evaluation Procedure in NZSEE (2012).

ASCE/SEI 41-13 requires that data "be collected to permit evaluation of the effects of building pounding, wherever a portion of an adjacent structure is located within 4% of the height above grade at the location of potential impact." The evaluation procedure uses the square root sum of the squares (SRSS) criteria allowing the drift of the adjacent building to be estimated using available information. The total building separation need not exceed 4% of the height of the shorter building.

For Structural Performance Levels of Life Safety or lower, buildings adjacent to structures that have diaphragms located at the same elevation and differ in height by less than 50% of the height of the shorter building need not meet the minimum separation distance.

Additionally, ASCE/SEI 41-13 establishes certain drift limits in the Structural Performance Levels for vertical building elements at Collapse Prevention. For frame elements, the drifts vary from 2% to 4%. For wall elements, the drift ranges from 0.6% to 3%.

A final consideration of note is that if a potential collapse hazard exists due to pounding, then there is a responsibility to report such to the neighboring property owner.

6.2.6 The Performance of Unreinforced Masonry Buildings in the 2010/2011 Canterbury Earthquake Swarm

The Performance of Unreinforced Masonry Buildings in the 2010/2011 Canterbury Earthquake Swarm (Ingham and Griffith, 2011) report was created to be a resource document to parties planning to make submissions to the Royal Commission of Inquiry into Building Failure Caused by the Canterbury Earthquakes. It provides information regarding the characteristics and performance of unreinforced masonry (URM) buildings in the Central Business District, as well as commentary on the adequacy of current practice and methodologies being considered for adoption in response to the events in Christchurch, New Zealand.

Pounding is among the many performance issues observed. Specifically, shorter stiff buildings were shown to have caused damage to columns in taller adjacent buildings.

Damage levels were investigated for stand-alone and row buildings indicating that row buildings performed better overall. Similarly, end-of-row structures showed greater damage levels than mid-row buildings.

It was estimated that 12% of the 370 buildings in the Central Business District had some degree of damage attributed to pounding with an adjacent neighbor.

6.3 Pounding Criteria Determination

Based on the literature review including damage observed in recent earthquakes, the issue of pounding was determined to be of sufficient importance so as to re-introduce it into the third edition of FEMA P-154.

Four defining characteristics were chosen to be part of the *Third Edition* RVS procedure.

- *Separation gap between adjacent buildings.* For Level 2 screenings, the separation gap is defined as a percentage of building height. For simplicity, round, fixed dimensions were chosen for the Level 1 separation gap criteria. The criteria are set as follows:
  - Very High seismicity: 1.50% for Level 2 (or 2 inches per story for Level 1)
  - High seismicity: 1.00% for Level 2 (or 1-1/2 inches per story for Level 1)
  - Moderately High seismicity: 0.50% for Level 2 (or 1 inch per story for Level 1)
  - Moderate seismicity: 0.25% for Level 2 (or 1/2 inches per story for Level 1)
  - Low seismicity: 0.10% for Level 2 (or 1/2 inches per story for Level 1)

  Typical story heights are approximately 12 feet to 13 feet, but they can be higher or as low as 9 feet. For the 13 feet story height, the 1-1/2” and 1/2” dimensions for Level 1 High and Moderate seismicity, respectively, are approximately 1.0% and 0.3%. For the 9 feet story height, the 1-1/2” and 1/2” dimensions are nearly 1.5% and 0.5%. For shallow story heights, the Level 1 separation requirements are larger (and more conservative) than the Level 2 criteria. These values are considerably smaller than the 4% separation recommendation in ASCE/SEI 41-13, but somewhat in line with ASCE/SEI 41-13 drift limits for vertical building elements at Collapse Prevention averaged for all building types for High seismicity. The rationale for the reduction in Moderately High, Moderate, and Low seismicity regions recognizes the lower expected damage thresholds. See Section 6.3.1 for a more detailed explanation.

- *Floor and roof alignments.* This criterion establishes a simple discernible offset of two feet as the threshold trigger. This distance is easy to see from street level and approximates a point at which impact to building columns is likely to cause significant structural damage.
- *Building height differences.* The building height difference criterion of two stories is a reasonable measure at which point damage would accrue from both the roof and floor causing potential collapse.
- *End buildings in row.* End buildings have been identified as the recipients of significant damage from pounding. A threshold of three buildings minimum in a row recognizes the inertial effects of the interior building mass required to cause damage.

The effects of pounding in the Level 1 screening are acknowledged in a check box in the building data collection area and as a recommendation to consider an additional detailed structural evaluation in the Other Hazards summary area at the bottom of the form. The intent is to flag this potentially dangerous building feature for special consideration. The RVS Authority is then charged with determining the correct course of action.

In the Level 2 form, pounding is recognized as a Score Modifier. When the separation gap is less than the Level 2 requirements described above, three possible Score Modifiers may apply: (1) floors not aligning vertically within two feet; (2) building height differences greater than two stories; and (3) whether the building is at the end of the block. Column damage between floor levels and substantial building height differences represent significant issues for potential collapse and were assigned Score Modifiers equal to the Severe Vertical Irregularity Modifier for the FEMA Building Type. The end-of-row building Score Modifier is set at 50% of this value reflecting its potential importance. Although each criterion may be present at a particular building site, it was felt that a cap equal to the worst Severe Vertical Irregularity for all the FEMA Building Types would be most appropriate on the Level 2 form so as not to overstate its significance.

6.3.1 Rationale for Pounding Separation Determination

ASCE/SEI 41-13 recommends a separation distance between buildings of $0.04H$, where H is the height of the shorter building. However, that value may be excessively conservative. Alternatively, analytical methods can be used to derive a threshold separation distance at which pounding could reasonably affect collapse probability. A separation distance higher than the recommended value would trigger a Score Modifier.

6.3.2 Calculation of Pounding Separation

The following is a simplified calculation of the maximum out-of-phase relative displacement of two adjacent buildings: Two adjacent buildings of equal height *H* are each subjected to a level of shaking specified in terms of 5%-damped 0.2-second spectral acceleration response for short-period buildings ($T \leq 0.4$ second or so) or 5%-damped, 1.0-second spectral acceleration response for longer-period buildings, where *T* is the small-amplitude fundamental period of vibration. Let SA02 and SA10 denote the site-class-adjusted, risk-targeted (MCE_R) ground motions. Selected median values of SA02 and SA10 for each of five seismicity levels Low, Moderate, Moderately High, High, and Very High, as shown in Table 6-1, are considered. The table also shows SA10/SA02, which would be the period (in seconds) at which the constant-acceleration and constant-velocity portions of the idealized design spectrum intersect, the period below which a building is treated herein as primarily being sensitive to SA02 and above which it is treated as primarily sensitive to SA10.

Table 6-1 Spectral Acceleration Response Parameters SA02 and SA10

Seismicity		*SA02*	*SA10*	*SA10/SA02*
	Low	0.20g	0.08g	0.40
	Moderate	0.40g	0.16g	0.40
	Moderately high	0.80g	0.32g	0.40
	High	1.20g	0.48g	0.40
	Very high	2.25g	0.90g	0.40

For simplicity, the equal-displacement rule is assumed. Thus, the maximum roof displacement of each building, D_{max}, is calculated as follows.

$$\begin{aligned} D_{\max} &= \Gamma \cdot \frac{SA02}{\omega^2} = \Gamma \cdot T^2 \frac{SA02}{4\pi^2} & T < 0.4\,\text{sec} \\ &= \Gamma \cdot \frac{SA10}{T \cdot \omega^2} = \Gamma \cdot T \frac{SA10}{4\pi^2} & T \geq 0.4\,\text{sec} \end{aligned} \qquad (6\text{-}1)$$

where

$$\begin{aligned} T &= 0.035H^{0.80} && \text{for FEMA Building Type S1} \\ &= 0.018H^{0.90} && \text{for FEMA Building Type C1} \\ &= 0.032H^{0.55} && \text{for FEMA Building Types W1, W1A, W2} \\ &= 0.025H^{0.75} && \text{for others} \end{aligned} \qquad (6\text{-}2)$$

The formulae for steel frame and concrete frame in Equation 6-2 are taken from the regression-line (best-fit) curves that Goel and Chopra (1997) derived from strong motion observations of actual buildings. The wood frame period formula was derived by Camelo (2003) from strong motion and forced-vibration tests. The formula for other buildings is taken from the (lower-bound) formula offered by ASCE/SEI 7-10 (ASCE, 2010), increased by 25% to approximate a best-estimate relationship as opposed to the lower-bound formula favored by the code for conservativeness. Height, H, is measured in feet, T in seconds, the angular frequency is denoted by $\omega = 2\pi/T$. The term Γ is the modal participation factor, which is the approximate ratio of roof displacement to first mode spectral displacement response. This is the term labeled Γ_1 in Chopra and Goel (1999). Freeman (2004) calls it PF, and offers several examples that each happen to have $\Gamma \approx 1.3$. *Multi-hazard Loss Estimation Methodology, Earthquake Model, HAZUS-MH MR4 Technical Manual* (FEMA, 2009a), referred to as HAZUS TM, uses a term the authors call the modal factor for height, denoted by α_2, which is the inverse of Γ. It generally takes on values of 0.75 for low-rise and mid-rise construction and 0.6 for high-rise, equating with $\Gamma = 1.33$ for low-rise and mid-rise construction and 1.67 for high-rise. Because so much else of FEMA P-154 is calibrated to HAZUS TM, the present calculations use $\Gamma = 1.3$ for low-rise and mid-rise construction and 1.67 for high-rise.

Damped elastic spectral displacement response $S_d(T, 5\%)$ among low-rise buildings in a given location will probably be greatest among the tallest of the low-rise buildings (because it will tend to be the low-rise building with the longest period). The minimum separation distance for low-rise buildings to avoid pounding would be governed by 3-story buildings. Similarly, 7-story buildings likely govern pounding in mid-rise buildings. For high-rise buildings, the height chosen does not have an effect, thus 20 stories are considered here. Taking the typical story to be 13 feet tall, H is taken as

H = 39 ft (3 stories, controlling low-rise)

H = 91 ft (7 stories, controlling mid-rise)

H = 260 ft (20 stories, representing high-rise)

Both buildings are assumed to be of the same height and period, but during SA02 or SA10 shaking, the two buildings are π radians out-of-phase at the point in time when they both experience maximum displacement (i.e., both experience their spectral displacement response), and at the time of maximum displacement they are moving toward each other rather than away. The buildings can touch if the separation distance is less than or equal to $2D_{max}$.

ASCE/SEI 41-13 takes the square root of the sum of the squares to calculate the required gap from the D_{max} values of each building, but the rationale is unclear. The two buildings need not be moving toward each other at all at the moment of maximum displacement, nor must they even have the same moment of maximum displacement. Using an SRSS combination of the D_{max} values would make sense if they represented the simultaneous maximum displacement of an object in two orthogonal directions and the important issue was the maximum absolute displacement regardless of direction, but that is not what is occurring here. Using an SRSS combination obscures the assumptions of timing and phase difference rather than reflecting a physical reality.

In the worst case, the two buildings always reach their D_{max} displacement at the same time in every earthquake, and always in a direction toward each other. Furthermore, in the worst case, for the two buildings merely to touch at that moment aggravates collapse. In the best case, the two buildings must have no initial gap between them for pounding to aggravate damage. Reality almost certainly lies between these two extremes: the separation must be less than some fraction, f where $0 < f < 1$, of $2D_{max}$ for pounding to occur and be severe enough to aggravate damage. To estimate f properly, a series of two- or three-dimensional nonlinear dynamic analyses could be performed of various combinations of buildings to find the maximum value of f where pounding occurs and aggravates collapse. Based solely on the authors' judgment, f is probably less than 0.5, so 0.5 is probably conservative, meaning it will exaggerate the potential for pounding to aggravate collapse. Thus, it is assumed here that the collapse probability only significantly increases if $D \leq D_{max}$.

Consider, for example, two seven-story C1 reinforced concrete moment frame buildings in High seismicity. Assume the typical story height is 13ft. Applying Equations 6-2 and 6-1, the gap width that can cause pounding is estimated as

$$H = 13 \text{ ft/story} \times 7 \text{ stories} = 91 \text{ ft}$$

$$T = 0.018 \times (91\text{ft})^{0.90} = 1.05 \text{ sec}$$

$$D_{max} = 1.3 \times 1.05 \text{ sec} \times 0.48\text{g} /(4\pi^2) = 63.7 \text{ in} = 5.3 \text{ ft}$$

$$D_{max}/H = 5.3 \text{ ft}/ 91 \text{ ft} = 0.0058 = 0.6\%$$

The conclusion that pounding is a concern if $D < D_{max}$ may be conservative, since there remain four important sources of conservatism in the calculation of D_{max}:

1. Both buildings are maximum height among the height class,
2. Both buildings experience maximum displacement at exactly the same time,
3. They are exactly π radians out-of-phase and moving toward each other at the moment of maximum displacement, and
4. They are located where *SA02* or *SA10* are the maximum value for their seismicity level.

Equation 6-1 leads to the minimum separation distances as percentage of *H* in the following tables.

Table 6-2 Minimum Separation Distance for FEMA Building Types W1, W1A, W2 as a Percentage of *H*

Stories	Low	Mod	Moderately High	High	Very High
1	0.0%	0.1%	0.1%	0.2%	0.3%
3	0.0%	0.1%	0.1%	0.2%	0.4%
6	0.0%	0.1%	0.1%	0.2%	0.4%

Table 6-3 Minimum Separation Distance for FEMA Building Type C1 as a Percentage of *H*

Stories	Low	Mod	Moderately High	High	Very High
3	0.1%	0.2%	0.4%	0.6%	1.2%
7	0.1%	0.2%	0.4%	0.6%	1.1%
20	0.1%	0.2%	0.4%	0.7%	1.3%

Table 6-4 Minimum Separation Distance for FEMA Building Type S1 as a Percentage of *H*

Stories	Low	Mod	Moderately High	High	Very High
3	0.1%	0.3%	0.6%	0.9%	1.6%
7	0.2%	0.3%	0.6%	0.9%	1.7%
20	0.1%	0.3%	0.5%	0.8%	1.4%

The results in Tables 6-2 through 6-5 indicate that to one significant figure, the minimum separation distance is fairly independent of height. Thus, for simplicity, a single threshold separation distance can be used, based on the largest values shown above (those of steel moment frame buildings, as shown in Table 6-4), rounded to a nominal value, as shown in Table 6-6.

Table 6-5 Minimum Separation Distance for All Other FEMA Building Types as a Percentage of *H*

Stories	Low	Mod	Moderately High	High	Very High
3	0.1%	0.2%	0.3%	0.5%	0.9%
7	0.1%	0.1%	0.3%	0.4%	0.8%
20	0.1%	0.1%	0.3%	0.4%	0.8%

These are conservative for less-flexible building types, and particularly conservative for wood frame buildings.

Table 6-6 Recommended Minimum Separation Distance Values as a Percentage of *H*

Seismicity		All types
	Low	0.10%
	Moderate	0.25%
	Moderately high	0.50%
	High	1.00%
	Very high	1.50%

6.3.3 Validation

The minimum separation distance value of 1% of building height, *H*, for buildings in the High seismicity region is consistent with the threshold recommended by the NZSEE Study (2012), though far less conservative than ASCE/SEI 41-13. One additional case study is provided for validation.

In the 2011 Tohoku earthquake, Okazaki et al. (2013) observed that two 11-story steel reinforced concrete (SRC) buildings separated by a 10-cm gap (approximately 0.4% separation) "pounded against each other. Despite the cosmetic damage, the SRC buildings seemed to have suffered minimal structural damage. At the time of investigation, many residents had returned to occupy the building." The buildings are located near Sendai, where S_a(1.0 second, 5%) ≈ 0.7g at the nearby station DCRC No 23 was very close to the high-seismicity value for $S_{M1} \approx 0.8$g. These buildings had much less than the recommended 1.0% separation threshold, experienced motion very close to the high-seismicity S_{M1}, and survived with only cosmetic damage.

More detailed research would be needed to make more definitive statements about historical pounding damage among adjacent buildings subjected to near-design-level shaking.

Chapter 7

Building Additions

7.1 Introduction

Existing buildings are often expanded at a later time to increase the usable area. The expansions can be either vertical (adding stories over the entire floor area or over part of the floor area of the building) or horizontal (adding one or more stories adjacent to the one or more sides of the original building). This chapter summarizes the rationale behind the categorization of horizontal and vertical additions and the associated recommendations.

7.2 Identifying Building Additions

Penthouses are generally not considered to be additions since they are typically constructed as part of the original building and are thus likely to be integrally connected. If a penthouse has been added to an existing building and is not normally occupied, e.g., used as a mechanical penthouse, it can be excluded from consideration as an addition. Its framing system will not typically be an extension of the building framing. An occupied rooftop structure that has been added should be treated as a vertical addition.

Residential structures in urban areas are commonly constructed as multiple, contiguous residences, often referred to as row houses. These row houses would not be considered as additions since there are usually common party walls that separate the units. Party walls are identified by extension of the walls above the roof that provides a fire separation. See Figure 7-1.

Figure 7-1 Row houses are not considered additions.

FEMA P-154 provides guidance for assessing the effects of the addition on the overall response of the structure in cases where the addition and original building are well-defined. Where complex conditions regarding building additions are identified, e.g., where there is more than one interface plane between the addition and the original building or if it cannot be determined whether there is an addition or a separate structure, a Detailed Structural Evaluation should be recommended.

The interaction of an addition with the original building could affect the seismic response of either one or both structures. The critical characteristics of the addition that affect the seismic response of the building and addition are:

- Details of the structural connection of the horizontal addition to the original building,
- Types of seismic force-resisting systems of the addition and the original building, and
- The size of the addition.

These characteristics are discussed in the sections that follow.

7.2.1 Structural Connections

There are three types of structural connections between a horizontal addition and an original building.

First, the addition can be constructed to be structurally isolated from the original building with a seismic joint, such that the original building and the addition respond to an earthquake independently. In this case, the two structures should be treated as separate structures. However, the potential for pounding should be checked using the RVS pounding criteria.

Second, the building addition can be constructed as a separate and independent structure, but without a seismic joint to allow the original building and addition to respond separately to seismic motion. This will likely result in pounding between the building and the addition, as the two structures separate and then impact one another in subsequent cycles of shaking. The severity of potential pounding depends partly on the relative size of the structures and the degree of difference in structural systems between the structures. Additional guidance for RVS screening where the original building and addition are separate structures depends on factors described in Sections 7.4 and 7.5.

Third, the addition can be constructed to rely partially on the original building for gravity or lateral support. In many instances, it may not be possible to accurately assess by visual observation whether an addition is structurally connected to the original building. The guidance provided in FEMA P-154 assumes that when horizontal additions are significantly smaller than the original building and constructed with a different building type, it is likely that the addition relies on at least a partial structural connection between the addition and the original building. Where a structural connection of the addition and the original building occurs, differential movement between the original building and the addition during an earthquake can result in damage to the gravity or lateral connection, which may result in damage or partial collapse. Although the seismic interaction of the addition and the original building may have been considered in the design of the addition, for RVS screening, it should be assumed that this interaction was not considered.

7.2.2 Structural Framing

Differences in the seismic force-resisting systems of the original building and the addition can significantly affect the overall response of the structure. Differences such as configuration and construction materials can result in differing stiffness of structures, which may lead to vertical or plan irregularities.

Vertical additions may cause vertical irregularities due to differences in dynamic response of the addition and the original building. For multi-story vertical additions where the addition is constructed with the same seismic force-resisting system as the original building, the overall response of the structure will likely be similar to that of a single structure of the same height. Multi-story vertical additions with a seismic force-resisting system either stiffer or more flexible than the original building will cause potential irregularities in structural response.

If a seismic joint is not specifically provided between the original building and a horizontal addition, there is a potential for interaction depending on differences in stiffness. If a horizontal addition is constructed with the same seismic force-resisting system as the original building and there is no seismic joint, the original building and the addition could be considered as either one structure or two structures depending on the relative size of the addition to the original structure.

7.2.3 Size of Addition

If the size of the addition, in terms of either the number of stories or the horizontal dimensions, is very small with respect to the original building, particularly if the addition is of lightweight construction, the addition may have little, if any, influence on the overall behavior. For all other cases, the presence of the addition is likely to result in either a vertical or plan irregularity.

Vertical additions, which are occupied and with a plan area smaller than the plan area of the floor of the original building below, should be considered to cause a soft or weak story irregularity. The number of stories of the vertical addition may also influence its effect on the response of the building. A single story addition is less likely to affect the overall response of the building than a multi-story addition.

The effect of horizontal additions on the overall response depends on a number of factors including the relative size of the addition and the original building. The size difference may affect the mass distribution of the combined building relative to the original building. For RVS screening purposes, a determination of the center of mass and center of stiffness of the original and combined buildings is overly complex. A comparison of the floor area of the addition and original building may also be difficult unless a satellite image of the site is available. As a simplification, the relative length of the building and addition along the interface is used as a method of assessing the relative influence of the addition on the response of the original building. In the direction parallel to the interface plane, the possibility of significantly detrimental response due to stiffness differences between the original building and the addition is small and is not considered in the RVS procedure.

7.3 Implementing Irregularity Recommendations from the Building Additions Reference Guide on the Screening Forms

Neither the Level 1 nor the Level 2 form contains modifiers specific to additions. Instead, the effect of different addition configurations on the seismic performance of the building is addressed in Level 1 by either evaluating the original building and addition as a combined building or as separate buildings. In the Level 2 form, building additions are considered by assigning Score Modifiers (vertical or plan irregularities, pounding, or some combination of these) depending on the configuration of the original building and the addition.

When the building and the addition are evaluated as separate structures, the Score Modifiers related to building codes (Pre-Code and Post-Benchmark) should be applied independently to the original building and addition based on their dates of construction. For screening purposes, it should not be assumed that the original building was retrofitted at the time of construction of the addition. Separate RVS screening forms for the building and the addition should be prepared if there are separate owners for the building and the addition.

7.3.1 Level 1 Screening for Additions

FEMA P-154 Table 3-2 provides a simple checklist for horizontal additions for identifying whether a building should be treated as a single building, as separate buildings, or as a single building with an addition. For Level 1 screening, additions should be evaluated separately from the original building and the lower score should be recorded for the combined building since the seismic performance may be governed by either the original building or the addition. Conversely, separate structures should have RVS scores reported for each building.

The first step in the process of identifying an addition is to determine whether there is a visible joint between parts of the building. The joint should exist along the full height of the building on two sides and across the roof. (If the structures are different height, the joint will only occur along the height of the shorter building.) If a joint exists, the buildings should be treated as separate buildings, and the two buildings should be separately evaluated. The potential for pounding between the structures should be noted on the Level 1 form if it conforms to the pounding criteria for Level 1.

If there is no visible joint separating portions of a building, the building is assumed to be connected, and the second step is to assess whether there are other visual clues that can be used to determine whether a building was built as a single structure or as separate structures at different times. If built as a single structure, the building should be evaluated as a single building.

One indication of the presence of a separately constructed building or addition would be if there is a visible difference in the floor elevations between separate portions of the structure. In most cases, a single building will be constructed with floor levels that align, although some offsets over a portion of a floor level may occur or the building is located on a sloped site. If differences in floor elevations of two feet or more are observed, the original building and addition should be considered as separately constructed structures.

Another indication would be if there are obvious differences in the structural framing between portions of the building that may indicate that the portions of the building were constructed separately. The structural framing differences could be either the vertical framing (columns or walls) or the horizontal framing (roof or floors). The framing differences may be differences in construction materials (e.g., concrete, steel) or may be differences in configuration, such as shear walls in one portion of the building and moment frames in another portion of the building or differences in column spacing. If there are differences in construction, the portions with differing construction should be treated as separate structures.

Finally, noticeable differences in architectural style may be an indication that portions of the building were constructed separately. While some differences may exist along one side of a building, particularly for commercial buildings with different tenants, differences in architectural style that exist on more than one face of a building would tend to indicate that the portions of the building were constructed separately. The appearance of the street-facing sides(s) of a building may not accurately indicate differences in building construction, so careful observation of all sides of the building should be performed to identify the presence of construction differences. These differences in style may be variations in configuration of windows from one portion of the building to another or differences in exterior ornamentation or façade construction.

If differences in construction between portions of the building have been identified using the three criteria above, then the individual portions of the building delineated by the observed difference should be evaluated as separate buildings.

7.3.2 Level 2 Screening for Additions

The Building Additions Reference Guide in Table B-6 of Appendix B of FEMA P-154 provides guidance for considering additions. Based on the characteristics of the addition, the Guide directs the screener to either consider the original building and addition as a single building or consider them as two separate buildings and perform two separate screenings. Additional notes and instructions are contained within the Guide to direct the screener to look for likely pounding and irregularity conditions depending on the relative configuration of the original building and addition.

7.3.2.1 Vertical Additions

When a building has a vertical addition that is smaller in footprint than the plan of the original building, the seismic force-resisting system of the addition and the original building are not likely to be aligned. When there are offsets in the seismic force-resisting system, a vertical setback irregularity may be present. For the purposes of the RVS screening, if more than one exterior wall of the vertical addition does not align with the exterior walls of the original building below, a setback of the seismic force-resisting system is assumed to be present. If the vertical addition has a plan area that is not less than 90% of the plan area of the original building below, the setback is considered to be minor, and the setback irregularity need not be assumed. See Figure 7-2.

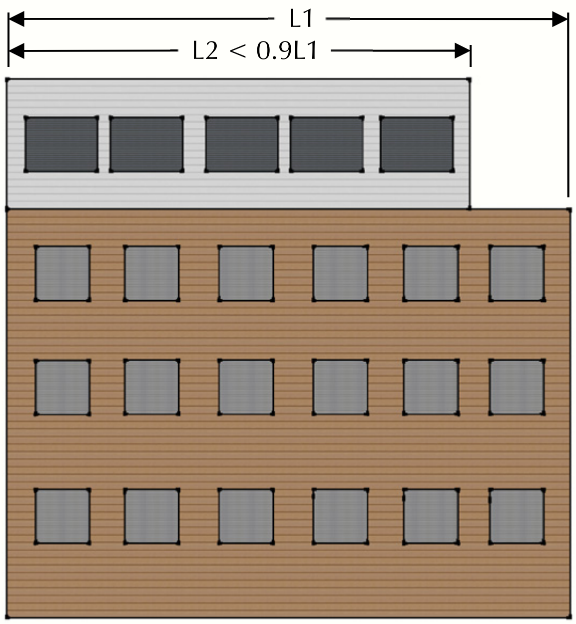


Figure 7-2 Vertical addition considered as a setback irregularity.

When the vertical addition has a similar footprint to that of the original building below, the factors that affect the seismic performance are type of construction of the addition compared to that of the original building and number of stories. When the addition is of the same building type as that of the original building, the addition and original building are assumed for the purposes of rapid visual screening to be integrally connected such that they respond to earthquake shaking as a single structure. When the building types of the original building and the addition are different, it is likely that the structure's response to earthquake shaking will be more complex, with the possible presence of a weak or soft story.

Vertical additions that are more than one story are likely to be constructed with a different seismic force-resisting system than the original building. Often the additions are constructed with lighter framing systems; as a result, the added stories of the vertical addition are not likely to have similar story stiffnesses as the original building. See Figure 7-3. If the stiffness of the addition is less than that of the original building, there can be an amplification of the motion of the added stories. This condition is not directly considered in the Level 2 Score Modifiers, so to account for this concern, the moderate Vertical Irregularity Score Modifier should be indicated.

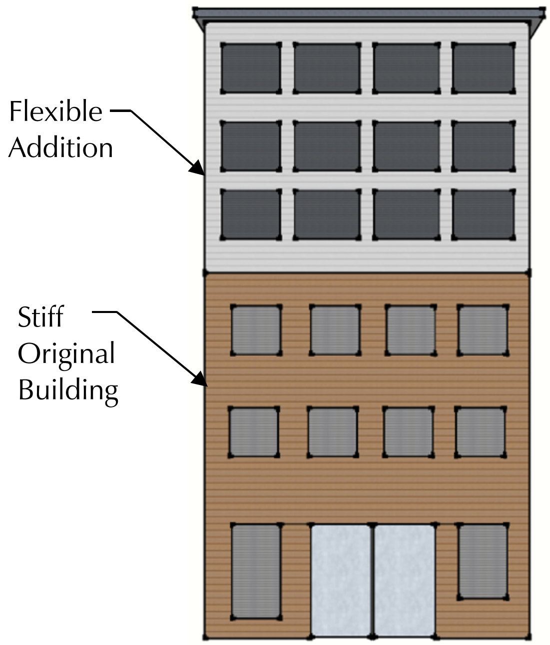
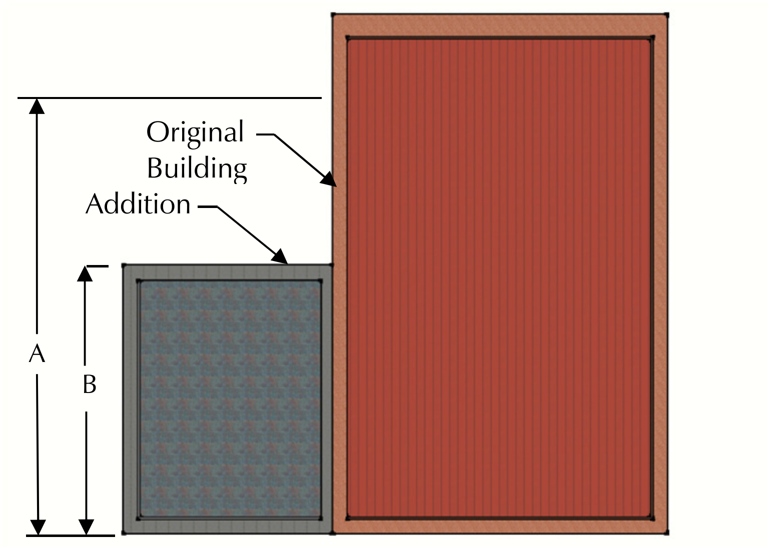


Figure 7-3 Stiff original building with a flexible addition leading to a moderate vertical irregularity.

7.3.2.2 Horizontal Additions

If joints exist along the entire interface between an original building and a horizontal addition, the original building and the addition can be considered separate structures and evaluated separately. The separate structures should be evaluated for pounding using the guidance in the Level 2 form. Where the joints between the structures are covered, the width of the gap may be estimated based on the size of the cover. If joints do not exist, the horizontal addition should be considered as potentially integrally connected or that the buildings will interact with each other during seismic motion. FEMA P-154 Table 4-1 provides guidance for horizontal additions that are not separated by gaps as described below.

- If the building types of the original building and the horizontal addition are similar, and if the heights of the buildings are the same, the two structures can be assumed to behave as a single structure. If there is a large difference in horizontal dimension of the original building and addition along the interface, there is a potential for torsional response due to the differences in stiffness between the building and the addition. A difference in horizontal dimension at the interface of less than 50% is assumed to create a potential for torsional response, and therefore the need to indicate a torsional irregularity. The reentrant corner plan irregularity should be applied if the difference in horizontal dimension is between 50% and 75% by denoting that the smaller horizontal building dimension at the interface is less than 75% of the length of the larger building. See Figure 7-4.



If B < 0.5 A Torsional irregularity

If 0.5A < B < 0.75 A Reentrant corner

Figure 7-4 Plan view illustrating irregularity caused by difference in horizontal dimension or original building and addition.

- If the height of the original building and the addition are different, there is a potential for pounding damage to either the taller portion or the shorter portion. Therefore, a pounding condition should be indicated as described in Section 6.2 if the height difference is two or more stories or if the floor levels do not align within 2 feet. Each portion should be scored separately considering the building type of each portion and the Pounding Score Modifier should be applied to both the shorter and taller building. The score should be based on the lower Final Score of the buildings.
- When the addition is constructed as a different building type than the original building, there may be a difference in stiffness of the original building and addition. A difference in stiffness may cause either torsional response of the buildings acting together or may cause the more rigid building to resist some of the lateral forces from the more flexible building. The buildings could be evaluated separately and include a Pounding Score Modifier for each building. Conversely, the building could be evaluated as a single, combined building, which would include

a Torsional Plan Irregularity Score Modifier due to the differences in stiffness. The combined building evaluation should consider the lower Basic Score of the building and the addition. If the horizontal dimension of the building and addition along the interface are different, a Reentrant Corner Plan Irregularity Score Modifier could be indicated; however, since the Torsional Plan Irregularity Modifier is more severe than the Reentrant Corner Plan Irregularity Score Modifier, considering the combined building with the Torsional Plan Irregularity Score Modifier would be more conservative and is thus the recommended approach.

- Another condition that may occur is when an addition is structurally attached to the original building in a manner that the original building provides gravity load support for a portion of the addition. If the addition is constructed with framing similar to the original building, the building and addition can be evaluated as a single building. If the addition is of different construction than the original building, the addition may become separated due to differences in stiffness or lack of adequate attachment and there is a risk of collapse of part of the addition. Therefore, the addition should be evaluated separately from the original building and a Severe Vertical Irregularity Score Modifier should be indicated to account for the potential loss of gravity load support. Since the potential for separation is reduced if the construction type of the addition and original building are the same, the separate evaluation of the building and the addition is not necessary if the construction types are the same. See Figure 7-5.

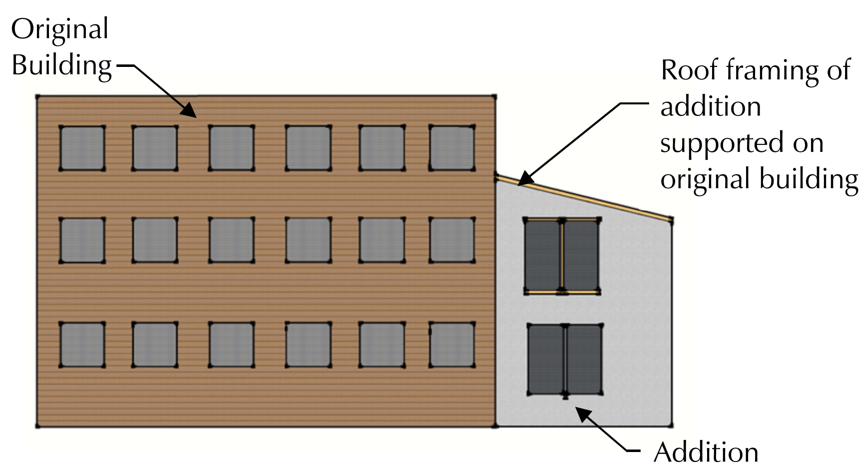


Figure 7-5 Addition relying on the original building for gravity support.

Chapter 8
Risk Associated with the RVS Score

8.1 Introduction

This chapter addresses how score relates to risk. As used here, risk means the rate at which collapse occurs, as opposed to collapse probability given the occurrence of MCE_R shaking. Previous editions of FEMA 154 did not address risk in this sense. Collapse can occur at higher and lower levels of shaking than MCE_R. Higher shaking generally produces higher collapse probability but occurs at a lower mean annual frequency than does MCE_R shaking. Lower shaking produces lower collapse probability but occurs more frequently than MCE_R shaking. This chapter shows how one can account for the entire range of shaking.

Section 8.2 explains the difference between collapse probability in MCE_R shaking and the rate of collapse-causing earthquakes of any possible level of shaking. Section 8.3 introduces a new measure of performance called the Risk Score, denoted by S_R, which measures building safety in terms of how frequently collapse-causing earthquakes occur. The Final Score, S, by contrast measures building safety in terms of the collapse probability given MCE_R shaking. Section 8.4 shows how the Risk Score is approximately one unit greater than the Final Score.

Section 8.5 shows how the Risk Score relates to risk. It shows how different values of the Risk Score equate with the chance that an earthquake will cause the building to collapse during various periods of time.

8.2 Risk versus Probability

The Final Score, S, is intended as an estimate of the negative base-10 logarithm of the collapse probability given MCE_R shaking. Mathematically, if P denotes the collapse probability in MCE_R shaking, then FEMA P-154 derives scores S that satisfy the equation

$$S = -\log_{10}(P) \tag{8-1}$$

and equivalently

$$P = 1/10^S \tag{8-2}$$

For example, $S = 2$ equates with collapse probability P of 1 in 100, or 1%, or 0.01, given MCE_R shaking. A Final Score of $S = 3$ implies a collapse probability P of 1/1000, or 0.1%, or 0.001 given MCE_R shaking.

A building may experience many earthquakes during its economic life and almost none of them have shaking exactly equal to MCE_R shaking. Lower and higher levels of shaking can occur. Lower levels of shaking generally occur more frequently; higher levels, less frequently. Lower levels are generally less likely to cause collapse; higher levels, more likely.

Prior editions of FEMA 154 do not address these other levels of shaking. A person making an expensive decision about whether to retrofit a building might ask: what about these other levels of shaking? Could the building collapse in a more frequent earthquake? What is the chance that an earthquake will occur and cause the building to collapse in the next 5 years? Or in the next 25 years? What is the chance that it will be an earthquake that causes the building to be demolished, rather than some other cause such as the building becoming obsolete and demolished in a safe, controlled, predictable way? Considering all these other possible levels of shaking, how risky is the building?

The Final Score, S, does not speak to any of these points, because it relates only collapse probability given MCE_R shaking. It does not speak to shaking less than or greater than MCE_R shaking, or to the likelihood of collapse given those levels of shaking, or to the frequency with which those other levels of shaking occur.

To deal with risk resulting from these other levels of shaking, one must consider three factors that were not considered in prior editions:

- The complete seismic hazard curve – the relationship between earthquake shaking and the frequency with which various levels of shaking occur.
- The building's collapse probability when subjected to other levels of shaking.
- The design life of the building, which affects how long it is assumed to be exposed to earthquakes.

8.3 Introducing the Risk Score

This section introduces a new measure of performance called the Risk Score, denoted by S_R, which measures building safety in terms of how frequently collapse-causing earthquakes occur. It is intended as an estimate of the negative base-10 logarithm of the number of earthquakes that could cause building collapse during the design life of the building, which is commonly taken to be 50 years. Another way to say the same thing is that the expected number of collapse-causing earthquakes during the design life of the building is 1 per 10^{S_R} lifetimes. This is a different measure of performance from *S*. *S* has nothing to do with the design life of the building or the number of collapse-causing earthquakes. S_R does.

Thus, a value of $S_R = 2$ means $1/10^2$ collapse-causing earthquakes per 50 years, or 1 collapse-causing earthquake per 100 design lifetimes. $S_R = 3$ means $1/10^3$ collapse-causing earthquakes per 50 years, or 1 collapse-causing earthquake per 1,000 building design lifetimes. That does not mean that a particular building that has a score of $S_R = 3$ would wait 50,000 years to experience a collapse-causing earthquake. Rather it means that, if one were to pick 1,000 similar buildings at random, on average, 1 of them would experience an earthquake that would cause it to collapse during the next 50 years.

The Risk Score sums the probability of collapse given any particular level of shaking times the number of times in 50 years that that level of shaking will occur, summing over all levels of shaking, and taking the negative base-10 logarithm of that value. It is like the rate at which people are killed in automobile accidents, considering that one is more likely to be killed in a higher-speed accident than in a lower-speed accident, considering the number of low- and high-speed accidents that occur per year. The Final Score is like the probability of being killed in an automobile accident that occurs at a given speed.

8.4 Calculating the Risk Score

Before calculating the Risk Score, it is worthwhile to review the development of risk-targeted design motion MCE_R. Luco et al. (2007) offer a method to relate collapse probability conditioned on a particular level of shaking to frequency of collapse-causing earthquakes, for a particular building and a particular location. Their purpose was to select a level of shaking at that site (which they named MCE_R, risk-targeted maximum considered earthquake) such that, if the building had a 10% collapse probability conditioned on MCE_R, it would also have a 1% probability of collapse in 50 years, considering all levels of shaking that could occur at that location, and how the probability of collapse varies with shaking. One could then design a new building at that location to have a 10% collapse probability at MCE_R shaking, and indirectly achieve a specified probability of collapse during the design life of the building.

In the following, the collapse probability conditioned on a particular level of shaking is referred to by the shorthand term "fragility," and the frequency of collapse-causing earthquakes is referred to as "risk."

Luco et al. (2007) address new design, where design strength is under the control of the designer. They answer the question of whether one can design a building for a specified level of fragility and indirectly achieve a specified level of risk. In the present work, a different question arises: if one is interested in an existing building in a particular location, can one also somehow relate fragility to risk? The fragility is imposed: it is an attribute of the existing building. One can estimate it, but one cannot change it. FEMA P-154 provides an estimate of fragility, but not control over it. A building examined using FEMA P-154 may have a collapse probability given MCE_R shaking that differs from 10%.

The question addressed here is: what if the Final Score is 1.5, or 3, or 4? Can one say anything about the risk to the building, in the sense of the frequency with which collapse-causing earthquakes occur? What if any relationship exists between collapse fragility and collapse risk for existing buildings?

The question is addressed here using the fragility functions developed for FEMA P-154 for FEMA Building Types without vertical or plan irregularities, on Soil Type CD, and neither post-benchmark nor pre-code design. For simplicity, a factored lognormal cumulative distribution function was fit to the fragility estimates implied by the Basic Score of each FEMA Building Type for each seismicity region. By "a factored lognormal cumulative distribution function," the following is meant:

$$P = P_c \times y(x) \tag{8-3}$$

where

$$y(x) = \Phi\left(\frac{\ln(x/\theta)}{\beta}\right) \tag{8-4}$$

and where P denotes the collapse probability given shaking of S_a(1.0 sec, 5%) = x, P_c denotes the fraction of the building area that collapses given that the building is in the complete structural damage state (note that P_c is equivalent to the collapse factor, P[*COL*|*Complete Damage*], described in Chapter 4 and Chapter 5), y denotes the probability of complete structural damage, Φ denotes the cumulative standard normal distribution evaluated at the term in parentheses, and θ and β are parameters of the distribution, referred to here as the median and logarithmic standard deviation, respectively. The values of x are taken as the values of $F_V S_1$ for each of the seismicity regions used in FEMA P-154. The values of P and P_c are those assumed in developing the Basic Scores. The value of θ for each baseline-condition FEMA Building Type is found by interpolating (by parabolic spline) the function defined by the pairs (P/P_c, x) at $P/P_c = 0.5$. The value of β for each baseline-condition FEMA Building Type is found by interpolating the pairs (P/P_c, x) at $P/P_c = 0.1$. Let the value of x at this point be denoted by $x_{0.10}$. Then β can be estimated as shown in Equation 8-5. Results are shown in Table 8-1.

$$\beta = \frac{\ln\left(x_{0.10}/\theta\right)}{\Phi^{-1}\left(0.10\right)} = \frac{\ln\left(x_{0.10}/\theta\right)}{-1.28} \tag{8-5}$$

Table 8-1 Parameters of Fragility Functions Used to Relate Fragility to Risk

FEMA Building Type	P_c	$x_{0.10}$	θ	β
W1	0.05	1.04	2.09	0.55
W1A	0.05	0.89	1.81	0.55
W2	0.05	0.83	1.75	0.58
S1	0.08	0.68	1.48	0.61
S2	0.08	0.59	1.27	0.59
S3	0.08	0.82	1.76	0.60
S4	0.08	0.59	1.27	0.59
S5	0.08	0.47	0.95	0.56
C1	0.13	0.39	0.96	0.70
C2	0.13	0.71	1.30	0.47
C3	0.13	0.32	0.70	0.60
PC1	0.15	0.50	1.21	0.70
PC2	0.15	0.33	1.02	0.89
RM1	0.13	0.44	1.12	0.73
RM2	0.13	0.44	1.12	0.73
URM	0.15	0.26	0.57	0.60
MH	0.05	0.46	0.90	0.52

There appears to be no functional relationship between θ and β values in Table 8-1. That means that the two are independent, so one can simulate θ as a random variable and β as another random variable whose distribution is unaffected by the value that θ takes on. (A mathematical test to support the assertion that θ and β are independent was also conducted.) This is important because it means one can explore the relationship between fragility and risk for the general case $0.7 \le \theta \le 2.1$ and $0.47 \le \beta \le 0.89$ and apply the conclusions to the particular cases in Table 8-1. Furthermore, one can treat the pair (θ, β) as jointly lognormally distributed with expected values (1.25, 0.62) and standard deviations (0.41, 0.10); these parameter values come from the sample values of θ and β in Table 8-1. Both distributions pass a Lilliefors goodness-of-fit test at the 1% significance level. That fact is useful because it means one can examine the general case of a building with jointly lognormal median and logarithmic standard deviation and evaluate the probability that fragility relates to risk in some interesting way that this chapter seeks to discover. Let bold $\boldsymbol{\theta}$ denote the uncertain median, and bold $\boldsymbol{\beta}$ denote the uncertain logarithmic standard deviation.

A fragility function with uncertain, lognormally distributed median $\theta \sim$ LN(1.25, 0.41) and uncertain, lognormally distributed logarithmic standard deviation $\beta \sim$ LN(0.62, 0.10) were chosen as the representative fragility function. This function is representative in the sense that it represents all of the baseline fragility functions before multiplying by P_c. The expression $\boldsymbol{\theta} \sim$ LN(1.25, 0.41) means that $\boldsymbol{\theta}$ is distributed like a lognormal random variable with mean 1.25 and standard deviation 0.41. Then

$$y = \Phi\left(\frac{\ln\left(x/\boldsymbol{\theta}\right)}{\boldsymbol{\beta}}\right) \tag{8-6}$$

which is y of Equation (8-4) but with uncertain θ and β. The values of MCE_R and the hazard curves that might be encountered in a FEMA P-154 evaluation are then considered in the following example.

The seismicity regions considered in FEMA P-154 are defined in terms of ranges of MCE_R, each range with a specified central value of F_AS_S and F_VS_1. The U.S. Geological Survey distributes gridded text files containing S_S and S_1 parameter values from the 2012 *International Building Code* (USGS, 2014a). One of the files, which provides 0.2s and 1.0s risk-targeted MCE (MCE_R) ground motions on a 0.05-degree grid covering the range of latitudes 24.6°-50° N and longitudes 125°-65° W, was acquired. For each gridpoint in the database, F_A and F_V for Soil Type CD were calculated, and the quantities F_AS_S and F_VS_1 were calculated and rounded to the nearest 0.01g. Sites with F_VS_1 that match FEMA P-154's central values were selected from all of the gridpoints. These were grouped into five sets, one set for each seismicity region. Ten sites were selected at random from each of the five sets, for a total of 50 sites. The selected sites are listed in Table 8-2. The 1-second hazard curve at each site was extracted from the USGS's 2008 National Seismic Hazard Map gridded data archive (USGS, 2014b). The hazard curve for each site was adjusted to account for site amplification on Soil Type CD.

Table 8-2 Sites with Hazard Curves that Were Used to Relate Fragility to Risk

Seismicity Region	Site ID	Lat deg N	Lon deg E	$F_v S_1$, g
Low	L0	48.90	-112.35	0.16
	L1	36.60	-80.35	0.16
	L2	46.75	-77.75	0.16
	L3	37.00	-111.10	0.16
	L4	44.80	-69.20	0.16
	L5	33.20	-121.45	0.16
	L6	32.50	-83.45	0.16
	L7	31.25	-106.60	0.16
	L8	46.20	-68.45	0.16
	L9	32.75	-110.90	0.16
Moderate	M0	28.20	-113.25	0.30
	M1	38.90	-88.00	0.30
	M2	43.10	-119.85	0.30
	M3	38.70	-90.25	0.30
	M4	41.15	-116.40	0.30
	M5	34.35	-79.30	0.30
	M6	35.40	-115.30	0.30
	M7	44.20	-120.40	0.30
	M8	39.10	-115.65	0.30
	M9	48.00	-115.15	0.30
Moderately High	MH0	33.95	-115.45	0.52
	MH1	45.10	-122.20	0.52
	MH2	42.50	-121.85	0.52
	MH3	42.65	-111.25	0.52
	MH4	35.25	-89.70	0.52
	MH5	31.05	-113.80	0.52
	MH6	38.65	-124.10	0.52
	MH7	43.05	-122.85	0.52
	MH8	35.70	-116.20	0.52
	MH9	39.55	-118.35	0.52
High	H0	47.70	-122.20	0.68
	H1	39.50	-124.30	0.68
	H2	48.00	-122.20	0.68
	H3	33.60	-79.95	0.68
	H4	36.45	-121.30	0.68

Table 8-2 Sites with Hazard Curves that Were Used to Relate Fragility to Risk (continued)

Seismicity Region	Site ID	Lat deg N	Lon deg E	$F_V S_1$, g
High (continued)	H5	41.05	-110.85	0.68
	H6	37.30	-118.55	0.68
	H7	35.10	-117.30	0.68
	H8	44.20	-123.35	0.68
	H9	34.95	-116.75	0.68
Very High	VH0	34.35	-118.25	1.26
	VH1	34.35	-119.35	1.26
	VH2	37.95	-122.35	1.26
	VH3	39.40	-122.90	1.26
	VH4	34.20	-119.10	1.26
	VH5	34.05	-117.10	1.26
	VH6	32.65	-115.35	1.26
	VH7	34.50	-119.90	1.26
	VH8	34.50	-119.95	1.26
	VH9	36.70	-89.80	1.26

The hazard curves of each set were averaged. That is, at each x value of S_a(1.0 second, 5%) on Soil Type CD, the 10 values of the mean exceedance frequency for each seismicity region were averaged, resulting in what can be considered a sample-average hazard curve for the seismicity region. The resulting hazard curves, referred to as nominal hazard curves, are shown in Figure 8-1.

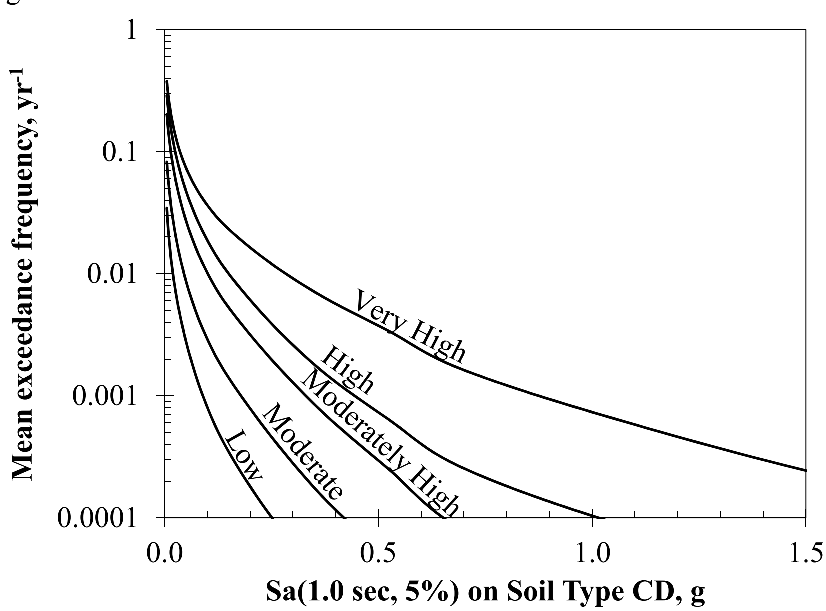


Figure 8-1 Sample-average hazard curves used to relate fragility to risk.

To recap: a random fragility function is created that represents the range of baseline-condition FEMA Building Types. Median values of MCE_R shaking in each seismicity region have already been selected; the values considered here are those of 5%-damped, 1-second spectral acceleration response on Soil Type CD. A sample-average hazard curve has also been evaluated for each seismicity region.

The following new terms λ, τ, and PMF_R, as shown in Equations 8-7 and 8-8, are defined:

$$S_R = -\log_{10}\left(\lambda \times \tau\right) \tag{8-7}$$

$$PMF_R = S_R - S \tag{8-8}$$

where

λ	=	collapse rate, measured in events per year, and defined as the expected rate of collapse-causing earthquakes per year at a given site and for a given building.
τ	=	design life of the building, commonly taken to be 50 years
PMF_R	=	Risk Modification Factor, a number added to the Final Score, S, to get the Risk Score, S_R

The collapse rate, λ, for a given fragility function and location can be estimated as shown in Equation 8-9. In the two integrals, $G(x)$ denotes the mean hazard curve, expressed in terms of mean rate of exceeding shaking x in events per year; ϕ denotes the standard normal probability density function, Φ denotes the standard normal cumulative distribution function, and θ, β, and P_c are as previously defined. The two integrals can be shown to be equal through integration by parts.

$$\begin{aligned} \lambda &= P_c \times \int_{x=0}^{\infty} G\left(x\right) \times \phi\left(\frac{\ln\left(x/\theta\right)}{\beta}\right) dx \\ &= P_c \times \int_{x=0}^{\infty} \left|\frac{dG\left(x\right)}{dx}\right| \times \Phi\left(\frac{\ln\left(x/\theta\right)}{\beta}\right) dx \end{aligned} \tag{8-9}$$

It will be useful to ignore P_c. Note that by the definition of the Final Score S,

$$\begin{aligned} S &= -\log_{10}\left(P_c \times \Phi\left(\frac{\ln\left(F_V \times S_1/\theta\right)}{\beta}\right)\right) \\ &= -\log_{10}\left(\Phi\left(\frac{\ln\left(F_V \times S_1/\theta\right)}{\beta}\right)\right) - \log_{10}\left(P_c\right) \end{aligned} \tag{8-10}$$

and by the definition of the Risk Score S_R,

$$S_R = -\log_{10}\left(P_c \times \left(\int_{x=0}^{\infty} G(x) \times \phi\left(\frac{\ln(x/\theta)}{\beta} \right) dx \right) \times \tau \right)$$
$$= -\log_{10}\left(\tau \times \int_{x=0}^{\infty} G(x) \times \phi\left(\frac{\ln(x/\theta)}{\beta} \right) dx \right) - \log_{10}(P_c) \tag{8-11}$$

If one substitutes Equations 8-10 and 8-11 into Equation 8-8, the $\log_{10}(P_c)$ terms cancel out of the right hand side of Equation 8-8. Thus the particular value of P_c for any given FEMA Building Type does not affect PMF_R.

The integral in Equation 8-9 can be evaluated numerically, as shown in Equation 8-12, which is exact if y is linear between values of x, and G is loglinear between values of x. For the derivation of Equation 8-12, see Porter et al. (2006).

$$\lambda = \sum_{i=1}^{n} \left(y_{i-1} a_i - \Delta y_i b_i \right) \tag{8-12}$$

In this equation, i denotes an index to n + 1 values of shaking x and

$$y_i = \Phi\left(\frac{\ln(x_i/\theta)}{\beta} \right)$$

$$\Delta x_i = x_i - x_{i-1}$$

$$\Delta y_i = y_i - y_{i-1}$$

$$m_i = \ln\left(G_i / G_{i-1} \right) / \Delta x_i$$

$$a_i = G_{i-1}\left(1 - \exp(m_i \Delta x_i) \right)$$

$$b_i = \frac{G_{i-1}}{\Delta x_i}\left(\exp(m_i \Delta x_i)\left(\Delta x_i - \frac{1}{m_i} \right) + \frac{1}{m_i} \right)$$

One can evaluate PMF_R of Equation 8-8 using the representative fragility function $y(x)$ of Equation 8-6 and the five nominal hazard curves $G(x)$ shown in Figure 8-1. Using Monte Carlo simulation to account for uncertain θ and β, it is found that the expected value of PMF_R varies by seismicity region, but not very much, as shown in Table 8-3.

Table 8-3 shows that, for all seismicity regions between Moderate and Very High, one can add approximately 1.0 to the Final Score to get the Risk Score. That is,

$$S_R = S + 1 \tag{8-13}$$

Table 8-3 Expected Value of PMF_R

Seismicity Region		PMF_R
(green)	Low	0.1
(yellow)	Moderate	0.9
(orange)	Moderately High	1.2
(red)	High	1.1
(purple)	Very High	0.9

This means that the collapse rate per 50 years is approximately 1/10th the collapse probability given MCE_R shaking. (Recall the negative base-10 logarithmic nature of the Final Score and the Risk Score: a $PMF_R = 1.0$ means that the collapse rate per τ years is $10^{-1} = 0.1$ times the collapse probability given MCE_R shaking.) Thus, the same ratio of collapse probability given MCE_R shaking to collapse rate per 50 years that Luco et al. (2007) established for new buildings also applies to existing buildings. Those authors set MCE_R such that the collapse probability given MCE_R shaking was 0.10, and the collapse probability per 50 years was 0.01. There is a difference between probability and rate: the former has no units, and the latter has units of yr^{-1}, but for small values, less than about 0.1, the two take on approximately the same numerical value.

The present results are somewhat more general than the one established by Luco et al. (2007). Whereas Luco et al. (2007) fixed the new-building collapse probability given MCE_R shaking and the collapse rate per 50 years at 0.10 and 0.01 respectively, the present results allow for other values of collapse probability given MCE_R shaking, like the values estimated using FEMA P-154. The present results show that, on average, the ratio of the two quantities is the same, even if the particular value of collapse probability given MCE_R shaking is not 0.10. Luco et al. (2007) also fixed the logarithmic standard deviation $\beta = 0.80$. The present results allow β to vary randomly according to the fragility functions derived elsewhere in FEMA P-154.

8.5 Relating the Risk Score to Risk

The Risk Score is useful in that one can use it to relate the FEMA P-154 Final Score to fatality risk. Different stakeholders in a risk-management program may understand risk best in different ways, so it may be useful to explain the Risk Score several different ways.

First, the fatality risk posed by an existing building is compared with that of a new code-compliant building. Although the collapse risk in new buildings varies from building to building, one can use Equation 8-7 to estimate that they have collapse probabilities approximately equivalent to $S_R = 3.5$. The value of $\lambda\tau$ in the equation is taken from the FEMA P-695 (FEMA, 2009b) upper-bound limit of 1% collapse probability in 50 years, which is approximately equivalent to 0.01 collapses per 50 years, reduced (by judgment) to 0.005 per 50 years to account for conservativeness of the upper bound, multiplied by a collapsed portion of 0.1 as discussed in FEMA P-154 Chapter 4, and the result of the equation rounded to the nearest 0.5 to avoid appearing excessively accurate. That is, $S_R = -\log_{10}(0.0005) = 3.3$, rounded to 3.5. Table 8-4 presents relative risk for various values of S_R in existing buildings to the risk posed by new buildings.

Table 8-4 Fatality Risk in Existing Buildings Compared with New Buildings

S_R	Fatality Risk Multiplier of Existing Buildings Compared with New Buildings
1.5	100 x
2.0	32 x
2.5	10x
3.0	3 x
3.5	1 x
4.0	0.3 x
4.5	0.1 x

Next, the improvement in life safety that comes about by strengthening a number of buildings is considered. Suppose a certain city contained 2,800 soft-story high-occupancy woodframe residential buildings with $S \approx 1.25$, and thus $S_R \approx 2.25$. Suppose that by retrofit, the buildings could be improved to $S_R \approx 3.3$ at a cost of approximately $260 million. Suppose the buildings provide residences for 64,000 people, all of whom are home at night and half of whom are home in the daytime. These are approximately the conditions of San Francisco's soft-story high-occupancy woodframe residential buildings in 2008 (ATC, 2009). Suppose further that if one were in a collapsed portion of a building, one would have a 10% chance of being killed, as suggested by HAZUS. One can estimate using these figures that the retrofit program will reduce the fatality risk from approximately 27 fatalities per 50 years to approximately 2 fatalities per 50 years, using

$$s = n \times 10^{-S_R} \times f \times \frac{t}{50} \tag{8-14}$$

where *s* denotes lives saved per *t* years, *n* denotes average number of occupants, and *f* denotes the expected fraction of occupants in the collapsed portion of a building who are killed. Given that these buildings have already stood for 90 years and seem reasonably likely to exist another 150, one can estimate that the retrofit program could realistically prevent on the order of 75 fatalities. (That is, 25 statistical fatalities avoided in 50 years, and an estimated 150 years of useful life remaining, means 75 statistical fatalities avoided). One can then estimate the cost per statistical fatality avoided to be $3.4 million, which is less than the amount that the U.S. government deems to be a reasonable expense to avoid a fatality of an unknown person at an uncertain future date. For example, the figure used by the U.S. Department of Transportation (Trottenberg and Rivkin, 2013) is $9.1 million (2012 US dollars) value per statistical life (VSL) saved. The cost per statistical fatality avoided is lower than $3.4 million if one considers avoided repair and replacement costs, additional living expenses, business interruption costs, and nonfatal injuries avoided. Since the $3.4 million cost per statistical fatality avoided is less than the $9.1 million VSL, the retrofit is cost effective—it has a benefit cost ratio greater than 1.0—even before adding the reduced repair costs, living expenses, business interruption losses, and nonfatal injuries.

The Risk Score can also be used to estimate the probability that at least one earthquake occurs during any given period of time that would cause collapse. Let *t* denote a particular number of years, let τ denotes the design life of the building, and let $R(t)$ denote the probability that at least one earthquake occurs during *t* years that is strong enough to cause collapse. $R(t)$ is given by Equation 8-15, which is evaluated in Table 8-5 for various combinations of S_R and *t*.

$$R(t) = 1 - \exp\left(-\frac{10^{-S_R}}{\tau} \times t\right) \tag{8-15}$$

Table 8-5 Relationship Between Risk Score S_R and Collapse Probability $R(t)$

S_R	*t* = 1 yr	*t* = 10 yr	*t* = 50 yr	*t* = 100 yr	*t* = 200 yr
2.0	0.02%	0.2%	1%	2%	4%
2.5	0.006%	0.06%	0.3%	0.6%	1.3%
3.0	0.002%	0.02%	0.1%	0.2%	0.4%
3.5	0.0006%	0.006%	0.03%	0.06%	0.13%
4.0	0.0002%	0.002%	0.01%	0.02%	0.04%

Table 8-5 can be used to consider the risk to a given building in light of how long it is expected to be useful. Suppose for example a building with a Risk

Score of 2 is likely to be demolished and replaced in 10 years. There is a 0.2% (1 in 500) chance that it will experience earthquake-induced collapse during that time. If, on the other hand, it is an important building that is likely to remain in use for 200 years, there is a 4% (1 in 25) chance that an earthquake will cause collapse during its expected lifetime.

Chapter 9
Comparison of Paper-Based and Electronic Scoring Methodologies

9.1 Introduction

The purpose of the Electronic Scoring Methodology is to use the seismic hazard associated with the building site to improve the scoring. It is an alternative to using the paper forms. Site-specific seismic hazard and soil conditions can be used to develop Basic Scores and Score Modifiers for a given building that more accurately account for the seismic hazard compared with the relatively coarse step functions used in the paper forms. Another advantage is that the electronic scoring can be incorporated into the data collection system to avoid the need to transcribe data from the paper forms into an electronic database.

The use of the Electronic Scoring Methodology is optional. The decision to use it should be based on consideration by the Supervising Engineer and the RVS Authority. The Electronic Scoring Methodology can be implemented into an RVS Program in a variety of ways, ranging from the use of simple tools, such as spreadsheets, to more complex tools, such as programming smartphones, tablet computers, or laptop computers. The use of any of the methods for incorporating electronic scoring is not a substitute for a Detailed Structural Evaluation. Electronic scoring can be used for Level 1 screening and for Level 2 screening. However, as Level 2 Score Modifiers have not been developed for the high end of the Very High seismicity region range, for Level 2 screenings, one cannot interpolate beyond the median value for Very High seismicity.

9.2 Development of Scores for the Electronic Scoring Methodology

Chapter 4 of this document describes the basis for the Basic Scores developed for the *Third Edition*. In the development of the *Third Edition* scores, the Basic Scores and Score Modifiers have been developed for six levels of seismic hazard values (S_S and S_1): the five pairs of values used as medians in the five seismicity levels, as described in Chapter 4, plus one hazard values, one can interpolate Basic Scores and Score Modifiers at seismic hazard values between these medians. The sixth level, at the high end of very high seismicity, allows the user to interpolate at seismicity values above the median of the Very High seismicity region. Note that one might still have to extrapolate in cases of buildings at sites with seismic hazard below the median values used for low seismicity. A seventh set of scores at very low seismic hazard levels was not created because the Low seismicity region scores are already sufficiently high enough that it is highly unlikely that further reduced seismicity levels would produce a Final Score below the recommended cut-off score and trigger a Detailed Structural Evaluation.

9.3 Interpolating and Extrapolating Basic Scores and Score Modifiers

To implement the electronic scoring methodology, first the site-specific seismic hazard is determined. The geographic coordinates for the site can be determined using a map or Global Positioning System (GPS) equipment. The S_S and S_1 hazard values for those coordinates can be determined from a map, such as those in ASCE/SEI 7-10 (ASCE, 2010), or from online tools, such as those provided by the U.S. Geological Survey. Then, S_S and S_1 are adjusted for Soil Type CD, by multiplying by F_A and F_V (per Table 9-1) to obtain values of F_AS_S and F_VS_1.

Table 9-1 Site Coefficients for Soil Type CD

Spectral Acceleration on Soil Type B	Amplification Factor for Soil Type CD
Short-Period, S_S (g)	**Short-Period Amplification Factor[1], F_A**
$\leq$ 0.25	1.40
0.50	1.30
0.75	1.15
1.0	1.05
$\geq$ 1.25	1.00
1-second Period, S_1 (g)	**1.0-second Period Amplification Factor[1], F_V**
$\leq$ 0.1	2.05
0.2	1.80
0.3	1.65
0.4	1.50
$\geq$ 0.5	1.40

[1] Soil Type C and Soil Type D values of F_A and F_V for are taken from Table 5-3 and averaged to obtain the Soil Type CD values shown above.

Next, a decision is made on whether to interpolate (or extrapolate) the Basic Score and Score Modifiers on the basis of $F_A S_S$ values or $F_V S_1$ values. For a building estimated to have a small-amplitude fundamental period of vibration, T, where $T \leq S_S / S_1$, the interpolation is made on the basis of $F_A S_S$. For a building with $T > S_S / S_1$, the interpolation is made on the basis of $F_V S_1$. The reason is that, while the building remains elastic, its spectral acceleration response in a given earthquake will lie on the constant-acceleration portion of the idealized response spectrum if $T \leq S_S / S_1$, and it will lie on the constant-velocity portion if $T > S_S / S_1$. The present document employs only a constant-acceleration portion and constant-velocity portion of the response spectrum. The building fundamental period, T, can be estimated from the following equations depending on FEMA Building Type:

$$
\begin{aligned}
T &= 0.035H^{0.80} \text{ for FEMA Building Type S1} \\
&= 0.018H^{0.90} \text{ for FEMA Building Type C1} \qquad (9\text{-}1) \\
&= 0.032H^{0.55} \text{ for FEMA Building Types W1, W1A, W2} \\
&= 0.025H^{0.75} \text{ for others}
\end{aligned}
$$

where H is the building height measured in feet and T is measured in seconds. Lacking better information, H can be estimated as 12 ft per story. Chapter 6 provides the sources for Equation 9-1.

As a simpler but more approximate alternative, one can interpolate and extrapolate the Basic Score and Score Modifiers on the basis of $F_A S_S$ for low-rise (1-3 story) buildings and on the basis of $F_V S_1$ for mid-rise and high-rise buildings (at least 4 stories).

The Supervising Engineer should decide whether to require extrapolation for $F_A S_S$ or $F_V S_1$ values below the lowest values in the tables or whether to cap the values.

Next, the Basic Scores and Score Modifiers are linearly interpolated (or extrapolated). Basic Scores and Score Modifiers provided in the FEMA P-154 *Handbook* and shown on the Data Collection forms are based on median values of $F_A S_S$ or $F_V S_1$ for each seismicity region. The median values are defined in Table 5-4 and repeated below in Table 9-2. For a given $F_A S_S$ or $F_V S_1$, Basic Scores and Score Modifiers can be interpolated using the seismicity regions immediately above and below it.

Some spreadsheet programs and other software can perform the interpolation or extrapolation automatically, but for the user who needs to program the interpolation, the math is offered here.

Table 9-2 Median Spectral Acceleration Values in Each Seismicity Region Adjusted for Soil Type CD

Region	Median F_aS_S (g)	Median F_VS_1 (g)
L	0.28	0.16
M	0.54	0.30
MH	0.90	0.52
H	1.21	0.68
VH	2.25	1.26
VH_{max}	3.80	2.10

For linear interpolation, choose the two (x, y) pairs that have x-values immediately below and above the site's x-value, denoted by (x_0, y_0) and (x_1, y_1), and the site's x-value (F_AS_S or F_VS_1) simply by x. Then the y-value (the Basic Score or Score Modifier, as appropriate) is estimated as:

$$y = y_0 + (x - x_0)\frac{(y_1 - y_0)}{(x_1 - x_0)} \qquad (9\text{-}2)$$

where y_0 and y_1 values for all FEMA Building Types and all seismicity regions are provided in Table 5-10.

Alternatively, to avoid concerns about kinks in the functional relationship between shaking and Basic Score or Score Modifier, the interpolation is done by fitting a spline. A spline is a smooth curve fit to a set of (x, y) pairs such that there is no kink at the x-values in the (x, y) pairs. The hazard value (F_AS_S or F_VS_1, as determined above) is treated as the x-value. The Basic Score and each Score Modifier are treated as the y-value in the interpolation.

There are many ways to fit a spline; the Newton form of the quadratic interpolating polynomial is used here. Accordingly, three pairs of (x, y) data are chosen: (1) one pair with an x-value immediately above the site's hazard value; (2) one with an x-value immediately below; and (3) one pair either above the higher x or below the lower x, as convenient. These data points are denoted by (x_0, y_0), (x_1, y_1), and (x_2, y_2), in increasing order of x-value. The Newton form of the quadratic interpolating polynomial is given by

$$y = b_0 + b_1(x - x_0) + b_2(x - x_0)(x - x_1) \qquad (9\text{-}3)$$

The coefficients b_0, b_1, and b_2 are found by solving for the interpolating conditions:

$$y_0 = b_0$$
$$y_1 = b_0 + b_1(x_1 - x_0) \tag{9-4}$$
$$y_2 = b_0 + b_1(x_2 - x_0) + b_2(x_2 - x_0)(x_2 - x_1)$$

It can be shown that

$$b_0 = y_0$$
$$b_1 = \left(\frac{y_1 - y_0}{x_1 - x_0}\right) \tag{9-5}$$
$$b_2 = \left(\frac{\frac{(y_2 - y_1)}{(x_2 - x_1)} - \frac{(y_1 - y_0)}{(x_1 - x_0)}}{(x_2 - x_0)}\right)$$

For example, consider a W1 building located where $F_A S_S$ = 0.322g. The building has a severe vertical irregularity, plan irregularity, and is on Soil Type E (and is a low-rise building). Its Basic Score is interpolated by the quadratic interpolating polynomial as follows:

x = 0.322g

x_0 = 0.28g (Table 9-2, $F_A S_S$, L seismicity row)

x_1 = 0.54g (Table 9-2, $F_A S_S$, M seismicity row)

x_2 = 0.90g (Table 9-2, $F_A S_S$, MH seismicity row)

y_0 = 6.2 (Table 5-10, Basic Score, W1, Low Seismicity Region)

y_1 = 5.1 (Table 5-10, Basic Score, W1, Moderate Seismicity Region)

y_2 = 4.1 (Table 5-10, Basic Score, W1, Moderately High Seismicity Region)

$$b_0 = y_0$$
$$= 6.2$$

$$b_1 = \left(\frac{y_1 - y_0}{x_1 - x_0}\right)$$
$$= \left(\frac{5.1 - 6.2}{0.54 - 0.28}\right)$$
$$= -4.231$$

$$b_2 = \left(\frac{\frac{(y_2 - y_1)}{(x_2 - x_1)} - \frac{(y_1 - y_0)}{(x_1 - x_0)}}{(x_2 - x_0)} \right)$$

$$= \left(\frac{\frac{(4.1 - 5.1)}{(0.90 - 0.54)} - \frac{(5.1 - 6.2)}{(0.54 - 0.28)}}{(0.90 - 0.28)} \right)$$

$$= 2.344$$

$$y = b_0 + b_1(x - x_0) + b_2(x - x_0)(x - x_1)$$

$$= 6.2 - 4.231(0.322 - 0.28) + 2.344(0.322 - 0.28)(0.322 - 0.54)$$

$$= 6.0$$

The Basic Score is calculated as 6.0. In comparison, the paper-based Basic Score is 6.2. Figure 9-1 illustrates the spline fit. The rest of the parameter values for this example are shown in Table 9-3.

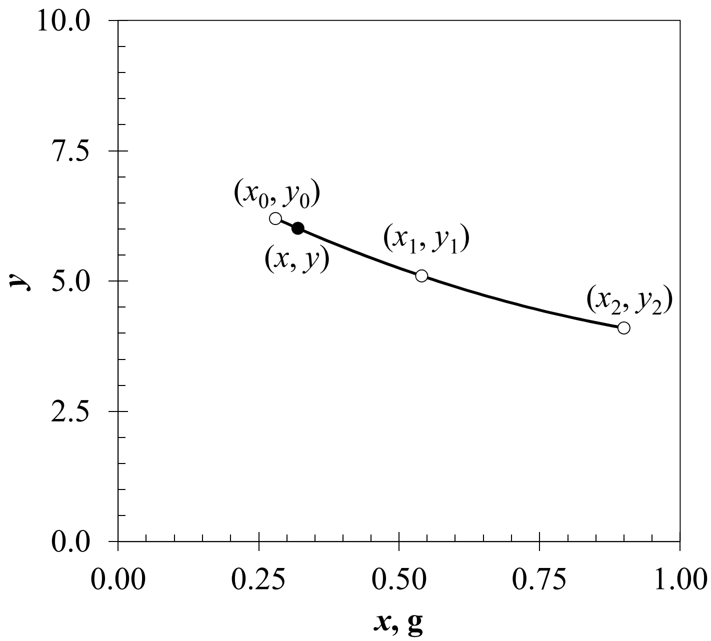


Figure 9-1 Spline fit to the example data.

Table 9-3 Low-Rise W1 Building, $F_A S_S$ = 0.322g, with Severe Vertical Irregularity, Plan Irregularity, on Soil Type E

Interpolation Parameters						Score	
	y_0	y_1	y_2	b_1	b_2	Electronic	Paper
Basic Score	6.2	5.1	4.1	-4.23	2.34	6.00	6.2
Severe Vert. Irreg.	-1.5	-1.4	-1.3	0.38	-0.17	-1.48	-1.5
Mod. Vert. Irreg.	0	0	0	0	0	0	0
Plan Irregularity	-1.6	-1.4	-1.3	0.77	-0.79	-1.56	-1.6
Pre-Code	0	0	0	0	0	0	0
Post-Benchmark	0	0	0	0	0	0	0
Soil B	0	0	0	0	0	0	0
Soil E - Low-Rise	-1.2	-1.2	0	0.00	5.38	-1.25	-1.2
Soil E - Mid/High	0	0	0	0	0	0	0
Minimum Score	2.7	1.6	1.6	-4.23	6.82	2.46	2.7
					Score =	2.46	2.7

9.4 Comparison of Scores Derived with Electronic Scoring versus Paper-Based Scores[1]

Within a given seismicity region, the seismic hazard can vary by a factor from about 1.5 to 2. The effect of changes in seismic hazard on the Basic Score values are less dramatic, but can still be significant in determining either the relative ranking of buildings or whether a building passes the screening based on a comparison with the cut-off score.

One can estimate the chance that using electronic scoring will yield a different result from the paper-based methodology. The main difference of interest here is whether the paper-based methodology yields a Final Score less than or equal to 2.0 while the electronic methodology yields a Final Score of over 2.0 (referred to here as incorrect failure) or vice versa (referred to here as incorrect passing). These probabilities are estimated by calculating scores under both methodologies, and calculating the fraction of all combinations where the paper-based and electronic methodologies yield different results in terms of whether the Final Score is above or below the cut-off. The approach used here is to treat as equiprobable every combination of shaking (in equiprobable increments of $F_A S_S$), FEMA Building Type, and

[1] The comparisons presented in this section were made using draft values of Basic Scores and Score Modifiers. In a limited number of instances, Basic Scores and Score Modifiers were subsequently revised. Such revisions included adjustments to W1A Basic Scores and Post-Benchmark Score Modifiers, and are not expected to have a significant effect on the results of this section.

allowable Level 1 Score Modifier combinations (irregularities, era, and soil). Quadratic interpolation is used as described in Section 9.3.

To calculate the probabilities of incorrect failure and incorrect passing, it was first necessary to determine the probability that a particular building is exposed to a particular level of $F_A S_S$, and the probability of observing a given combination of FEMA Building Type and Score Modifiers.

For the former, it was assumed that buildings are distributed similarly to the population. One can readily estimate how the population is distributed versus $F_A S_S$. Two data sources provide the necessary information:

- The U.S. Geological Survey's seismic design data sets derived from 2008 USGS Hazard Data (USGS, 2014a). These are text files containing risk-targeted S_S and S_1 parameter values from the 2012 *International Building Code* on a gridded basis: 0.01 or 0.05 degrees for the conterminous United States and Alaska, 0.02 degrees for Hawaii, and 0.01 degrees for Puerto Rico and the U.S. Virgin Islands.
- The U.S. Census Bureau's "National Places Gazetteer." This data set contains population and location data (among others) for all incorporated places and census designated places (CDPs) in the 50 states, the District of Columbia and Puerto Rico as of January 1, 2010.

The value of risk-targeted $F_A S_S$ was calculated for each populated place in the Gazetteer using F_A for Soil Type CD. One can then sort the population by increasing $F_A S_S$ and calculate the cumulative fraction of the population exposed to a given value of $F_A S_S$ or less, as a function of $F_A S_S$, and fit a smooth curve to the cumulative distribution function of $F_A S_S$ for convenience. The cumulative distribution of the population of the United States was found to be approximately lognormally distributed, with median 0.27g and logarithmic standard deviation 1.08g, as shown in the smooth curve of Figure 9-2. A set of 100 equiprobable values of $F_A S_S$ were then selected by inverting the cumulative distribution function at 0.005, 0.015, 0.025, … 0.995.

There does not appear to be sufficient available evidence to estimate the probability that any arbitrarily selected building will exhibit a particular combination of FEMA Building Type and set of Score Modifiers, so each combination was treated as equiprobable. There are 96 possible sets of Score Modifiers for each FEMA Building Type, ignoring the fact that some Score Modifiers are not applicable to some building types and seismicity levels. By "possible sets" is meant that, for example, a building cannot have both moderate and high vertical irregularity.

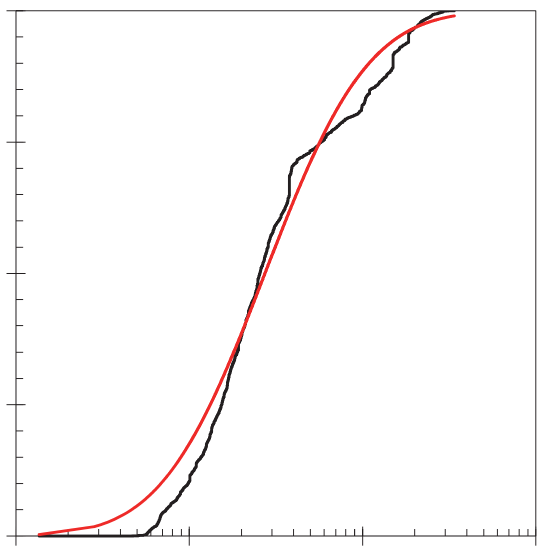


Figure 9-2 Distribution of the population of the United States by $F_A S_S$.

With 100 levels of $F_A S_S$, 96 sets of Score Modifiers per FEMA Building Type, and 17 FEMA Building Types, one can calculate paper and electronic scores for each of 163,200 samples of FEMA Building Type, Score Modifier set, and value of $F_A S_S$. For electronic scoring, Basic Scores, Score Modifiers, and Minimum Scores were calculated using a quadratic interpolating polynomial, that is, by fitting a smooth spline as discussed above. Extrapolation below the lowest values of S_S and S_1 is allowed in these calculations.

As shown in Table 9-4, among the 163,200 samples, if calculated using the paper methodology, 9,223 samples (approximately 6%) would produce incorrect-failure results, meaning that they would call for Detailed Structural Evaluation ($S \leq 2$) while the electronic scoring would not ($S > 2$). Another 1,495 samples (approximately 1%) produce incorrect-passing results, meaning that the paper-based methodology yields $S > 2$ while the electronic scoring yields $S \leq 2$.

Table 9-4 Errors avoided Using Electronic Scoring

Incorrect failure	9,223	6%
Incorrect passing	1,495	1%

Table 9-5 shows an example that demonstrates how electronic scoring can avoid incorrect-passing scores produced by the paper-based methodology. It reflects FEMA Model Building Type W2, moderate vertical irregularity, plan irregularity, low-rise on Soil Type E, subject to $F_A S_S$ = 0.133g.

Table 9-5 Low-Rise W2, $F_A S_S$ =0.133g, with Moderate Vertical Irregularity, Plan Irregularity, on Soil Type E

Interpolation Parameters						Score	
	y_0	y_1	y_2	b_1	b_2	Electronic	Paper
Basic Score	5.7	3.8	3.2	-7.31	9.10	7.32	5.7
Severe Vert. Irreg.	0	0	0	0	0	0	0
Mod. Vert. Irreg.	-0.9	-0.9	-0.8	0.00	0.45	-0.87	-0.9
Plan Irregularity	-1.3	-1.2	-1.1	0.38	-0.17	-1.37	-1.3
Pre-Code	0	0	0	0	0	0	0
Post-Benchmark	0	0	0	0	0	0	0
Soil B	0	0	0	0	0	0	0
Soil E - Low-Rise	-2.3	-1.4	-0.3	3.46	-0.65	-2.85	-2.3
Soil E - Mid/High	0	0	0	0	0	0	0
Min. Score	1.5	0.9	0.8	-2.31	3.27	2.04	1.5
					Score =	2.23	1.5

Figure 9-3 shows how incorrect failures and incorrect-passing results tend to occur near boundaries between seismicity regions. Incorrect failures occur at the low values of $F_A S_S$ within each seismicity region; incorrect passing at high values. Table 9-6 shows that incorrect failures and incorrect-passing results occur in all FEMA Building Types. Table 9-7 shows that they occur in all seismicity regions, with the exception of incorrect failures in Low seismicity.

Among the 163,200 samples, 56% of the Final Scores calculated using the electronic scoring methodology are higher than the Final Scores calculated using the paper-based scoring methodology, 14% are lower, and the remaining 30% are the same within ± 0.1. Figure 9-4 shows the distribution of the difference. The differences are to be expected. The ranges of $F_A S_S$ and $F_V S_1$ values for the five hazard regions are all substantial. The upper value is generally double the lower, so one would expect the Final Score for a building in a location at the high end of the seismicity region to be very different from one at the low end. The values of $F_A S_S$ and $F_V S_1$ used for the paper-based methodology were chosen to provide a conservative estimate of Final Score for their seismicity region, which is why one would expect more Final Scores in the electronic methodology to be higher than the Final Score for paper-based methodology rather than lower. That is, the characteristic

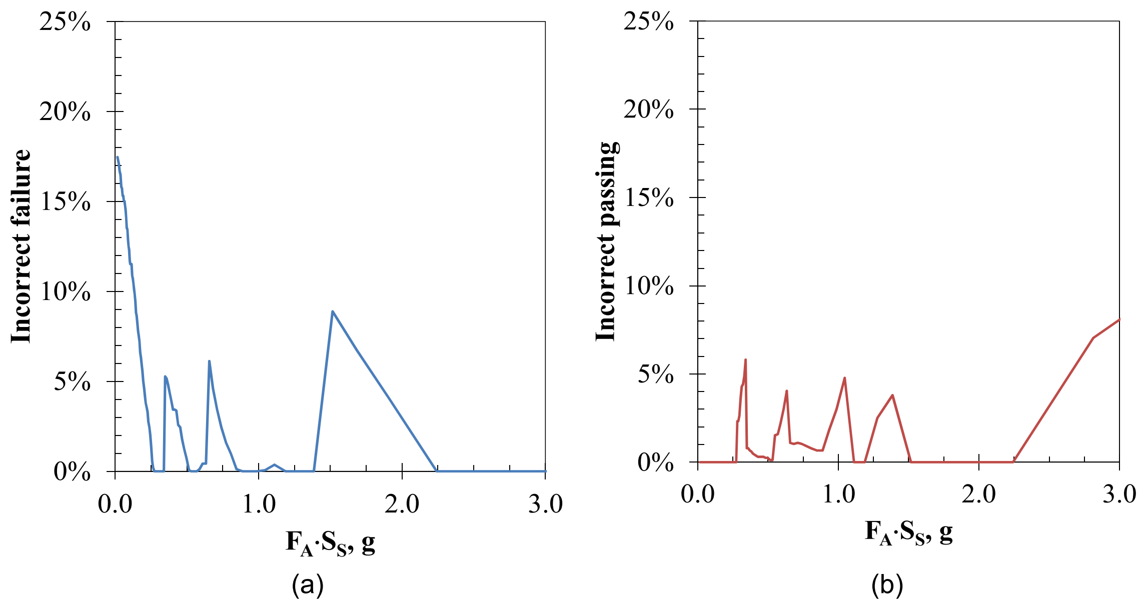


Figure 9-3 (a) Incorrect failures and (b) incorrect-passing scores resulting from the use of the paper-based scoring, as a function of site-specific $F_A S_S$.

Table 9-6 Incorrect Failures and Incorrect Passing Resulting from the Use of Paper-Based Scoring, by FEMA Building Type

Model Building Type	Incorrect Failure	Incorrect Passing
W1	0.8%	0.8%
W1A	1.0%	0.7%
W2	3.1%	1.1%
S1	8.4%	0.7%
S2	7.2%	0.9%
S3	3.4%	1.8%
S4	7.4%	0.6%
S5	8.8%	0.7%
C1	6.8%	1.1%
C2	6.1%	1.1%
C3	10.5%	0.7%
PC1	5.4%	0.8%
PC2	6.0%	0.8%
RM1	5.0%	1.3%
RM2	4.6%	1.4%
URM	8.3%	0.7%
MH	3.2%	0.5%

Table 9-7 **Incorrect Failures and Incorrect Passing Resulting from the Use of Paper-Based Scoring, by Seismicity Region**

	Seismicity Region	Incorrect Failure	Incorrect Passing
	Low	10.2%	0.0%
	Moderate	1.8%	1.4%
	Mod-High	1.2%	1.5%
	High	0.1%	2.2%
	Very High	3.3%	3.3%

values of $F_A S_S$ and $F_V S_1$ for each seismicity range, the values used to calculate structural response and collapse probability for each seismicity range, are slightly higher than the average value of the range to avoid unconservative scores. In addition, the electronic scoring methodology is likely to produce a higher score in practice, because in practice each county is assigned the highest seismicity level of any place in the county.

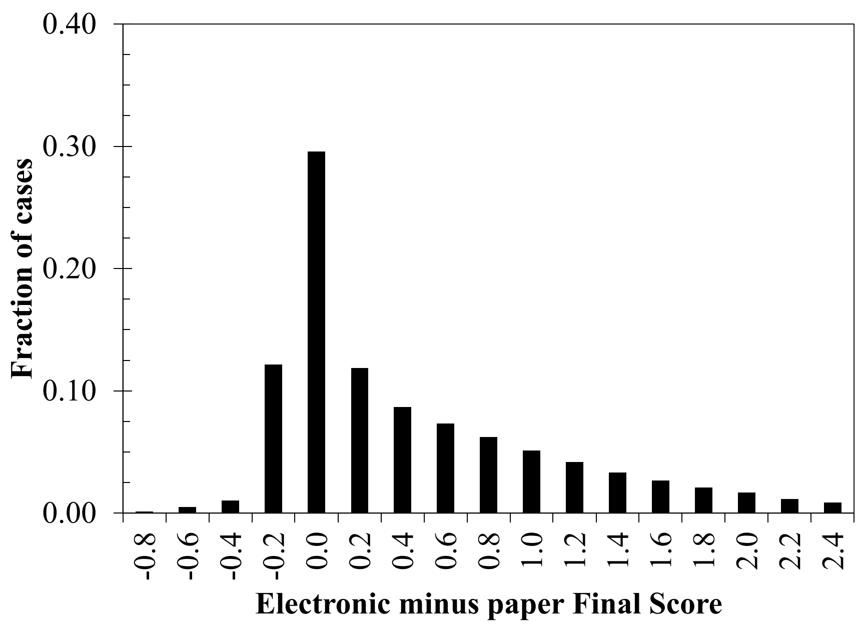


Figure 9-4 Distribution of the difference between the Final Score when calculated using the electronic method and the paper method.

On average, the electronic scoring methodology produces a Final Score 0.5 units higher than the paper-based scoring methodology. The standard deviation of the difference between the two is 1.8.

9.5 Conclusions

The RVS methodology is approximate. Although it is a building-specific methodology, it only uses a few building-specific features, far fewer than are used in a Detailed Structural Evaluation. Its many approximations introduce substantial uncertainty into the estimate of risk, compared with the Detailed Structural Evaluation. However, using electronic scoring can reduce that uncertainty by avoiding the approximation of seismic hazard that comes with lumping seismic hazard into five seismicity regions. Based on the study described above, use of electronic scoring can avoid 6% of cases from incorrectly requiring a Detailed Structural Evaluation and 1% of cases from incorrectly not requiring a Detailed Structural Evaluation. Since a Detailed Structural Evaluation can take days or more of analysis, electronic scoring of 100 buildings could reduce the required effort required for Detailed Structural Evaluation by five buildings (six fewer buildings flagged for Detailed Structural Evaluation and one added), potentially saving hundreds of labor hours and tens of thousands of dollars' expense.

Electronic scoring could potentially avoid other errors. If the electronic scoring is part of a system that geolocates buildings, it becomes easier to estimate Soil Type and thus avoid unnecessary assumptions and scoring errors associated with incorrect Soil Type. If the system also involves using satellite imagery, one may be able to more easily identify plan irregularities that may be hidden in mid-block buildings by adjacent buildings. If the system also involves data entry directly into an electronic database rather than paper, one may also avoid transcription errors, along with avoiding the expense of transcription. With electronic scoring and an electronic database of screened buildings, one can more easily use the screening data as part of a broader risk-management program.

Chapter 10
Benchmarking Studies and Trial Runs

10.1 Purpose

Throughout the three-year effort to update FEMA 154, numerous benchmarking studies and trial runs were performed. They served to check the evolving Data Collection Forms for usability and to assess the accuracy of the updated FEMA P-154 scores. Insight gained from these benchmarking studies and trial runs helped to shape the final *Third Edition* rapid visual screening procedure, resulted in additional guidance within the *Handbook*, and significantly influenced the content and layout of the *Third Edition* Data Collection Forms and Reference Guides.

10.2 AOC Benchmarking Study[1]

In 2003, California's Administrative Office of the Courts (AOC) developed and implemented the Superior Courts of California Seismic Assessment Program. A summary report of preliminary findings was published in 2004 (Administrative Office of the Courts, 2004). The database of seismic evaluations of California courthouses created for this program was used for benchmarking. The benchmarking study was performed in the first year, and again at the midpoint of the third year. The sections below focus on the results of the third year benchmarking efforts since they most closely relate to the final version of the *Third Edition* updates.

10.2.1 Overview of the AOC Seismic Assessment Program

The purpose of the AOC program was to develop reliable seismic risk assessments for California court buildings, of which ownership and management responsibility were to be transferred from the county to the state level. Seismic assessments of over 200 buildings were performed by engineers from eight consulting engineering firms. Each building was

[1] The benchmarking study presented in this section was performed with draft values of Basic Scores and Score Modifiers. In a limited number of instances, Basic Scores and Score Modifiers were subsequently revised. Such revisions included adjustments to W1A Basic Scores and Post-Benchmark Score Modifiers, and are not expected to have a significant effect on the results of this study.

assigned a "DSA Risk Level," where Risk Level I represents repairable structural damage and negligible risk to life, and Risk Level VII represents total collapse and imminent threat to life. The vast majority of the court buildings are rated Risk Level IV (moderate risk to life) or V (substantial risk to life).

The first phase of the evaluation process was an initial screening by the most experienced engineers of the eight firms. These engineers reviewed construction drawings and, for each building, decided using expert judgment whether the seismic performance of the building was obviously acceptable (rated as a Risk Level IV or better, indicated as "IVb") or obviously unacceptable (rated as a Risk Level V or worse, indicated as "Vw"). Those that could not be obviously assigned a IVb or Vw were sent to a detailed evaluation. The detailed evaluation was performed using ASCE/SEI 31-03, *Seismic Evaluation of Existing Buildings* (ASCE, 2003). If the ASCE/SEI 31-03 Tier 1 evaluation did not result in a conclusive rating, a Tier 2 evaluation was performed. Based on the ASCE/SEI 31-03 evaluation results, each building was assigned to Risk Level IV, Risk Level V, or Risk Level VI.

The buildings evaluated by the AOC are not only numerous, but diverse, making this database an attractive resource for benchmarking. The buildings include wood, steel, concrete, reinforced masonry, URM and precast structures. The oldest was constructed in 1854 and the most recent in 1993. They vary from one-story to 17 stories. There are buildings that have been retrofitted and buildings with pounding potential.

The resources used for this benchmarking effort include the following:

- AOC Building Matrix: An Excel database that contains key information for all 225 buildings including building name, building location, building type, building age, number of stories, liquefaction potential, and dates of retrofits. Values of S_S and S_1 are also provided for each building. A DSA rating of IVb, IV, V, VI, or Vw is provided for each building.
- Initial screening forms for each building.
- Final evaluation reports for each building that underwent an ASCE/SEI 31-03 evaluation.

10.2.2 Selection of Buildings for Benchmarking

Of the 225 court buildings that were evaluated, 45 are part of large complexes consisting of multiple, adjoining structures. To simplify the benchmarking effort and to focus on the accuracy of the *Third Edition* scoring rather than on the implementation of RVS on complex conglomerations of buildings, these 45 courthouses were not considered as part of the benchmarking effort.

Of the remaining 180 buildings, a majority received a DSA Rating of V (114 total). Roughly a quarter (49 total) of the buildings were selected for this benchmarking effort. The buildings were selected such that the benchmarking subset would be well distributed by DSA rating, building type, building height and building size, building age, and seismicity region.

The seismicity region for each building was determined based on the AOC reported values of S_S and S_1. The AOC seismicity values are based on the 1997 NEHRP maps considering Soil Type B and MCE ground motions. The MCE values are generally similar to the MCE_R values considered in the *Third Edition*. In California, the ratio of MCE to MCE_R varies between 0.9 and 1.1 (ASCE, 2010). For the purpose of this benchmarking study, the 10% variation is ignored and the AOC reported values of S_S and S_1 are compared directly to the criteria of Table 5-1 to determine seismicity region. More than half of the buildings are in Very High seismicity (for both the full AOC Database and the benchmarking subset).

Table 10-1 presents the characteristics of the 49 buildings.

Table 10-1 Characteristics of 49 Benchmarked Buildings

Building Number	FEMA Building Type	Building Age	Number of Stories	DSA Rating	Seismicity	Notes
1	S4	1935	13	V	VH	
2	C2	1961	5	V	VH	
3	S1	1982	1	IV	VH	
4	S4	1977	5	IVb	VH	
5	C2	1958	2	V	VH	Retrofit
6	RM2	1976	3	V	VH	
7	URM	1928	1	V	VH	
8	URM	1860	3	VI	M	
9	RM1	1968	1	V	MH	
10	W2	1963	1	IV	MH	
11	RM1	1966	1	V	MH	
12	PC1	1964	1	IV	M	
13	RM1	1973	2	Vw	VH	
14	W2	1982	1	IVb	VH	

None of the buildings is identified by name or address in order to protect private information.

Table 10-1 Characteristics of 49 Benchmarked Buildings (continued)

Building Number	FEMA Building Type	Building Age	Number of Stories	DSA Rating	Seismicity	Notes
15	W2	1950	1	IVb	VH	Retrofit
16	S5	1911	3	V	M	Retrofit
17	W2	1984	1	IVb	M	
18	W2	1974	2	V	VH	Pounding
19	URM	1894	2	V	MH	Retrofit
20	C2	1923	3	V	VH	
21	C2	1922	2	V	H	
22	C1	1991	2	IVb	MH	
23	C2	1978	1	IV	MH	
24	W2	1965	1	IVb	VH	
25	C3	1915	3	Vw	MH	
26	C2	1983	4	IV	VH	
27	RM1	1952	1	V	VH	
28	RM1	1972	1	V	VH	
29	RM1	1970	1	Vw	VH	
30	RM1	1956	1	V	VH	
31	S4	1964	7	IV	VH	
32	S1	1989	10	V	VH	
33	C2	1954	2	Vw	VH	
34	C2	1969	2	Vw	VH	
35	C2	1950	1	IV	MH	
36	C2	1937	2	IV	VH	
37	C1	1968	2	Vw	VH	Pounding
38	S1	1989	6	IV	VH	
39	C2	1926	4	VI	VH	
40	S1	1981	3	V	H	
41	S2	1976	2	V	VH	
42	C1	1965	5	V	VH	Pounding
43	W1	1974	1	IV	VH	
44	URM	1920	2	Vw	MH	
45	C2	1917	3	IV	MH	
46	S2	1986	3	V	VH	Retrofit
47	C2	1916	2	V	VH	Retrofit
48	C2	1903	1	V	VH	Retrofit
49	URM	1866	3	IVb	VH	Retrofit

None of the buildings is identified by name or address in order to protect private information.

Figures 10-1 through 10-6 show the distribution of the building properties.

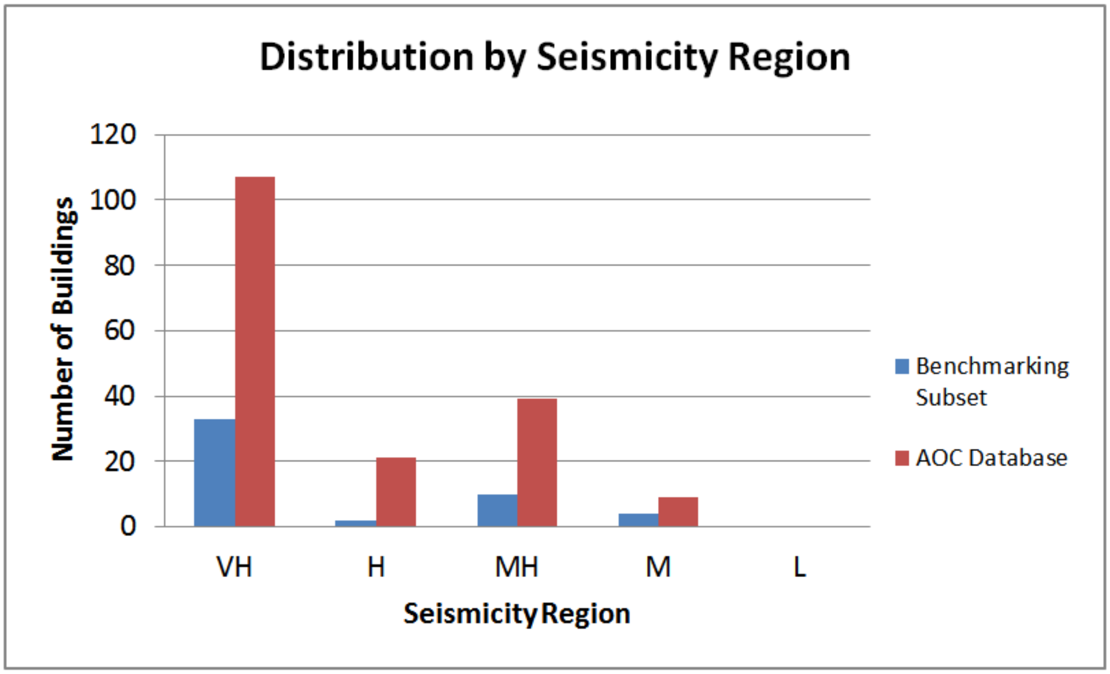


Figure 10-1 Distribution of AOC database buildings and benchmarking subset by seismicity region.

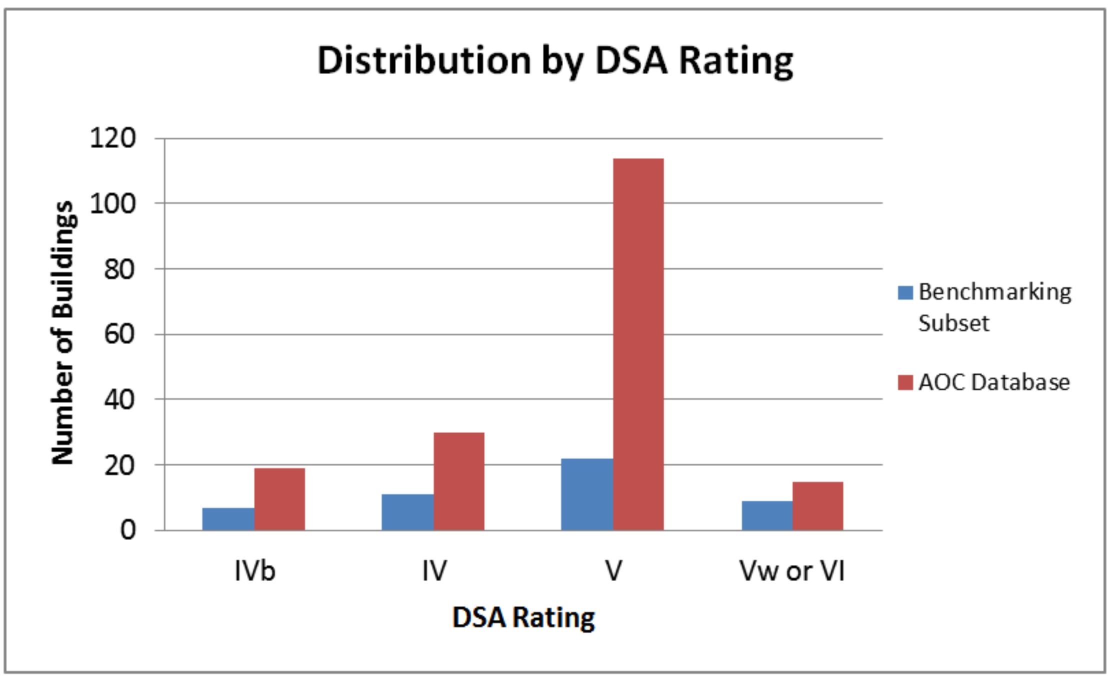


Figure 10-2 Distribution of AOC database buildings and benchmarking subset by DSA rating.

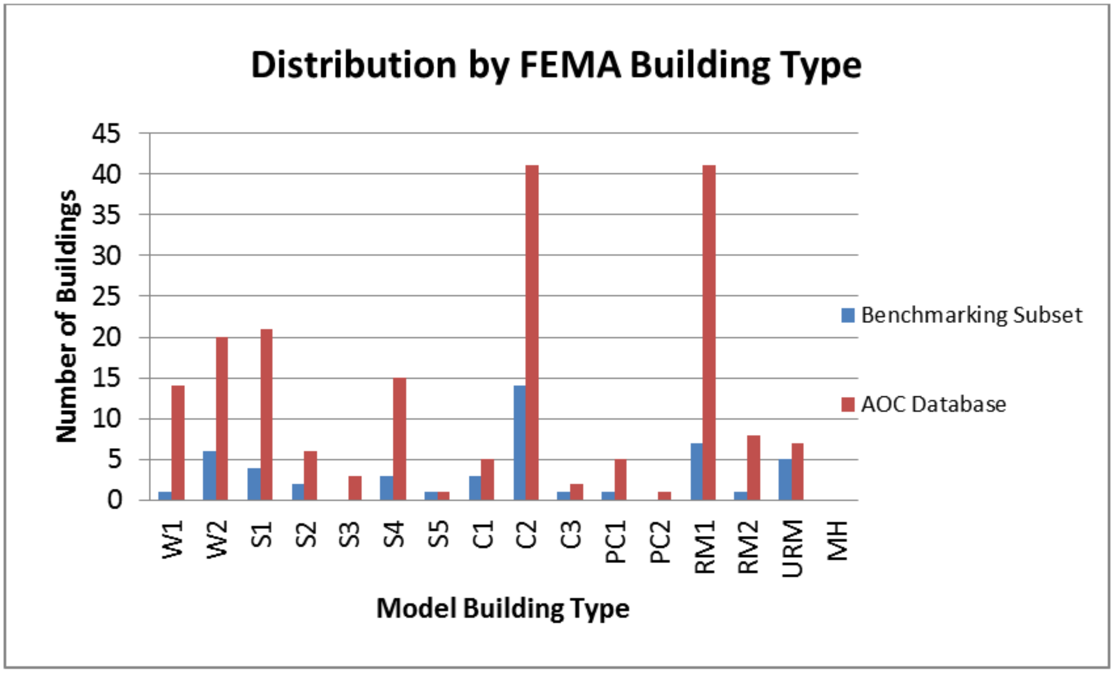


Figure 10-3 Distribution of AOC database buildings and benchmarking subset by FEMA Building Type.

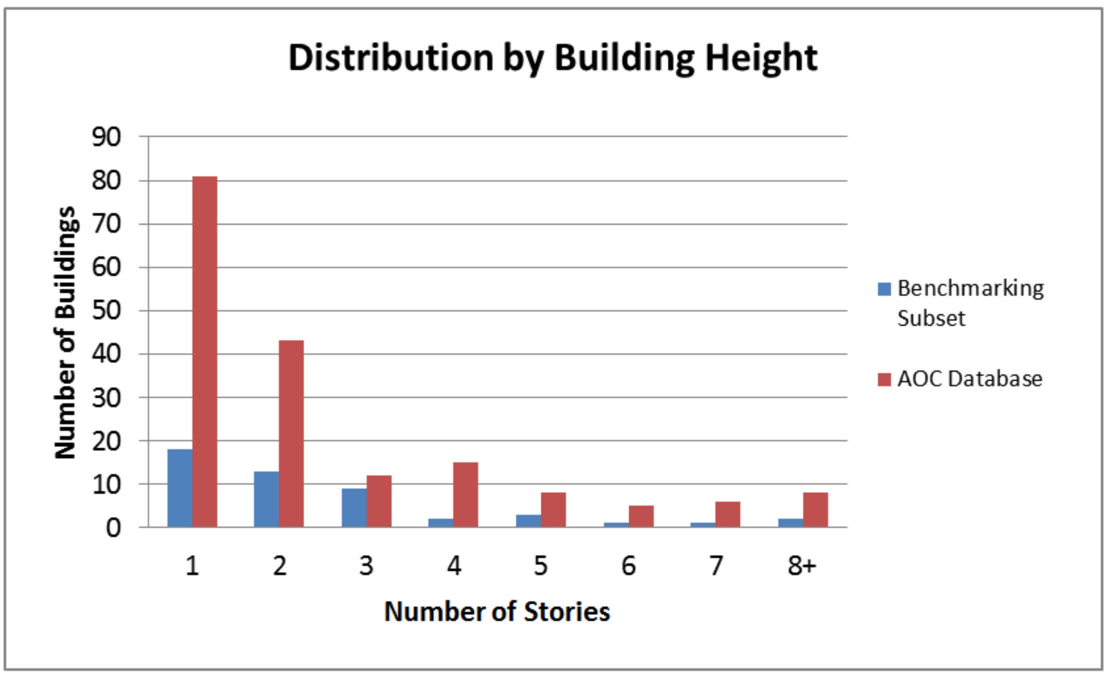


Figure 10-4 Distribution of AOC database buildings and benchmarking subset by building height.

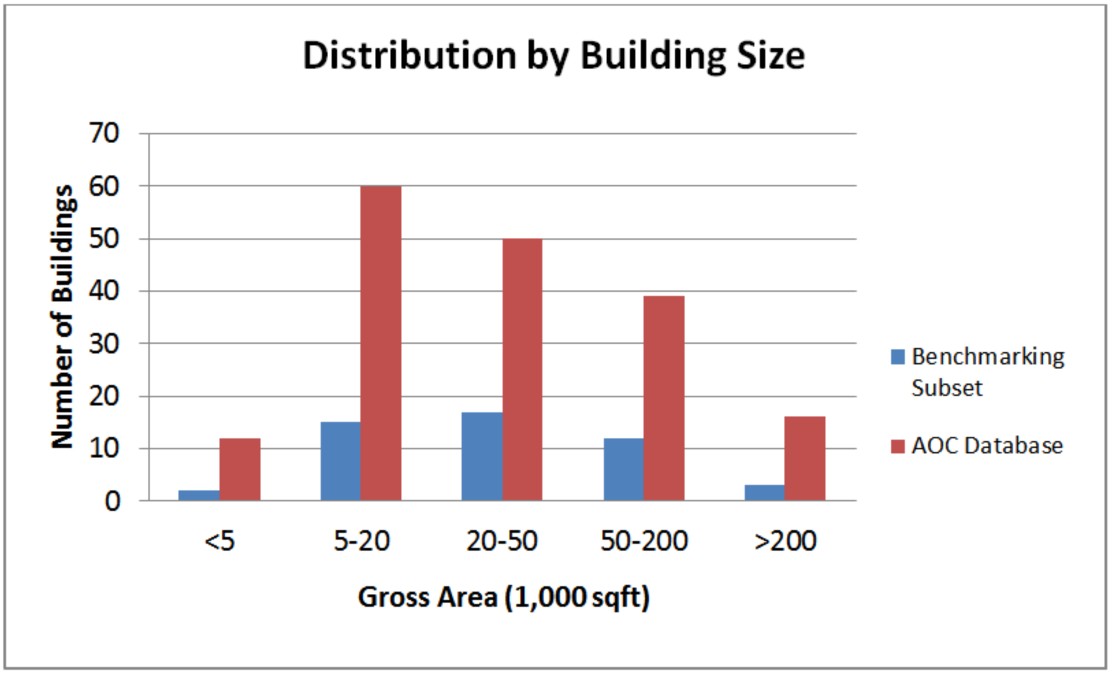


Figure 10-5 Distribution of AOC database buildings and benchmarking subset by building size.

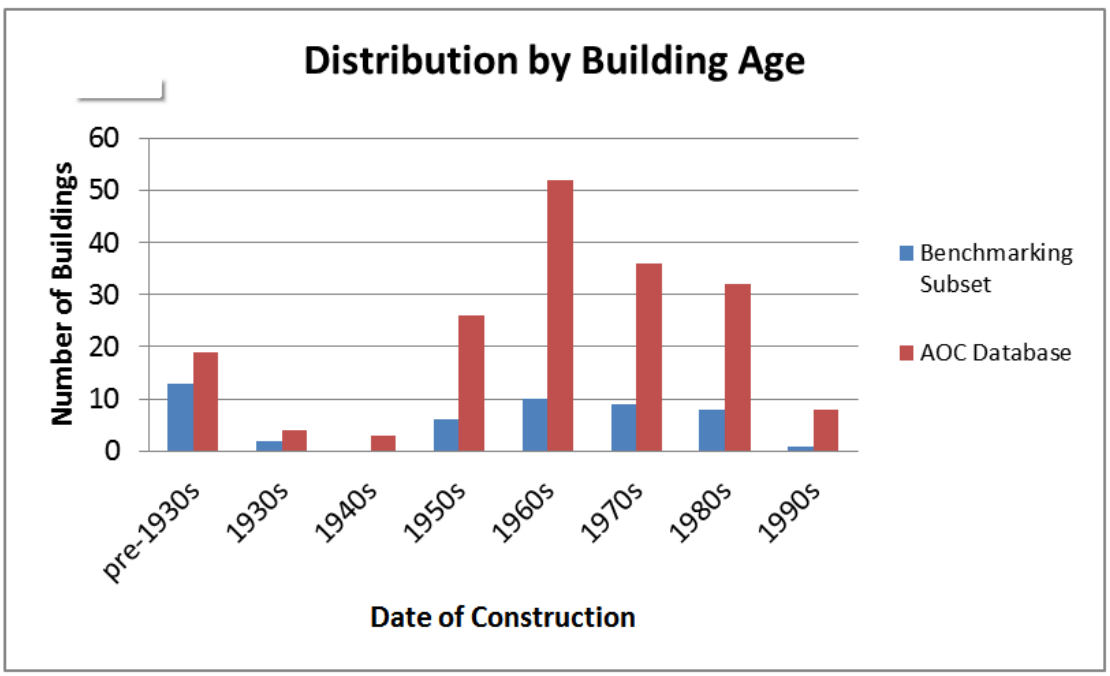


Figure 10-6 Distribution of AOC database buildings and benchmarking subset by building age.

10.2.3 Calculating the RVS Score

For the benchmarking effort, it was necessary to calculate the RVS score for each building under consideration. Because the buildings are located throughout California, it was not practical to perform an actual rapid visual screening of each building. Rather, building characteristics were compiled from a variety of sources and the scores were calculated based on these characteristics using an Excel spreadsheet. In an actual RVS scenario, the building's age, lateral system, and soil type are not always known and must be estimated. For this benchmarking exercise, these building characteristics were provided, resulting in more accurate scores than might be expected from an actual RVS program.

Many of the building characteristics needed for RVS are provided in the AOC Building Matrix, such as building type and number of stories. Additional building characteristics, such as soil type, were determined by reviewing the initial screening forms or the final evaluation reports. The evaluation reports also provide some information about the presence of vertical and plan irregularities, pounding potential, damage and deterioration, and details about existing retrofits. Internet tools, such as Google Streetview, Google image searches, and http://www.ecourthouses.com, were used as secondary sources to view the building and identify irregularities and pounding potential. Site visits were made to three selected courthouses to confirm building properties.

Some information on the Level 2 form was estimated. For example, the gap between buildings could not be measured, so an approximation was made based on available images as to whether pounding potential exists. Unbraced cripple walls in W1 buildings were never visible from the photographs. Therefore, the accuracy of this Level 2 statement modifier has not been verified as part of this benchmarking effort.

Using a spreadsheet to calculate scores, the following was recorded for each building:

- The *Second Edition* Score, S, and whether a Detailed Structural Evaluation is required. A Detailed Structural Evaluation is considered to be required when $S \leq 2.0$.
- The *Third Edition* Level 1 Score, S_{L1}, and whether a Detailed Structural Evaluation is required. A Detailed Structural Evaluation is considered to be required when $S_{L1} \leq 2.0$ or if there is another hazard present, such as liquefaction or deterioration.
- The *Third Edition* Level 2 Score, S_{L2}, and whether a Detailed Structural Evaluation is required. A Detailed Structural Evaluation is considered to be required when $S_{L2} \leq 2.0$ or if there is another hazard, such as liquefaction or deterioration present.

- The DSA Risk Level converted to a numerical value (IVb = 3, IV = 4, V = 5, Vw and VI = 6).

10.2.4 Benchmarking Results

Summary results for the 49 buildings are shown in Table 10-2. "DSE Req'd" indicates that the screening triggers a Detailed Structural Evaluation.

Table 10-2 Summary AOC Benchmarking Results

Building Number	DSA Rating	Numerical DSA Rating	*Second Edition*		*Third Edition* Level 1		*Third Edition* Level 2	
			S	Result	S_{L1}	Result	S_{L2}	Result
1	V	5	1.2	DSE Req'd	0.5	DSE Req'd	0.9	DSE Req'd
2	V	5	1.6	DSE Req'd	0.5	DSE Req'd	0.1	DSE Req'd
3	IV	4	2.2		1.5	DSE Req'd	0.8	DSE Req'd
4	IVb	3	2.7		1.7	DSE Req'd	2.7	
5	V	5	1.2	DSE Req'd	0.5	DSE Req'd	1.7	DSE Req'd
6	V	5	1.2	DSE Req'd	0.4	DSE Req'd	0.6	DSE Req'd
7	V	5	0.5	DSE Req'd	0.5	DSE Req'd	0.6	DSE Req'd
8	VI	6	1.5	DSE Req'd	1.9	DSE Req'd	1.8	DSE Req'd
9	V	5	2.2		1.8	DSE Req'd	1.8	DSE Req'd
10	IV	4	3.0		3.2		3.5	
11	V	5	1.7	DSE Req'd	1.1	DSE Req'd	2.1	
12	IV	4	1.5	DSE Req'd	0.4	DSE Req'd	2.1	
13	Vw	6	1.7	DSE Req'd	0.7	DSE Req'd	1.1	DSE Req'd
14	IVb	3	4.9		3.3		3.8	
15	IVb	3	2.5		1.2	DSE Req'd	2.8	
16	V	5	2.2		2.4		3.8	
17	IVb	3	2.9		6.0		7.5	
18	V	5	2.9		2.4	DSE Req'd	2.2	
19	V	5	0.5	DSE Req'd	0.7	DSE Req'd	2.2	
20	V	5	0.7	DSE Req'd	0.5	DSE Req'd	1.0	DSE Req'd
21	V	5	1.8	DSE Req'd	1.2	DSE Req'd	1.2	DSE Req'd
22	IVb	3	3.3		3.6		3.6	
23	IV	4	2.2		2.1		2.1	
24	IVb	3	5.4		3.8		3.8	
25	Vw	6	-0.1	DSE Req'd	0.6	DSE Req'd	1.0	DSE Req'd
26	IV	4	1.1	DSE Req'd	0.3	DSE Req'd	0.7	DSE Req'd
27	V	5	1.7	DSE Req'd	0.7	DSE Req'd	1.1	DSE Req'd
28	V	5	1.7	DSE Req'd	0.7	DSE Req'd	1.1	DSE Req'd

Table 10-2 Summary AOC Benchmarking Results (continued)

Building Number	DSA Rating	Numerical DSA Rating	*Second Edition*		*Third Edition* Level 1		*Third Edition* Level 2	
			S	Result	S_{L1}	Result	S_{L2}	Result
29	Vw	6	1.9	DSE Req'd	0.7	DSE Req'd	1.3	DSE Req'd
30	V	5	2.2		1.1	DSE Req'd	1.1	DSE Req'd
31	IV	4	1.1	DSE Req'd	0.5	DSE Req'd	1.3	DSE Req'd
32	V	5	1.3	DSE Req'd	0.5	DSE Req'd	1.0	DSE Req'd
33	Vw	6	0.7	DSE Req'd	0.3	DSE Req'd	0.6	DSE Req'd
34	Vw	6	2.4		1.2	DSE Req'd	1.2	DSE Req'd
35	IV	4	1.7	DSE Req'd	0.6	DSE Req'd	1.2	DSE Req'd
36	IV	4	-0.3	DSE Req'd	0.3	DSE Req'd	1.3	DSE Req'd
37	Vw	6	-0.1	DSE Req'd	0.3	DSE Req'd	0.3	DSE Req'd
38	IV	4	2.6		1.5	DSE Req'd	1.5	DSE Req'd
39	VI	6	1.6	DSE Req'd	1.0	DSE Req'd	1.0	DSE Req'd
40	V	5	0.9	DSE Req'd	0.5	DSE Req'd	0.5	DSE Req'd
41	V	5	1.9	DSE Req'd	0.9	DSE Req'd	1.4	DSE Req'd
42	V	5	2.3		1.0	DSE Req'd	0.3	DSE Req'd
43	IV	4	4.4		2.1		2.1	
44	Vw	6	1.2	DSE Req'd	1.2	DSE Req'd	1.2	DSE Req'd
45	IV	4	0.7	DSE Req'd	0.3	DSE Req'd	2.2	
46	V	5	0.9	DSE Req'd	0.7	DSE Req'd	1.7	DSE Req'd
47	V	5	1.2	DSE Req'd	1.0	DSE Req'd	1.5	DSE Req'd
48	V	5	0.4	DSE Req'd	0.3	DSE Req'd	0.7	DSE Req'd
49	IVb	3	1.0	DSE Req'd	0.9	DSE Req'd	2.1	DSE Req'd

Numerical DSA ratings are plotted against RVS scores for *Second Edition*, *Third Edition* Level 1, and *Third Edition* Level 2 in Figure 10-7, Figure 10-8, and Figure 10-9, respectively. Linear trendlines are also shown, including the R-squared values, which indicate the relative correlation between the numerical DSA rating and the resulting RVS score. An R-squared value of 1.0 indicates perfect correlation, while an R-squared value of zero indicates that there is no correlation. The correlation is best for the *Third Edition* Level 2 screening results.

The plots of RVS Score versus Numerical DSA Rating shown in Figure 10-7 through Figure 10-9 show that for any given DSA rating, the RVS screening can result in a range of scores (S, S_{L1}, or S_{L2}). Averaging the scores of a group of buildings with similar DSA Ratings results in a trend of decreasing average score versus increasing DSA Rating, as desired.

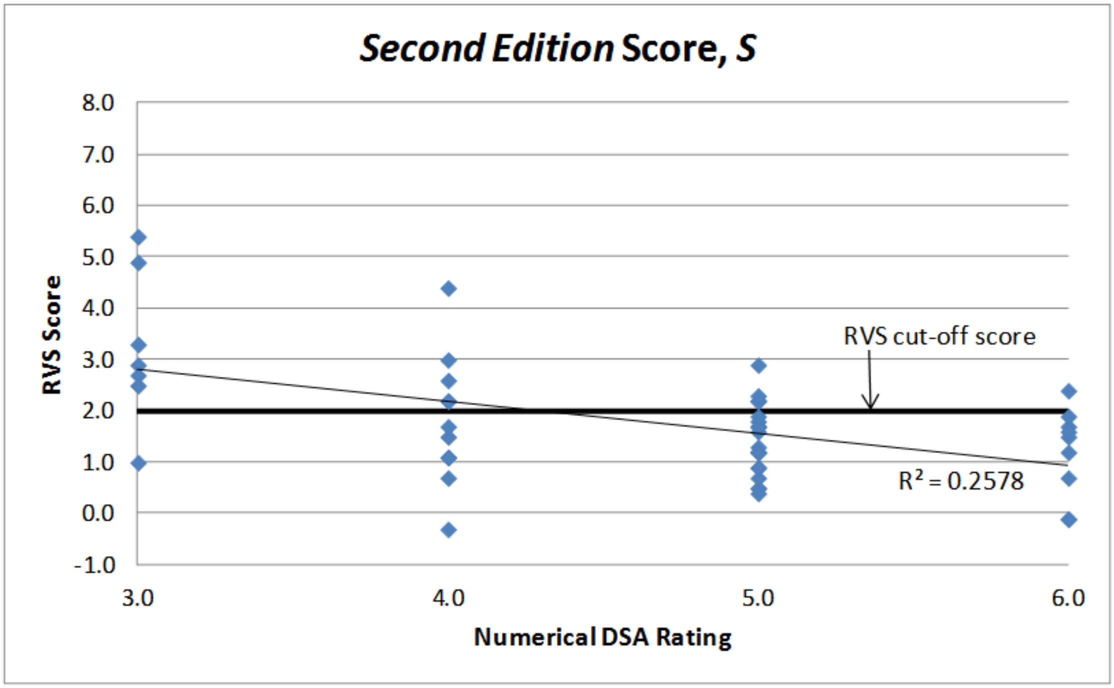


Figure 10-7 *Second Edition* Score versus DSA Rating.

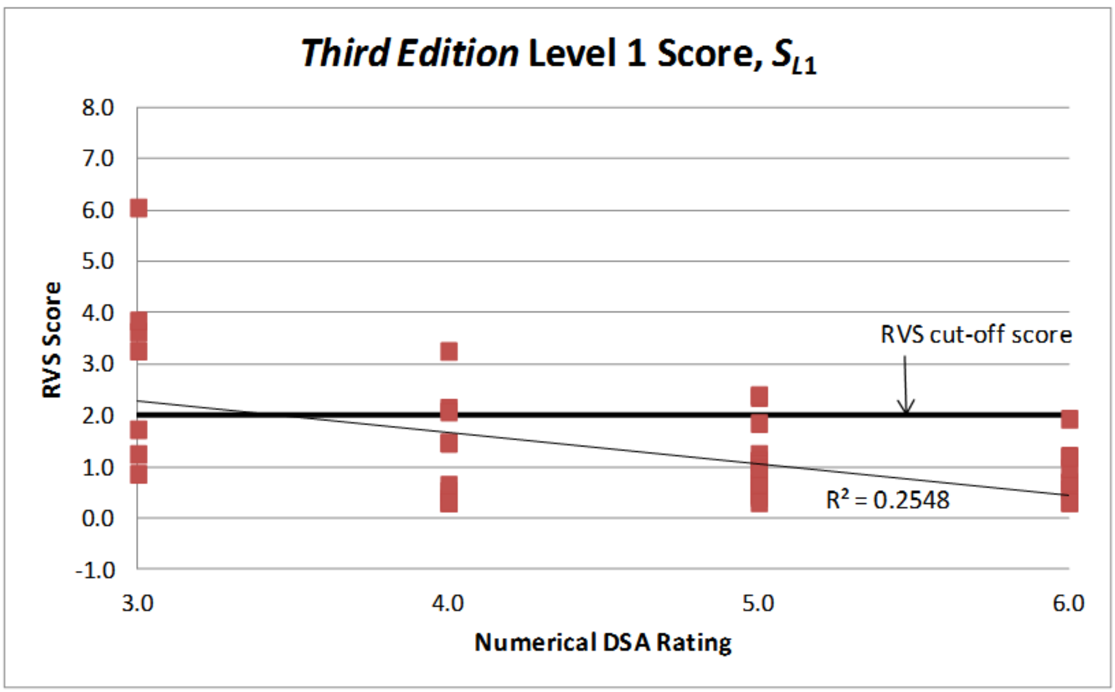


Figure 10-8 *Third Edition* Level 1 Score versus DSA Rating.

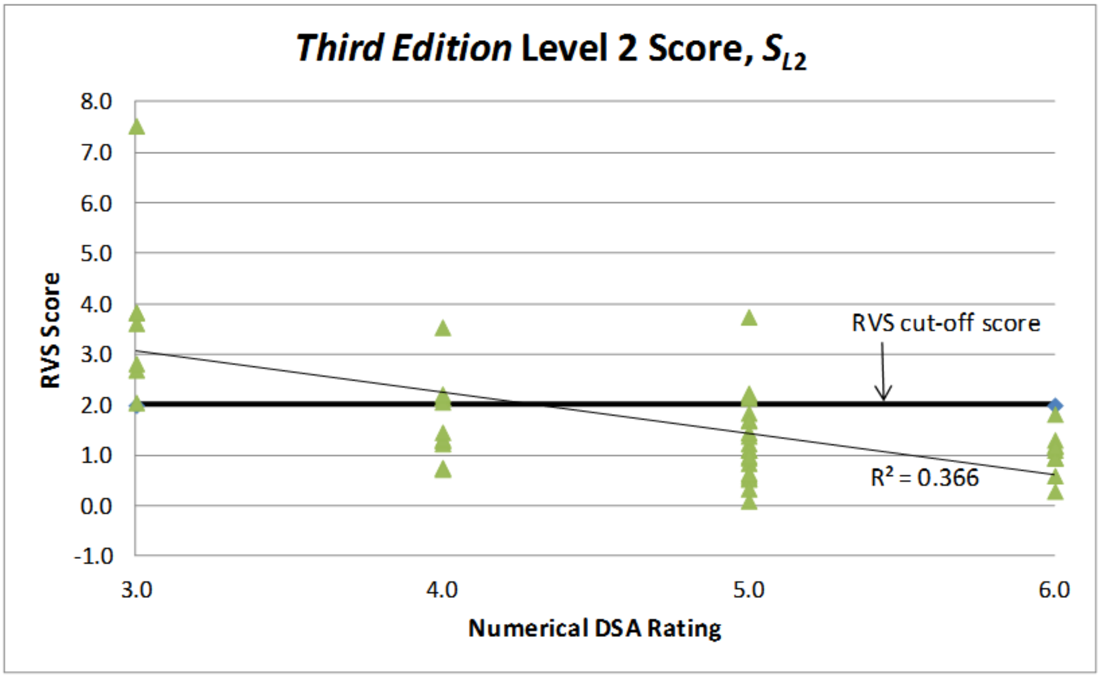


Figure 10-9 *Third Edition* Level 2 Score versus DSA Rating.

Table 10-3 shows the RVS results by DSA Rating.

Table 10-3 RVS Results by DSA Rating

DSA Rating		IVb	IV	V	Vw or VI
Number of Buildings		7	11	22	9
Second Edition	Average *S*	3.2	1.8	1.5	1.2
	Number of DSE Req'd	1	6	17	8
	Percentage of DSE Req'd	14%	55%	77%	89%
Level 1	Average S_{L1}	2.9	1.2	0.9	0.9
	Number of DSE Req'd	3	8	21	9
	Percentage of DSE Req'd	43%	73%	95%	100%
Level 2	Average S_{L2}	3.8	1.7	1.3	1.1
	Number of DSE Req'd	1	6	18	9
	Percentage of DSE Req'd	14%	55%	82%	100%

"DSE Req'd" indicates that the screening triggers a Detailed Structural Evaluation.

It is most helpful to consider the set of buildings with DSA Rating of IVb. Recall that buildings with DSA Ratings of IVb were those that were deemed obviously acceptable during the initial screening phase. The initial screening phase was performed by engineers highly experienced in the seismic design and evaluation of buildings. Each engineer had experience exceeding the requirements for Level 2 screeners defined in FEMA P-154 Chapter 2.

During the initial screening phase, these experienced engineers often had the benefit of access to construction drawings. The engineers worked in pairs, typically spending 30 minutes per building. Through this process, seven of the 49 selected buildings (14%) were given a DSA Rating of IVb (when considering the full AOC stock, approximately 10% of the buildings received DSA Ratings of IVb). The experienced engineers indicated that 42 of the 49 buildings (86%) were either obviously unacceptable (DSA Rating Vw) or required more detailed evaluations.

By comparison, the Second Edition screening sent only 65% of buildings to a Detailed Structural Evaluation, while the Third Edition Level 1 screening sent 86% of buildings to a Detailed Structural Evaluation. The Third Edition Level 2 screenings sent 70% of the buildings to a Detailed Structural Evaluation.

10.2.5 Benchmarking Conclusions and Recommendations

The AOC Benchmarking results show that the *Third Edition* Level 1 scores are typically smaller than the *Second Edition* scores. One cause of this is the increased seismicity considered by the *Third Edition*. Many of the buildings (33 out of 49) were considered Very High seismicity by the *Third Edition*, corresponding to ground motions of $S_S = 2.25$g and $S_1 = 0.90$g. All of these buildings were considered High seismicity by the *Second Edition*, corresponding to ground motions of $S_S = 1.23$g and $S_1 = 0.45$g. The increase in considered seismicity contributes to the decrease in score in the *Third Edition*. (If all the buildings in Very High seismicity were instead considered to be in High seismicity, the average Level 1 Score, S_{L1}, increases from 1.2 to 1.5, which more closely aligns with the average *Second Edition* Score, S, of 1.8) In addition, the removal of the benefit for mid- and high-rise buildings also contributes to the decrease in scores from the *Second Edition* to the *Third Edition*.

The AOC Benchmarking results show that Level 1 scores are typically smaller than the Level 2 scores. Level 1 screenings trigger Detailed Structural Evaluations more often than Level 2 screenings (86% versus 70%), typically due to the more severe treatment of vertical and plan irregularities in the Level 1 screening and the absence of benefit for retrofits in Level 1. In particular, the criteria for reentrant corners in Level 2 are much narrower than in Level 1.[2]

[2] The Level 2 criterion for reentrant corners was revised subsequent to this benchmarking study. The final Level 2 criterion is closer to the Level 1 criterion.

The percentage of buildings that are sent to Detailed Structural Evaluations in the benchmarking study is consistent with the percentage of buildings recommended for detailed evaluations by experienced engineers in the initial screening phase for the AOC study and helps confirm the FEMA P-154 RVS methodology and cut-off score selection as appropriate. The AOC buildings are located in areas of high seismicity. It should be noted that screenings conducted in areas of lower seismicity should expect a smaller number of buildings to require Detailed Structural Evaluations.

10.3 Trial Runs

In order to study the usability of the *Third Edition* rapid visual screening procedure, trial runs were performed. Throughout the three-year update project, team members from around the country performed rapid visual screenings using continuously evolving Data Collection Forms. Feedback from team members was used to improve the forms and reference guides, as well as the screening advice in the *Handbook*.

10.3.1 Year 1 Trial Runs

In Year 1, the Data Collection Form was updated and expanded to include an optional Level 2 screening. Trial screenings were performed using an early draft of this updated and expanded Data Collection Form.

Members of the Project Technical Committee screened seventeen buildings in Memphis, Salt Lake City, and the San Francisco Bay Area. FEMA Building Types screened included W2, S1, S4, C1, C2, C3, RM1, and URM. All the buildings were assumed to be in High seismicity so that a single form could be used.

The screeners were asked to consider and provide feedback on the following topics:

- How long did each Level 1 screening take? How long did each Level 2 screening take?
- Are the forms easy to use?
- Did the Level 1 and Level 2 scores appear appropriate? Were the Level 2 scores generally higher than the Level 1 scores?
- Do the plan irregularity questions on the Level 2 form appear appropriate? In particular, is the first question (about torsional irregularity) too vague? Is the modifier too severe?

- Do you have any other recommendations on revisions to the form that would make it easier to use or more accurate?

The Level 1 screening typically took 20 minutes (ranging from 10 to 30 minutes), and the Level 2 screening typically took 10 minutes (ranging from 5 to 20 minutes). The Level 2 scores were often lower than the Level 1 scores. In many cases, this was due to the effect of pounding, which was not considered in the Level 1 score (the building is directed to go straight to a Detailed Structural Evaluation), but did reduce the Level 2 score. All the buildings that were found to pass the Level 1 screening also passed the Level 2 screening. In one case, a building that failed the Level 1 screening passed the Level 2 screening.

The screeners provided valuable comments on the content, formatting, and layout of the forms. For example, one screener noted that a place was needed on the top of the Level 2 form to identify the name of the building being screened. These comments were used to improve the form. The screeners also commented on additions that should be made to the *Handbook*. For example, one noted that guidance should be provided on when to consider two linked buildings as one or as separate. This later led to the Building Additions Reference Guide.

The screeners also commented on issues relating to scoring. Several felt that the Level 2 form did not capture enough issues, and they provided suggestions for additional Level 2 statements.

10.3.2 Year 2 Trial Runs

In Year 2, a workshop was held in the San Francisco Bay Area. Participants of the workshop included the Project Technical Committee, the Project Review Panel, and past users of *Second Edition* FEMA 154. Workshop participants performed trial screenings at the workshop. They were provided with a packet of information that, for each of six buildings, contained a narrative description of the building, a Level 1 form and a Level 2 form filled with partial “pre-field” information, and photographs of the building. The Project Technical Committee members who developed the examples were available in the room to answer questions. The workshop participants were also given the Reference Guides and a listing of the benchmark years.

The workshop participants performed the trial runs and then were asked for their feedback on the forms. Valuable feedback was provided on the Level 2 statements. For example, a Level 2 statement meant to capture the benefit of a redundant gravity system was revised to emphasize redundancy rather than regularity. The exercise also highlighted items that required additional guidance, such as how to consider certain types of additions and how to avoid double counting of irregularities that may be both plan and vertical in nature.

10.3.3 Year 3 Trial Runs

In Year 3, members of the Project Technical Committee again performed trial runs using the latest Data Collection Forms. Screeners generally found the forms to be easy to use and the guidance in the *Handbook* complete. Some suggestions were made for updates to the forms and the reference guides in the *Handbook*. Revisions to the final forms and *Handbook* were implemented accordingly.

As a second part to this Trial Run exercise, members of the Project Technical Committee used previously performed screenings to consider how *Second Edition* scores could be converted to *Third Edition* scores and to highlight potential issues.

10.4 Conclusions

Much effort has been spent attempting to optimize the *Third Edition* RVS procedure for ease of use and accuracy of results. The *Third Edition* procedure is more comprehensive than the *Second Edition* procedure, and it retains the layout and ease of use of the *Second Edition*. The benchmarking and trial run results generally show that RVS screening results are reasonably consistent with the judgment of experienced engineers.

Appendix A
Third Edition Scoring Parameters

Tables A-1 through A-11 provide the parameter values used in the *Third Edition* scoring update. See Chapter 4 and Chapter 5 for additional information. CAC (2010), FEMA (2009a), and FEMA (2003) contain the sources for OSHPD HAZUS, HAZUS TM, and HAZUS AEBM, respectively.

Table A-1 Building Height, HR, and Elastic Period, Te

No. Stories	W1, W2		S1		S2		S3, PC1		S4, S5		C1		C2, C3, PC2, RM1, RM2, URM		MH	
	H_R	T_e	H_R	T_e	H_R	T_e	H_R	T_e	H_R	T_e	H_R	T_e	H_R	T_e	H_R	T_e
1	14	0.35	14	0.4	14	0.4	15	0.35	14	0.35	12	0.40	12	0.35	10	0.35
2	24	0.38	24	0.5	24	0.43	25	0.39	24	0.35	20	0.40	20	0.35		
3	34	0.49	36	0.69	36	0.59	35	0.50	36	0.44	30	0.48	30	0.39		
4	44	0.60	48	0.87	48	0.73			48	0.55	40	0.62	40	0.48		
5	54	0.70	60	1.04	60	0.86			60	0.65	50	0.76	50	0.57		
6			72	1.20	72	0.99			72	0.74	60	0.89	60	0.65		
7			84	1.36	84	1.11			84	0.84	70	1.03	70	0.73		
8			96	1.51	96	1.22			96	0.92	80	1.16	80	0.81		
9			108	1.66	108	1.34			108	1.01	90	1.29	90	0.88		
10			120	1.81	120	1.45			120	1.09	100	1.41	100	0.95		
11			132	1.95	132	1.55			132	1.17	110	1.54	110	1.02		
12			144	2.09	144	1.66			144	1.25	120	1.67	120	1.09		
13			156	2.23	156	1.76			156	1.33	130	1.79	130	1.16		
14			168	2.36	168	1.86			168	1.40	140	1.91	140	1.23		
15			180	2.50	180	1.96			180	1.48	150	2.04	150	1.29		

Notes:

1. Values of H_R and T_e are taken from OSHPD HAZUS Table A6-3 for all FEMA Building Types except MH.
2. Values for MH are taken from HAZUS TM Table 5.1.

Table A-2a Seismic Design Coefficient, CS, for Calculating Basic Scores

No. Stories	W1, S3				W2, S1, S2, S4, C1, C2, PC1, PC2, RM1, RM2				S5, C3, URM				MH			
	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH
1	0.1	0.1	0.125	0.15	0.055	0.055	0.082	0.109	0.055	0.055	0.055	0.055	0.100	0.100	0.100	0.100
2	0.1	0.1	0.125	0.15	0.046	0.046	0.069	0.092	0.046	0.046	0.046	0.046				
3	0.1	0.1	0.125	0.15	0.040	0.040	0.060	0.080	0.040	0.040	0.040	0.040				
4	0.1	0.1	0.125	0.15	0.036	0.036	0.053	0.071	0.035	0.035	0.035	0.035				
5					0.032	0.032	0.047	0.063	0.032	0.032	0.032	0.032				
6					0.029	0.029	0.043	0.057	0.029	0.029	0.029	0.029				
7					0.026	0.026	0.039	0.052	0.026	0.026	0.026	0.026				
8					0.024	0.024	0.036	0.048	0.024	0.024	0.024	0.024				
9					0.022	0.022	0.033	0.044	0.022	0.022	0.022	0.022				
10					0.021	0.021	0.031	0.041	0.021	0.021	0.021	0.021				
11					0.020	0.020	0.029	0.039	0.019	0.019	0.019	0.019				
12					0.018	0.018	0.027	0.036	0.018	0.018	0.018	0.018				
13					0.017	0.017	0.026	0.034	0.017	0.017	0.017	0.017				
14					0.016	0.016	0.024	0.032	0.016	0.016	0.016	0.016				
15					0.016	0.016	0.023	0.031	0.015	0.015	0.015	0.015				

Notes: (See Chapter 5 for additional explanation)

1. Values of C_S are taken from OSHPD HAZUS Table A6-2a and A6-2b using the following mapping (with exceptions noted below):

Seismicity	Source
L	Zone 3, Pre-1961
M	Zone 3, Pre-1961
MH	Average of H and M values
H,VH	Zone 4, Pre-1961

2. Values of C_S for S5, C3, and URM are set equal to Zone 3, Pre-1961 values for all seismicity regions.
3. Values of C_S for W1 and MH are taken from HAZUS TM Table 5.4 using the following mapping:

Seismicity	Source
L	Pre-Code
M	Low-Code
MH	Average of H and M values
H,VH	Moderate-Code

4. Values of C_S for S3 are set equal to W1 values.

Table A-2b Seismic Design Coefficient, C_S, for Calculating Pre-Code Score Modifiers

No. Stories	W1, S3				W2, S1, S2, S4, C1, C2, PC1, PC2, RM1, RM2				S5, C3, URM				MH			
	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH
1	0.1	0.1	0.1	0.1	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.100	0.100	0.100	0.100
2	0.1	0.1	0.1	0.1	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046				
3	0.1	0.1	0.1	0.1	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040				
4	0.1	0.1	0.1	0.1	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035				
5					0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032				
6					0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029				
7					0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026				
8					0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024				
9					0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022				
10					0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021				
11					0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019				
12					0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018				
13					0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017				
14					0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016				
15					0.016	0.016	0.016	0.016	0.015	0.015	0.015	0.015				

Notes: (See Chapter 5 for additional explanation)

1. Values of C_S are taken from OSHPD HAZUS Table A6-2a and A6-2b using the following mapping (with exceptions noted below):

Seismicity	Source
L	Zone 3, Pre-1961
M	Zone 3, Pre-1961
MH	Zone 3, Pre-1961
H,VH	Zone 3, Pre-1961

2. Values of C_S for W1 and MH are taken from HAZUS TM Table 5.4 using the following mapping:

Seismicity	Source
L	Pre-Code
M	Pre-Code
MH	Average of H and M values
H,VH	Low-Code

3. Values of C_S for S3 are set equal to W1 values.

Table A-2c Seismic Design Coefficient, CS, for Calculating Post-Benchmark Score Modifiers

No. Stories	W1, S3				W2, S1, S2, S4, C1, C2, PC1, PC2, RM1, RM2				S5, C3, URM				MH			
	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH
1	0.100	0.150	0.219	0.300	0.055	0.109	0.204	0.327					0.100	0.100	0.125	0.150
2	0.100	0.150	0.219	0.300	0.046	0.092	0.173	0.276								
3	0.100	0.150	0.219	0.300	0.040	0.080	0.150	0.240								
4	0.100	0.150	0.219	0.300	0.036	0.071	0.133	0.213								
5					0.032	0.063	0.118	0.189								
6					0.029	0.057	0.107	0.171								
7					0.026	0.052	0.098	0.156								
8					0.024	0.048	0.090	0.144								
9					0.022	0.044	0.083	0.132								
10					0.021	0.041	0.077	0.123								
11					0.020	0.039	0.073	0.117								
12					0.018	0.036	0.068	0.108								
13					0.017	0.034	0.064	0.102								
14					0.016	0.032	0.060	0.096								
15					0.016	0.031	0.058	0.093								

Notes: (see Chapter 5 for additional explanation):

1. Values of C_S are from Table A-2b adjusted by the following factors:

Seismicity	W1, S3	MH	All other FEMA Building Types
L	1.0	1.0	1.0
M	1.5	1.0	2.0
MH	1.8	1.25	2.5
H,VH	2.0	1.5	3.0

2. Post-Benchmark Score Modifiers are not calculated for S5, C3, and URM.

Table A-3 Gamma, γ, and Lambda, λ, Factors

No. Stories	MH	All Other FEMA Building Types	W1, W2, S1, S3, C1, C2	S4, C3	S2, S5, PC2, RM1, RM2	PC1, URM	MH	W1, W2, S1, S3, C1, C2	S4, C3	S2, S5, PC2, RM1, RM2	PC1, URM	MH
	γ		λ, Basic Score					λ, Pre-Code				
1	1.50	2.70	2.00	1.83	1.67	1.33	2.00	1.50	1.42	1.33	1.17	1.50
2		2.50	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
3		2.25	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
4		2.00	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
5		1.88	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
6		1.80	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
7		1.75	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
8		1.71	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
9		1.69	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
10		1.67	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
11		1.65	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
12		1.65	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
13		1.65	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
14		1.65	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	
15		1.65	2.00	1.83	1.67	1.33		1.50	1.42	1.33	1.17	

Notes: (See Chapter 5 for additional explanation)

1. For all FEMA Building Types except S3 and MH:

   Values of γ are taken from OSHPD HAZUS Table A6-5.

   Values of λ for Basic Score calculations are taken from OSHPD HAZUS Table A6-5 considering Baseline performance.

   Values of λ for Pre-Code calculations are taken from OSHPD HAZUS Table A6-5 considering USB performance.
2. S3 values set equal to W1 values.
3. For MH:

   Value of γ is taken from HAZUS TM Table 5.5.

   Value of λ for Basic Score calculation is taken from HAZUS TM Table 5.5.

   Value of λ for Pre-Code calculation is taken as 0.75 of the Basic Score value.

Table A-4 Ductility Factor, μ

No. Stories	All FEMA Building Types Ductility, μ, Basic Score	All FEMA Building Types Ductility, μ, Post-Benchmark
1	6.00	7.98
2	6.00	7.98
3	4.94	6.57
4	4.41	5.87
5	4.07	5.41
6	3.82	5.08
7	3.63	4.83
8	3.48	4.63
9	3.35	4.46
10	3.24	4.31
11	3.15	4.19
12	3.07	4.08
13	3.00	3.99
14	3.00	3.99
15	3.00	3.99

Notes: (See Chapter 5 for additional explanation)

1. Values of μ for Basic Score calculations are taken from OSHPD HAZUS Table A6-6.
2. Values of μ for Post-Benchmark calculations are taken as 1.33 of the Basic Score value.

Table A-5 Alpha 1, α_1, and Alpha 2, α_2, Factors

No. Stories	S1, C1, PC1, URM	W1, W2, S2, S3, S4, S5, C2, C3, PC2, RM1, RM2	MH	All FEMA Building Types (except MH)	MH
	α_1			α_2	
1	0.75	0.80	1.00	0.75	1.00
2	0.75	0.80		0.75	
3	0.75	0.80		0.75	
4	0.75	0.80		0.75	
5	0.75	0.80		0.75	
6	0.73	0.79		0.72	
7	0.71	0.78		0.69	
8	0.69	0.77		0.66	
9	0.67	0.76		0.63	
10	0.65	0.75		0.60	
11	0.65	0.75		0.60	
12	0.65	0.75		0.60	
13	0.65	0.75		0.60	
14	0.65	0.75		0.60	
15	0.65	0.75		0.60	

Notes: (See Chapter 5 for additional explanation)

1. Values of α_1 and α_2 are taken from OSHPD HAZUS Table A6-4.
2. S5 values set equal to S4 values.

Table A-6 Alpha 3, α_3, Modal Factors

No. Stories	α_3, Basic Score	α_3, Moderate Vertical Irregularity	α_3, Severe Vertical Irregularity
1	1.00	1.00	1.00
2	1.21	1.62	2.03
3	1.35	2.04	2.73
4	1.45	2.36	3.27
5	1.54	2.63	3.72
6	1.62	2.87	4.00
7	1.69	3.07	4.00
8	1.75	3.26	4.00
9	1.81	3.43	4.00
10	1.86	3.59	4.00
11	1.91	3.73	4.00
12	1.96	3.87	4.00
13	2.00	4.00	4.00
14	2.04	4.00	4.00
15	2.08	4.00	4.00

Notes: (See Chapter 5 for additional explanation)

1. Values of α_3 for Basic Score calculations are taken from OSHPD HAZUS Table A6-10 considering Baseline performance.
2. Values of α_3 for Moderate Vertical Irregularity calculations are taken from OSHPD HAZUS Table A6-10 considering SubBase performance combined with SubBase Interstory Drift Ratios.
3. Values of α_3 for Severe Vertical Irregularity calculations are taken from OSHPD HAZUS Table A6-10 considering USB performance combined with SubBase Interstory Drift Ratios.

Table A-7 Elastic Damping, β_E

FEMA Building Type	Elastic Damping (β_E)
W1	10.00
W2	10.00
S1	5.00
S2	5.00
S3	5.00
S4	5.00
S5	7.00
C1	7.00
C2	7.00
C3	7.00
PC1	7.00
PC2	7.00
RM1	7.00
RM2	7.00
URM	7.00
MH	5.00

Notes: (See Chapter 5 for additional explanation)

1. Values of β_E are taken from OSHPD HAZUS Table A6-7 for all FEMA Building Types except URM and MH.
2. Value of β_E for URM set equal to C3 and S5.
3. Value of β_E for MH is taken from HAZUS AEBM Table 5.1.

Table A-8 Degradation Factor, κ

	Seismicity Region			
	L	M	MH	H, VH
Basic Score	0.3	0.3	0.4	0.4
Pre-Code	0.3	0.3	0.4	0.4
Post-Benchmark	0.45	0.45	0.6	0.668

Notes: (See Chapter 5 for additional explanation)

1. Values of κ for Basic Score calculations are taken from OSHPD HAZUS Table A6-8 using the following mapping:

Seismicity	Scenario Earthquake Criteria (Minimum Distance to Fault, Maximum Magnitude)
L	> 50 km, Baseline Performance, Pre-1961
M	25 - 50 km, M > 7.0, Baseline Performance, Pre-1961
MH	10 - 25 km, M > 7.0, Baseline Performance, Pre-1961
H,VH	10 - 25 km, M > 7.0, Baseline Performance, Pre-1961

2. Values of κ for Post-Benchmark calculations are based on scaled Basic Score values using the following:

Seismicity	Source
L	1.5 x Basic Score Value
M	1.5 x Basic Score Value
MH	1.5 x Basic Score Value
H,VH	1.67 x Basic Score Value

Table A-9 Story Drift Ratio, Δ_C

	W1, W2				S1, S2, S5, C2				S3, S4, PC1, RM1, RM2				C1				PC2				C3, URM				MH			
	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH	L	M	MH	H, VH
Basic Score	0.075	0.075	0.075	0.075	0.050	0.050	0.055	0.060	0.044	0.044	0.049	0.053	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.056	0.070	0.070	0.070
Plan Irregularity	0.038	0.038	0.038	0.038	0.025	0.025	0.028	0.030	0.022	0.022	0.025	0.027	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.028	0.035	0.035	0.035
Severe or Moderate Vertical Irregularity	0.06	0.06	0.06	0.06	0.040	0.040	0.045	0.050	0.035	0.035	0.040	0.044	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.056	0.070	0.070	0.070
Pre-Code Modifiers	0.075	0.075	0.075	0.075	0.05	0.05	0.05	0.05	0.044	0.044	0.044	0.044	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.056	0.056	0.063	0.07
Post-Benchmark Modifiers	0.094	0.094	0.113	0.125	0.063	0.063	0.083	0.1	0.055	0.055	0.073	0.089	0.063	0.063	0.083	0.1	0.055	0.055	0.073	0.089					0.07	0.088	0.105	0.117

Notes: (See Chapter 5 for additional explanation)

1. Values of Δ_C are taken from OSHPD HAZUS Table A6-9 using the following mapping (with exceptions noted below):

Seismicity	Basic Score Source	Plan Irregularity Source	Severe or Moderate Vertical Irregularity Source	Pre-Code Source	Post-Benchmark Source
L	Pre-61, Baseline	Pre-61, USB	Pre-61, SubBase	Pre-61, Baseline	1.25 x Basic Score Value
M	Pre-61, Baseline	Pre-61, USB	Pre-61, SubBase	Pre-61, Baseline	1.25 x Basic Score Value
MH	Average of H and M values	Average of H and M values	Average of H and M values	Pre-61, Baseline	1.50 x Basic Score Value
H,VH	Post-61, Baseline	Post-61, USB	Post-61, SubBase	Pre-61, Baseline	1.67 x Basic Score Value

2. Values for S5 are set equal to values for S1, S2, and C2.
3. Values for C1 are set equal to values for C3 and URM for all but Post-Benchmark calculations. Values of C1 for Post-Benchmark calculations are set equal to values for C2.
4. Values for PC2 are set equal to values for C3 and URM for all but Post-Benchmark calculations. Values of PC2 for Post-Benchmark calculations are set equal to values for PC1.
5. Values for MH are taken from HAZUS TM Table 5.9 using the following mapping:

Seismicity	Basic Score Source	Plan Irregularity Source	Severe or Moderate Vertical Irregularity Source	Pre-Code Source	Post-Benchmark Source
L	Pre-Code	1/2 x Basic Score Value	Basic Score Value	Pre-Code	1.25 x Basic Score Value
M	Low-Code	1/2 x Basic Score Value	Basic Score Value	Pre-Code	1.25 x Basic Score Value
MH	Average of H and M values	1/2 x Basic Score Value	Basic Score Value	Average of H and M values	1.50 x Basic Score Value
H,VH	Moderate-Code	1/2 x Basic Score Value	Basic Score Value	Low-Code	1.67 x Basic Score Value

Table A-10 Lognormal Standard Deviation, $\beta_{C,D}$

No. Stories	All FEMA Building Types $\beta_{C,D}$, Basic Score	All FEMA Building Types $\beta_{C,D}$, Pre-Code	S1 $\beta_{C,D}$, Post-Benchmark	All FEMA Building Types (except S1) $\beta_{C,D}$, Post-Benchmark
1	0.95	1.00	0.75	0.85
2	0.95	1.00	0.75	0.85
3	0.95	1.00	0.75	0.85
4	0.94	0.99	0.75	0.84
5	0.93	0.98	0.75	0.83
6	0.92	0.97	0.75	0.82
7	0.91	0.96	0.75	0.81
8	0.90	0.95	0.75	0.80
9	0.89	0.94	0.75	0.79
10	0.88	0.93	0.75	0.78
11	0.87	0.92	0.75	0.77
12	0.86	0.91	0.75	0.76
13	0.85	0.90	0.75	0.75
14	0.85	0.90	0.75	0.75
15	0.85	0.90	0.75	0.75

Notes: (See Chapter 5 for additional explanation)

1. Values of $\beta_{C,D}$ for Basic Score calculations are taken from OSHPD HAZUS Table A6-11 considering Post-61 SubBase performance.
2. Values of $\beta_{C,D}$ for Pre-Code calculations are taken from OSHPD HAZUS Table A6-11 considering Pre-61 SubBase performance.
3. Values of $\beta_{C,D}$ for Post-Benchmark calculations are taken from OSHPD HAZUS Table A6-11 considering Post-61 Baseline performance, except values of β_C for Post-Benchmark S1 calculations are reduced by engineering judgment.

Table A-11 Collapse Factor (P[*COL*|*STR5*])

	W1, W2, MH	S1, S2, S3, S4, S5	C1, C2, C3, RM1, RM2	PC1, PC2, URM
Basic Score	0.05	0.08	0.13	0.15
Severe Vertical Irregularity	0.20	0.30	0.50	0.60
Moderate Vertical Irregularity and Plan Irregularity	0.10	0.15	0.25	0.30

Notes: (See Chapter 5 for additional explanation)

1. Values of P[*COL*|*STR5*] are taken from OSHPD HAZUS Table A6-12.
2. Values for Basic Score calculations use Baseline performance.
   Values for Severe Vertical Irregularity use USB performance.
   Values for Moderate Vertical Irregularity and Plan Irregularity use SubBase performance.
3. Values for URM are set equal to PC1, PC2 values.

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