Earthquake Risk Management: A Toolkit for Decision-Makers

California Seismic Safety Commission

Proposition 122 Seismic Retrofit Practices Improvement Program
Product 2.2 Earthquake Risk Management Tools for Decision-Makers
SSC Report 99-04

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Executive Summary

California's next earthquake could affect your community or business*!*

Are you prepared?

The only way you can answer this question is to have a clear understanding of your potential earthquake risk. Once the risk is defined, the best way to protect the lives, property, and economic well-being for which you are responsible is to implement a comprehensive earthquake risk management program.

This *Toolkit for Decision-Makers* provides the necessary tools for developing an effective program. It provides basic information on the following:

- What earthquakes are,
- Typical earthquake effects in California,
- Causes of earthquake damage and loss,
- Assessing the potential for damage and loss to the building structures and equipment systems in your community or business,
- Selecting an appropriate approach to reduce earthquake risk to acceptable levels, and
- How to develop and implement the selected approach.

In order to be effective, an earthquake risk management program must involve participation and have the support of all levels of the community or business enterprise, including the executive decision-makers, their management staff, technical and administrative support staff, constituents, and employees. Often, it will be necessary to retain professional consultants to assist with the implementation of phases of the program.

This *Toolkit* is intended for executive decision-makers, their management staff, and their technical and administrative support personnel. It provides the information they need to create and manage an effective program for understanding and mitigating the seismic risk to buildings and equipment systems. Useful information for other participants in the process is available from sources referenced in this *Toolkit*.

Many California communities, agencies, and businesses have already acted to understand and mitigate their potential earthquake losses. A companion volume to this *Toolkit*, *Mitigation Success Stories*, provides examples of successful earthquake risk management and loss reduction programs in California. The examples give useful insight into the practical aspects of the earthquake risk management process.

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1. Introduction

…rational action is merely a question of calculating the chances [and the consequences].

- Raymond Aron, *The Opium of the Intellectuals*

Earthquakes are serious problems for California. They cause damage to buildings and lifelines. In turn, this damage can cause injury, loss of life and economic hardship, and disrupt communities, organizations, and businesses. Executive decision-makers are responsible for protecting their enterprises[1] from such loss. Since most executives are not earthquake experts, they need tools to deal with this problem.

1.1 Purpose and Intent

This *Toolkit* provides an overview of the earthquake risk management process, as well as detailed, step-by-step information on how to implement the process.

In most enterprises the decision-maker will set earthquake risk management as a priority, select or approve specific strategic approaches to risk management, and authorize and monitor program progress. However, much of the earthquake risk management work must be done by others, including department managers, and administrative and technical support staff. This *Toolkit* provides useful information for all these users. We recommend that everyone read this introductory chapter. It guides the readers to those sections they are most likely to need.

This *Toolkit* is intended for the following individuals:

- **Decision-Maker** – The person who provides strategic direction for the enterprise. Decision-makers include mayors, supervisors, and members of boards of direction.
- **Risk Manager** – The person the appointed to develop and implement the risk management program. It may be the City Manager, Director of Public Works, Chief Financial Officer, or their designee.
- **Financial Manager** – The person responsible for maintaining the financial accounts for the enterprise. It may be the Chief Financial Officer, Comptroller, or Treasurer.
- **Asset Manager** – The person responsible for maintaining the physical property for the enterprise. It may include the Director of Public Works, Building Official, City Engineer, or Facilities Manager.

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[1] Through this *Toolkit*, we use the term enterprise to mean that community, public agency, or commercial entity for which the decision-maker is responsible.

1.2 Organization

Chapter 2 is primarily intended for the *Risk Manager*, although some *Decision-Makers* will find the material of interest. Chapter 2 discusses:

- **Earthquake Risk** – The likelihood of damage and consequent loss.
- **Hazard** – The probable intensity of earthquake natural effects, such as shaking, ground fault rupture and liquefaction.
- **Damage** -- The physical disruption due to an earthquake, such as collapsed buildings, walls, ceilings and fixtures, broken pipes, fires, and damaged highways and bridges.
- **Loss** – The human and financial consequences of damage, including injuries or deaths, the costs of repair, or loss of revenue.
- **Mitigation** – Any measure taken to reduce earthquake risk. Mitigation can take many forms, including building strengthening, occupancy reduction, change of function, equipment anchoring or bracing, effective emergency and contingency planning, and/or procuring earthquake insurance[2].
- **Decision-Making** – Analyzing data on the above issues and putting them into a rational framework whereby certain mitigation alternatives emerge as the most appropriate solution for the specific situation at hand.
- **Implementation** – Putting the mitigation program into action.

Chapter 3 is a step-by-step guide to assessing earthquake risk and evaluating alternatives for reducing it. The entire chapter is of interest to the *Risk Manager*. The *Asset Manager* and *Financial Manager* will also find some sections pertinent. The basic steps include:

- **Identifying the Assets at Risk** (of interest to the *Risk Manager*) – An inventory of everything the Decision-Maker is responsible for protecting that could be damaged or lost in an earthquake
- **Framing the Problem** (*Risk Manager*) – Determining performance goals for the physical assets at risk, that is, tolerable levels of damage for each asset for two different earthquake scenarios.
- **Data Collection** (*Risk Manager* and *Asset Manager*) – Collecting available information on the construction of the physical assets so that the existing level of risk can be determined.
- **Building Screening** (*Risk Manager* and *Asset Manager*) – Performing rapid evaluations of the probable earthquake performance of buildings to determine whether they are likely to meet the selected performance goals.
- **Building Assessment** (*Risk Manager* and *Asset Manager*) – Performing more detailed assessment of the probable earthquake performance of buildings that fail the screening test and developing mitigation concepts for them.

[2] Note, however, that insurance only provides reimbursement for part of the financial loss and does not reduce damage and/or risk of injury.

- **Equipment Screening** (*Risk Manager* and *Asset Manager*) – Performing rapid assessments of the probable performance of critical equipment and systems.
- **Equipment Assessment** (*Risk Manager* and *Asset Manager*) – Performing more detailed assessments of equipment and systems that fail the screening test and developing mitigation concepts for them.
- **Financial Loss Assessment,** (*Risk Manager* and *Financial Manager*) – Estimating the potential financial consequences of damage.

Chapter 4 provides a framework for decision-making. This will be of interest to the *Risk Manager* and the *Decision-Maker*.

Once the risk has been assessed, and a mitigation program decided upon, it remains to implement the program, that is, to *do* the work. ***Chapter 5*** discusses practical issues and steps involved in doing this. It will be of primary interest to the *Decision-Maker*.

Finally, a glossary and technical information on hazard and earthquake structural performance are included in the appendices, where the reader is also directed to publications and to resources on the Internet. Also contained in the appendices are clean copies of the Chapter 3 worksheets as well as sample scope-of-work statements that can be used to procure the services of professional consultants needed to assist with some of the above tasks.

Primary Interest:
Risk Managers

Secondary Interest:
Decision-Makers

2. Earthquake Risk Management

2.1 Introduction

Earthquakes are a significant risk in California. Everyone knows this, but what to do about that risk, and how, is not so clear. This chapter provides an overview of the earthquake risk management process. The next three chapters provide detailed information on how to implement this process.

2.2 Overview of Earthquake Risk

Earthquake loss results from a specific chain of events, illustrated in Figure 2.1. The links in this chain include:

- The *earthquake* causes a variety of earthquake *hazards*, including fault rupture, ground shaking (the primary hazard), liquefaction and other ground failures, and water wave hazards called tsunamis and seiches.

- For various reasons, which we discuss below, many buildings and other structures cannot fully resist these hazards, and sustain some degree of *primary damage*. Depending on the severity of the hazards and the vulnerability of the construction, primary damage can range from minor cracking to total collapse.

- Even when a building sustains no structural damage, its contents may be severely damaged. For certain occupancies, such as hospitals or emergency communication centers, damage to contents can be catastrophic. For any building, it is expensive and time-consuming to repair.

- Primary damage can lead to secondary forms of hazard and damage such as releases of hazardous materials, major fires, or flooding.

- Damage results in *loss*. Primary loss can take many forms, but life loss or injury is the major concern. Financial loss, as well as loss of function, are also serious issues. The likelihood of sustaining a loss is termed *risk*.

- Primary losses lead to secondary losses such as loss of revenues resulting from business interruption and loss of market share and/or reputation. These secondary forms of loss can affect enterprises in both the public and private sectors.

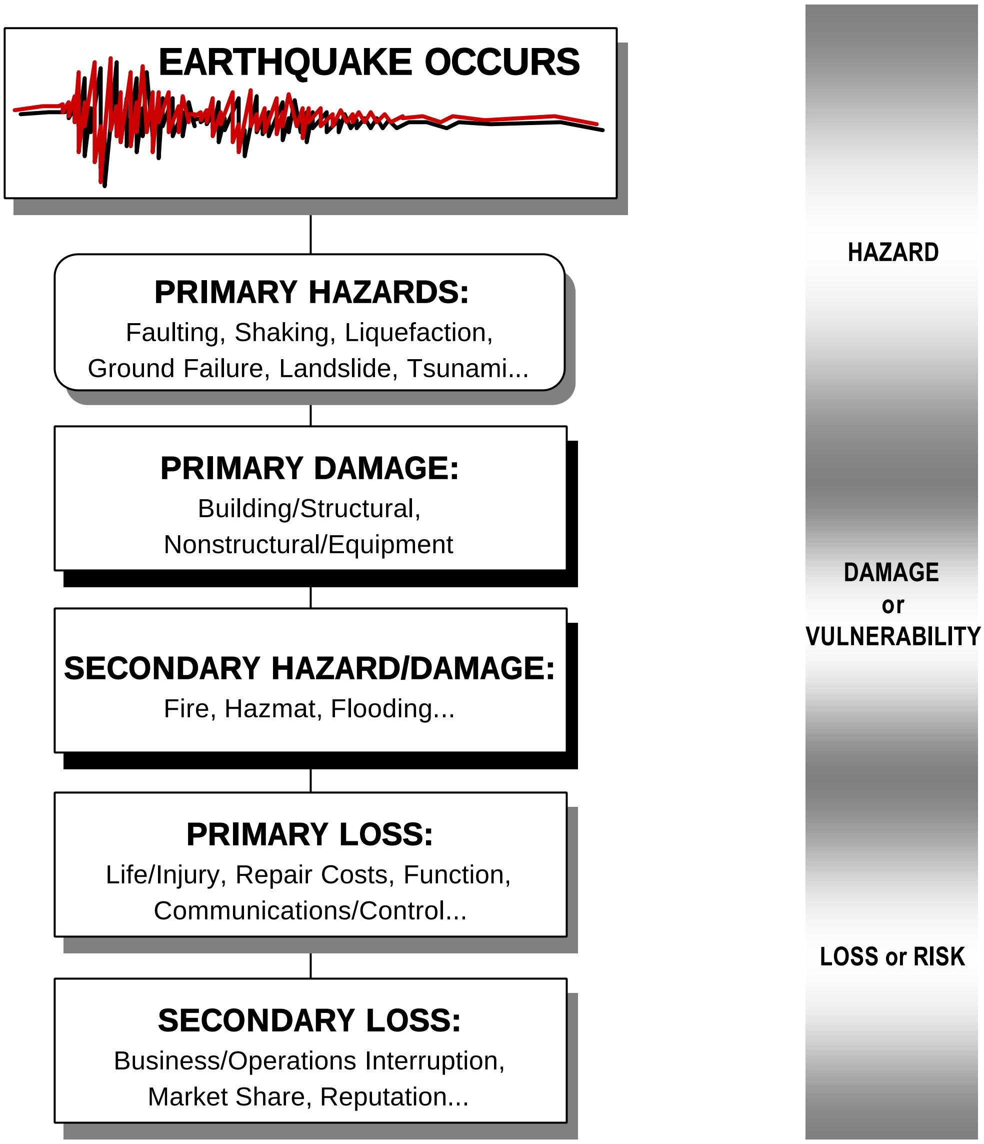

Figure 2-1: Earthquake Loss Process

2.3 Earthquake Hazard

Earthquake hazard can be expressed and measured in a variety of ways. Prior to the invention of modern scientific instruments, earthquakes were qualitatively measured by their effect or *intensity*, which varied from point to point. With the deployment of seismometers, instrumental quantification of the entire earthquake event became possible. Charles F. Richter was the first to define earthquake *magnitude* on the so-called Richter scale in 1935. A number of different scales for magnitude and intensity have been developed subsequently[1].

In the United States, intensity is qualitatively measured using the *Modified Mercalli Intensity (MMI)* scale (see Table C-1 in Appendix C). Engineers and scientists quantify seismic intensity in terms of *peak ground acceleration (PGA)* and other measures. PGA is often expressed in terms of a fraction of the acceleration of gravity (g), such as *0.5g* or 50% of the acceleration of gravity. Following each major earthquake, the United States Geological Survey (USGS) and the Strong Motion Instrumentation Program of the California Division of Mines and Geology (CDMG) typically publish maps showing the distribution of earthquake intensity in throughout the affected region. Figure 2-2 shows the MMI distribution published for the 1994 Northridge earthquake.

The identification and determination of earthquake hazards for a site or community is a critical element in the earthquake risk management process, and Appendix C discusses this aspect in more detail.

In brief, earthquake *ground shaking* is usually very strong on or very close to the fault, and decreases or *attenuates* with distance from the fault. This attenuation depends on the magnitude of the earthquake, and the geology of the region. Soils, especially soft soils such as old filled-in marshes or ancient lake beds, can greatly increase or *amplify* the ground motion. This effect of soils is a primary factor in the intensity of the shaking. Though shaking generally attenuates with distance from the fault, it can still be very strong at a great distance on poor soils.

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[1] Earthquake *magnitude* and *ground shaking intensity* are analogous to a lightbulb and the light it emits. A particular lightbulb has only one energy level, or wattage (e.g., 100 watts), which is analogous to an earthquake's magnitude. Near the lightbulb, the light intensity is very bright, while farther away the intensity decreases. Similarly, a particular earthquake has only one magnitude, but it has many intensity values depending on distance.

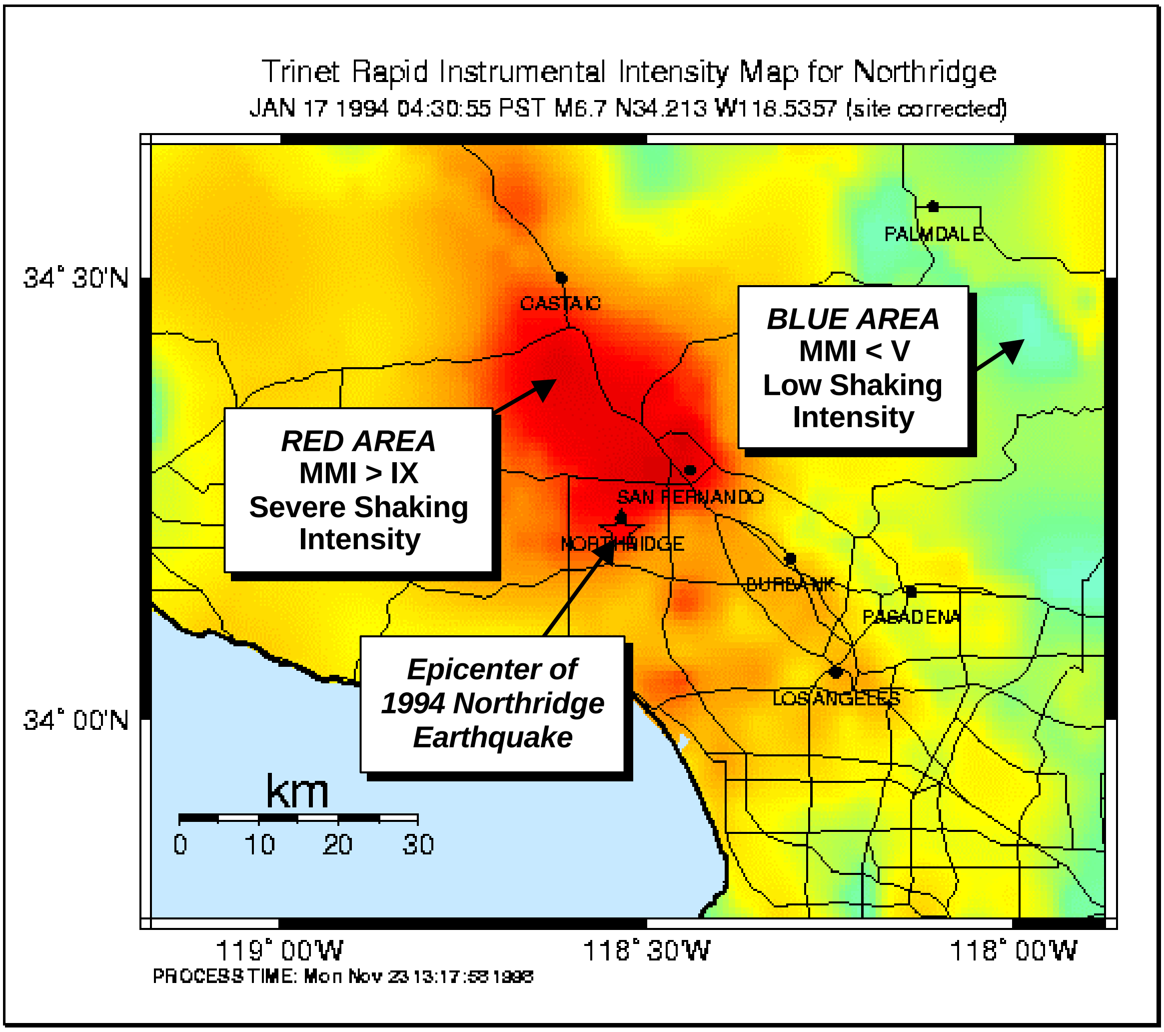

Figure 2-2: Modified Mercalli ground shaking intensities for the 1994 Northridge earthquake (courtesy TRINET)

2.4 Earthquake Damage and Loss

This section summarizes the kinds of damage and loss that earthquakes can cause. Appendix D provides more detailed information on the earthquake performance of specific structure types.

Buildings can be damaged in any of several ways in an earthquake. Below are the most common types of damage:

- *Exterior walls can fall away*. This is the primary deficiency of Unreinforced Masonry (URM) and older Tilt-Up buildings, and can result in partial or even total collapse of the roof and floor systems, posing a significant life hazard and, typically, a major financial loss.
- *Concrete columns can shear*, dropping the building in a *pancake* mode of collapse. This failure poses a great life safety hazard and is common in older, reinforced concrete frame buildings.
- *Concrete and masonry walls can crack,* causing unsightly damage. If cracking becomes severe, pieces of the wall can become loosened and fall away from the structure, creating a safety hazard. This is common in older, lightly reinforced structures.
- Certain kinds of *steel beam-column connections can crack.* This problem was discovered only recently, following the 1994 Northridge earthquake, when many steel building frames were found to have brittle fractures. None of the buildings with this damage collapsed, but they may be weakened. Inspection and repair costs can result in significant financial loss to the owners.
- Wood-frame buildings can *slide off their foundations.* This is the primary mode of failure for older single-family dwellings with a crawl space beneath the first floor. In addition, the crawl space can collapse, when the so-called *cripple walls* supporting the first floor fall over. This failure mode usually does not cause life loss, but can destroy the building and leave the residents homeless.

Structural damage occurs in varying degrees, depending on the intensity of earthquake hazards and individual building design and construction quality. While most buildings are not expected to collapse, damage is common. As a rule of thumb, certain types of construction, dating to certain eras, have particular vulnerability:

- Masonry buildings constructed prior to the Second World War (early 1940s) are typically unreinforced, and have a high likelihood of exterior wall and parapet collapse, as well as severe wall cracking, even in moderate shaking.
- Multi-story concrete frames constructed from the 1950s to early 1970s often have inadequate reinforcing in their columns. Consequently, these buildings have the potential for a pancake type of collapse, with great life loss.
- Steel moment frame buildings of the 1970s, 1980s, and early 1990s have welded beam-column connections for seismic resistance. As noted

above, certain kinds of these connections have recently been observed to crack in earthquakes.

- Tilt-up buildings (a common commercial and industrial building in California) constructed prior to 1994 may have a particularly weak wall-roof connection. This has resulted in many instances of damage and collapse. This weakness was first observed in the 1971 San Fernando earthquake, so newer tilt-ups may have better connections and many older ones have already been retrofitted.

When a building is damaged, it requires inspection, perhaps vacating, and structural and/or nonstructural repairs before normal occupancy and function can be resumed.

Nonstructural damage and repairs can be as significant as structural damage. Tumbled and broken furniture and equipment; fallen ceilings; cracked floors; broken water, sprinkler, and/or gas lines; broken windows; extensive cracking of non-weight-bearing interior walls; broken heating or air conditioning equipment; spilled noxious materials; and other types of nonstructural damage can result in occupant injuries or death, major costs, extended vacancies, and loss of productive use of the building.

For hospitals, fire stations, or emergency communication centers, this nonstructural damage can be catastrophic since these facilities are most needed following an earthquake. However, every enterprise can suffer severe financial hardships from of this type of disruption.

Infrastructure: When ground motion in a neighborhood is strong enough to cause significant damage to buildings, infrastructure is usually damaged as well. Serious infrastructure damages include the following:

- *Freeways, bridges and transportation structures* can collapse. Examples include the I-880 Cypress Structure in the 1989 Loma Prieta earthquake, and the collapsed bridges and interchanges on Los Angeles area freeways in the 1994 Northridge earthquake. CALTRANS has made significant improvements in the ability of our roadways to withstand strong earthquakes, but some vulnerability remains.

- *Underground piping* can break, especially in areas of poorer soils. The combination of broken gas and water lines provides the fuel for fires while taking the water necessary to fight them. More noxious materials, such as sewage or crude or refined oil, may also be spilled, causing major occupancy and clean-up problems.

- *Water and wastewater treatment plants* can be damaged, resulting in prolonged loss of potable water service, and spilling of raw sewage into bays or rivers.

- *Electric power and telecommunications* may suffer widespread short-term outages. Except in the hardest hit areas, these systems have performed reasonably well in recent quakes and been restored within a few days.

For certain types of businesses or services, however, even a day's disruption to these vital services can be a major problem.

Primary damage can lead to *secondary* forms of damage, such as releases of hazardous materials, major fires, or flooding. Fires frequently result from earthquakes because damages release ready fuels for fires and causes numerous ignitions. Impaired fire department response (which results from disrupted communications and loss of fire fighting equipment and personnel in damaged stations) and lack of water for firefighting (due to damaged infrastructure) can lead to a catastrophic situation.

Loss: Damage results in *loss*. Primary loss can take many forms.

- *Life loss or injury* is the primary concern[2]. If buildings collapse, major releases of hazardous materials and/or fires can be prevented; deaths and serious injuries would be reduced.

- Major *damage to property* is possible even when life loss/injury is minimal. The cost to repair or replace damaged buildings, contents, equipment, and other infrastructure is a direct financial loss. Additional losses are incurred as a result of disruption of use.

- *Loss of function* can also be a major loss. Loss of hospitals, city offices, emergency communication centers, and other important public functions are clear examples. If schools are closed for an extended period of time, the postponement of education is a loss.

- Primary losses lead to other forms of loss, such as loss of revenues resulting from *business interruption*, *loss of market share* and/or *reputation*. These forms of loss can affect both the public and private sectors.

- In the private sector, business interruption (usually termed ‘BI’) is a serious matter that some companies insure against. Business interruptions in recent California earthquakes have caused the failure of a number of small and medium-sized businesses. Failed businesses and reduced commercial activity bring significant reductions in sales, property, and other taxes, adversely affecting a local government’s finances.

- In the public sector, besides the obvious disruption to public services, many local governments rely on revenue from ports, airports, or other special facilities. If these are disrupted, finances are strained. Decreased tourism in the San Francisco Bay Area following the 1989 Loma Prieta earthquake reduced sales and airport tax revenues.

- When businesses or factories, with their jobs, are closed, it affects the

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[2] Earthquake-related natural hazards, such as tsunami or landslides, have killed hundreds of people in other parts of the earth, and have caused some fatalities in California. However, great loss of life from these causes seems unlikely in California.

well-being of the community. This is analogous to loss of market share in the private sector. If a jurisdiction relies on revenue or jobs from a facility, and the operation of that facility is disrupted for a prolonged period, the customers go elsewhere and never return. After the 1995 Kobe earthquake in Japan, the Port of Kobe -- the world's largest container port prior to the earthquake -- closed for about one year. In that time, it lost several major-shipping lines to other ports. Though the Port of Kobe was closed for one year, the customers were lost for many years, if not forever.

2.5 Mitigation Alternatives

Damage and loss can be reduced, or *mitigated*, in any of a number of ways. Figure 2-3 is modified from the previous figure, and indicates how mitigation is possible at each link in the earthquake risk chain. Just as Figure 2-1 laid out the earthquake loss chain of causation, Figure 2-3 shows that breaking that chain at any link reduces or eliminates the loss. Typically, the earlier (higher) in the process the chain is broken, the more effective is the mitigation.

Each of the mitigation approaches below is a proven technology:

- Hazards such as faulting and shaking can be mapped and, in many cases, have been mapped in detail in California. Over the last two decades, the California Division of Mines and Geology (USGS) has mapped the most active faults in California. Shaking intensity maps are also readily available, even through the Internet (see Appendix B). Such maps identify the presence of these hazards. When the potential for faulting or shaking is severe, the best mitigation is not to locate important facilities on sites subject to them.

  If the hazard is poor soil, where liquefaction or ground failure might occur, then ground remediation may be appropriate. Recent decades have seen the development of new methods for soil improvement and liquefaction reduction, including soil mixing, stone columns, soil wicks, and chemical and pressure grouting. Appendix C provides additional information on this topic.

- Primary damage mitigation is within the purview of structural engineers and other design professionals, who have developed competencies in bracing, strengthening, or otherwise improving the earthquake performance of buildings and other structures, nonstructural elements, equipment, and contents. Later in this report and in the appendices, we discuss some of these techniques in more detail.

- Secondary damage results from the interaction of several problems, and can be very complex to deal with. Therefore, it is best mitigated prior to the earthquake, through better handling of materials and infrastructure improvements. Since this cannot be done everywhere, secondary damage must be dealt with through improved emergency response: acquisition of the necessary equipment and on-going training and exercises for personnel.

- In certain circumstances, earthquake insurance can also be an effective method of mitigating financial loss. However, it does nothing to address life loss or injury, and typically only partially offsets primary financial loss.

The further down in the damage chain one progresses, the more difficult and less effective is mitigation. Secondary losses, such as damage to reputation, often cannot be fully mitigated.

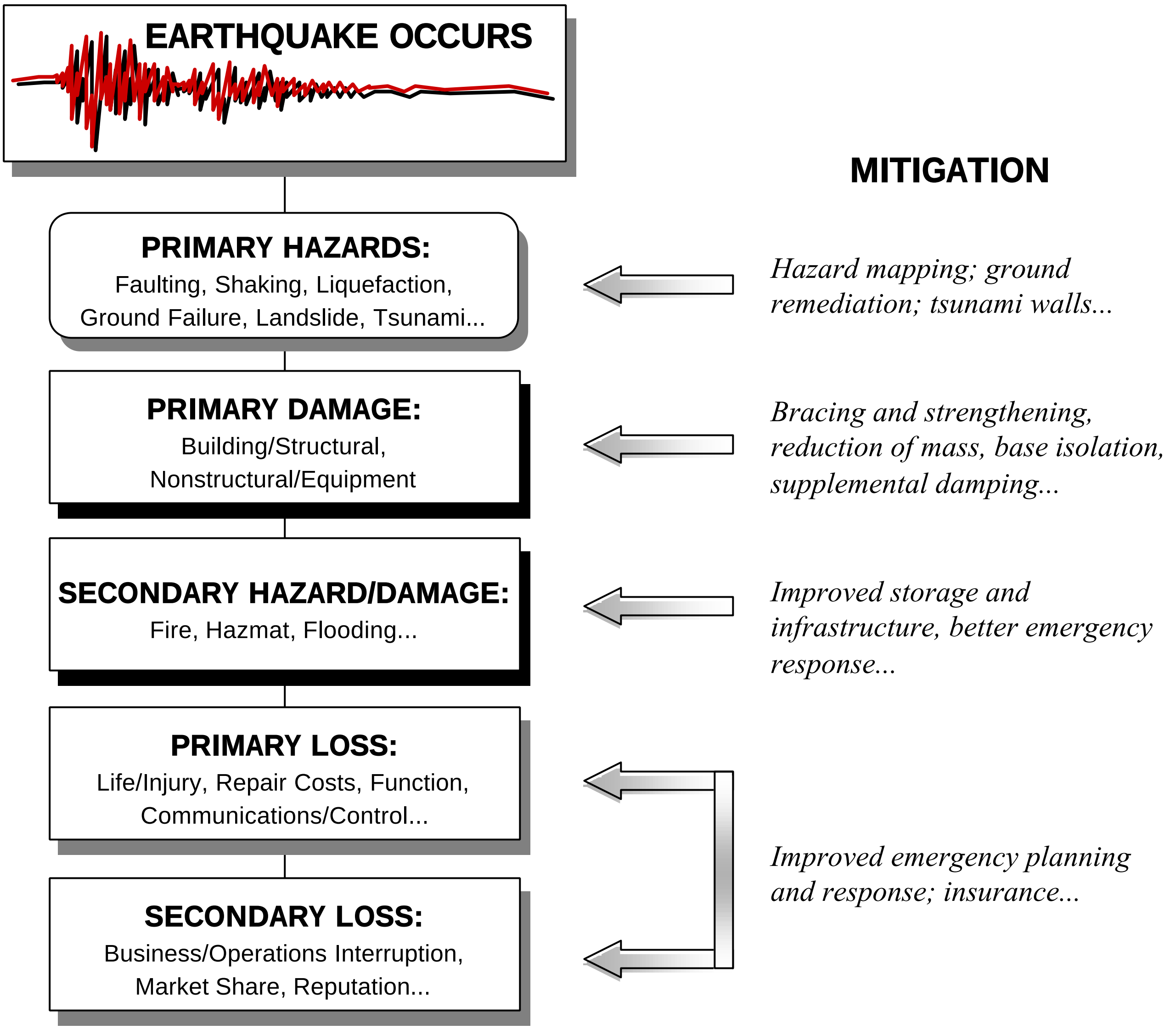


Figure 2-3: Earthquake Mitigation Spectrum

2.6 Earthquake Risk Management Decision-making

The fundamental problem of earthquake risk management is not to find any solution, but to find a "best" solution. What this "best" solution will be depends on the circumstances, values, and priorities of the individual enterprise. The decision-making process illustrated in Figure 2-4 is useful in decisions between available alternatives. The process consists of three basic steps:

Step 1 - Estimate the Risk

- **Define the Problem** – The *Risk Manager*, with the concurrence of the *Decision-Maker,* must identify the assets at risk and the acceptable performance for each asset. Typically, the assets at risk comprise all that property that the enterprise owns, occupies, relies upon, or must safeguard as part of its basic mission. At a minimum, acceptable performance implies protection of life safety. Preservation of ability to provide service, protection of cultural resources, and minimization of financial loss should also be considered in setting performance goals for some assets.

- **Quantify the Baseline Risk** – The *Risk Manager,* with assistance from the *Asset Manager,* the *Financial Manager* and technical consultants, must estimate the potential life, financial and other losses, under current conditions. This process is described in some detail in the next chapter.

- **Determine if Further Action is Needed** – If the baseline risk is acceptable, no further action is required. Otherwise, alternative mitigation approaches should be evaluated.

Step 2 - Examine Mitigation Alternatives

- **Select the Basis for Analysis** – The *Risk Manager*, with assistance from the *Decision-Maker,* should determine the constraints under which the enterprise must operate. For example, mandated retrofitting of residential buildings may not be politically feasible because the public will vote out whoever attempts to enact it. In such a case, the basis for analysis would be voluntary retrofitting, and the alternatives would consist of distributing information, providing financial incentives, and other more palatable measures.

- **Identify the Alternatives** – The *Risk Manager* and *Asset Manager,* together with assistance from technical consultants, should identify a broad spectrum of mitigation alternatives that fit within the given constraints. The previous section indicated how each link in the chain of earthquake loss causation offers opportunities for mitigation, often multiple ones. Develop as many alternatives as possible. Don't worry about their feasibility or ranking. Such evaluations are made later in the process.

- **Screen Alternatives** – Once the *Risk Manager*, *Asset Manager* and technical consultants have "brainstormed" a broad range of alternatives, it may become 'obvious' that some are not attractive or feasible. Eliminate these from further consideration.

- **Choose a Decision Method** – The *Risk Manager* and *Decision-Maker* should develop a framework and criteria for choosing among the alternatives. This is a very important step, since the basis for a decision may be subject to close examination after the decision is made. There are many different methods and criteria for deciding between alternatives, including simple scoring methods, benefit-cost analysis and multi-attribute utility theory. Refer to Chapter 4 for more information on the methods.

- **Describe the Alternatives** – The *Risk Manager*, with assistance from the *Asset Manager*, *Financial Manager* and technical consultants, should examine each feasible alternative to determine its efficacy in reducing the risk to acceptable levels. In order to do this, assume that an alternative is implemented and then calculate the residual risk with the same methods used previously to determine the baseline risk. Repeat this for each alternative.

Step 3 - Make a Decision

- **Collect and Organize the Data** – The *Risk Manager* should assemble information on the probable implementation cost and the effect of implementation on the baseline risk (residual risk) for each alternative. It is also important to determine how confident (or certain) you are in assessing this data. Many decision-makers will want to avoid selecting an alternative that has a highly uncertain cost or benefit. The *Financial Manager* and technical consultants should help the *Risk Manager* to determine the level of uncertainty.

- **Apply the Decision Method** – The *Risk Manager,* with the concurrence of the *Decision-Maker,* should evaluate each alternative using the criteria of the selected decision method. Chapter 4 presents information on the application of one such method.

- **Communicate the Results** – Once a specific set of alternatives emerges as the "best" solution, it is necessary to explain the basis for its choice to everyone who must approve of this decision. Different stakeholders (such as tenants, owners, parents, ratepayers, and others) will be interested in various aspects of the decision. The *Risk Manager* should attempt to identify and address the needs of all such persons.

Making the decision is not always as easy as it sounds. Others will question, and that will require further analysis and justification. Eventually, however, it is desirable to obtain consensus on the best alternative.

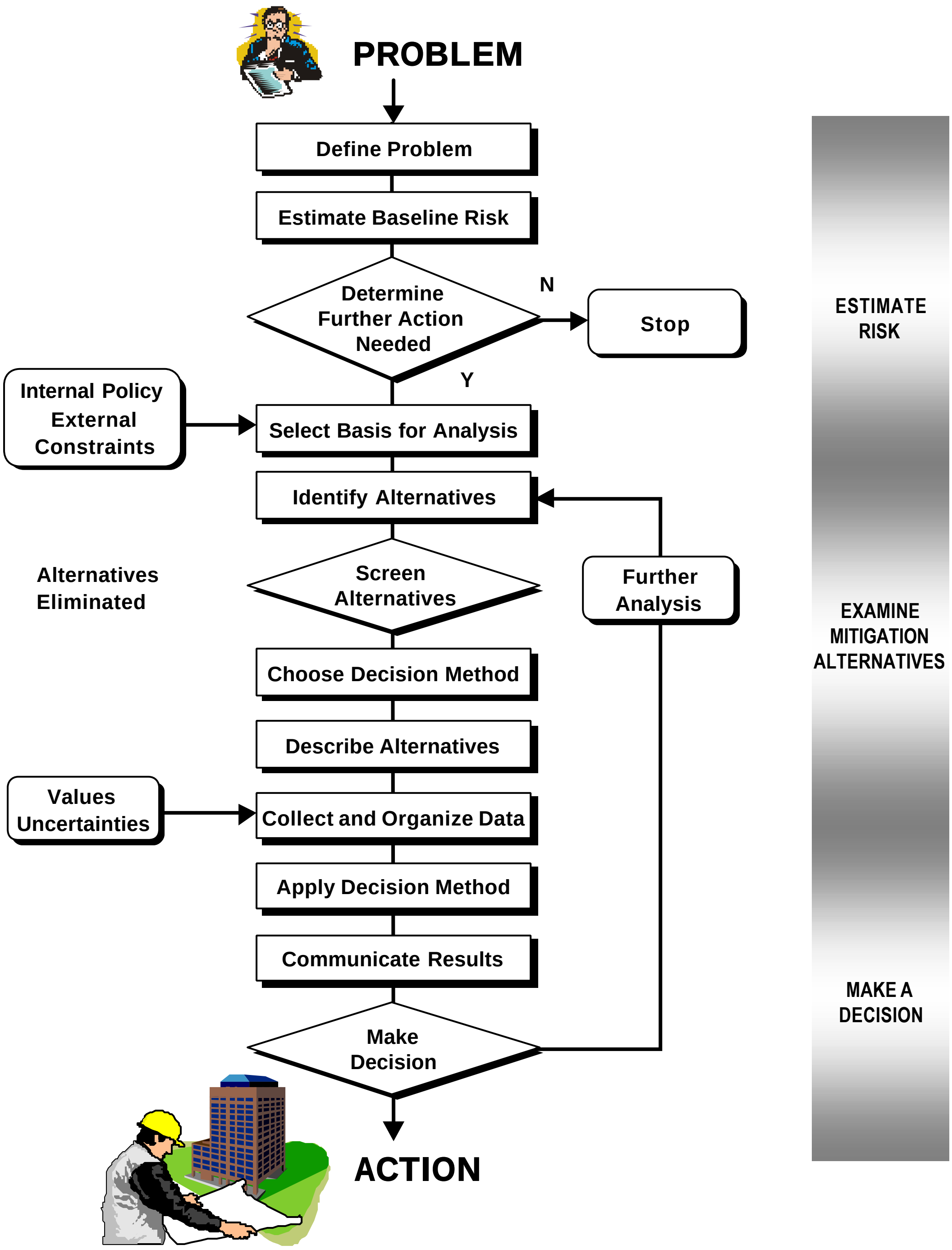


Figure 2-4: Earthquake Risk Management Decision Process

2.7 Implementing the Earthquake Risk Management Program

Once a set of alternatives has been selected, it remains to put the plan into action. The basic steps are shown in Figure 2.5 and discussed below:

- **Funding** – There are many ways to pay for earthquake risk mitigation, depending on the circumstances of your enterprise. Public agencies may allocate funds from general revenues, levy special assessments, sell bonds, establish user's fees and/or obtain grants from state or federal programs. In the private sector, there are analogous sources of funding: one-time charges, loans or bonds, and/or public subsidy.

- **Project Management** – Action requires a dedicated staff for managing the program; the engagement of specialists, consultants and/or contractors; scheduling the work; communicating with neighbors and affected parties; and follow-up to assure that goals are being met.

- **Strategies** – It is usually beneficial to conduct major strengthening and other large mitigation projects as part of the overall Capital Improvement Plan (CIP) or other Asset Management Program. Smaller projects, such as bracing of contents and anchoring equipment, may be included within regular maintenance outlays or funded directly using general revenues.

- **Risk Transference** – Instead of reducing the potential for damage and loss, it may be possible to transfer some of the risk to others. The most common method is through purchase of insurance. Recently, it has also become possible for some enterprises to transfer their risk to others through the securities markets, as an alternative to insurance. It is important to note here that it is actually possible to transfer only parts of the financial risk to third parties.

- **Post-earthquake Action Plans** – In California, it is seldom possible to eliminate earthquake risk completely. Therefore, every enterprise should have an emergency response plan in place. The basis for this plan should be the *residual risk*, that is, the portion of the baseline risk that the implemented mitigation alternatives cannot feasibly reduce. Understanding, preparing for, and clearly communicating this residual risk is necessary to avoid surprises and recriminations following an earthquake. It also should form the basis for a recovery plan.

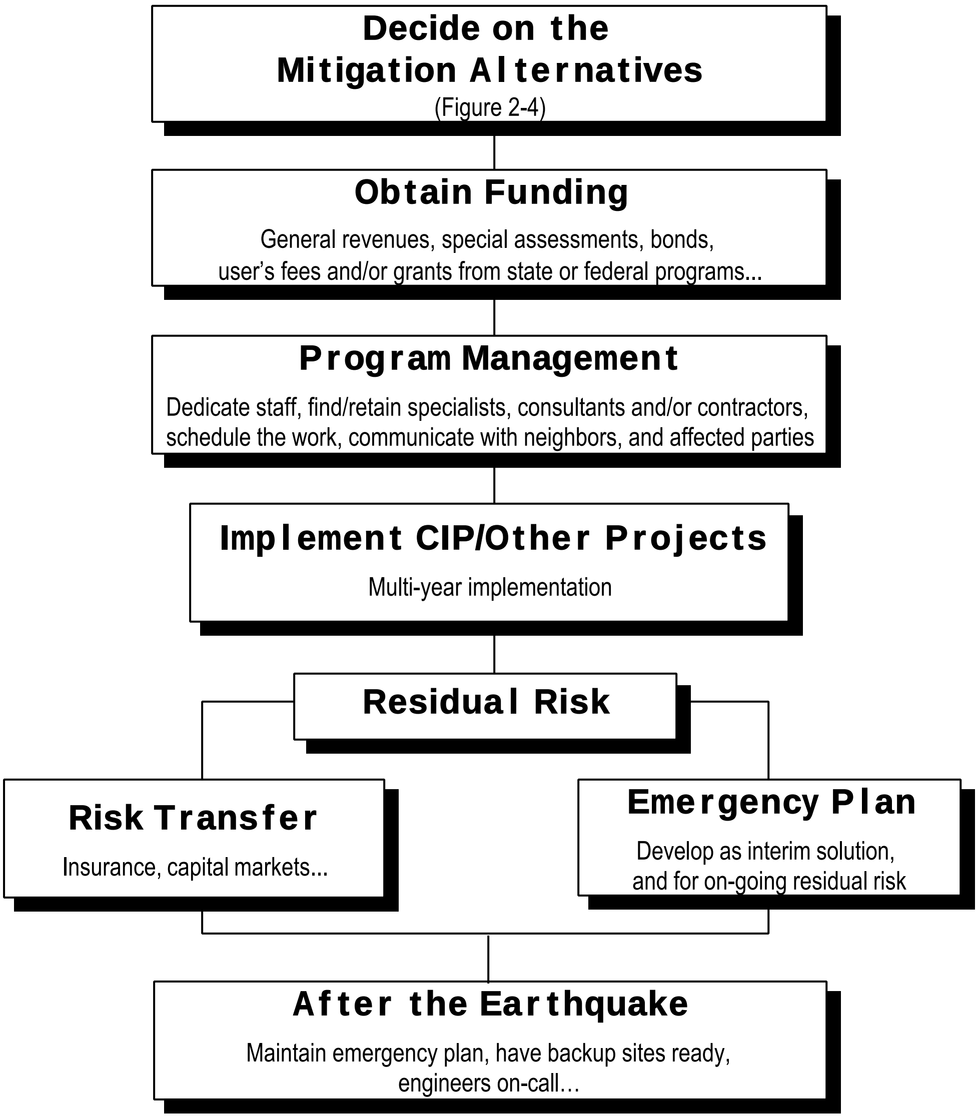


Figure 2-5: Earthquake Risk Mitigation Program

2.8 Summary

This chapter has provided an overview of the earthquake risk problem, and a guide to the management of this problem.

Earthquake risk management consists of a series of rational steps aimed at:

- identifying what is at risk – the *assets,*
- assessing how the earthquake places these assets at *risk,*
- determining which alternatives might *reduce* this risk ,
- selecting the *best* alternatives for the specific situation, and
- putting these alternatives *into practice.*

Primary Interest:
Risk Managers

Secondary Interest:
Asset Managers
Financial Managers

3. Assessing Earthquake Risk and Alternatives

3.1 Introduction

This chapter provides guidance on assessing the baseline earthquake risk. It is primarily intended for the *Risk Manager* who must initiate and lead the process of earthquake risk assessment. In order to actually perform the risk assessment, the Risk Manager will need assistance from the *Asset Manager*, *Financial Manager,* and technical consultants. This chapter may also be of interest to those individuals.

3.2 Assessing Earthquake Risk - Overview

Assessment of earthquake risk consists of a review of buildings, non-building structures, and equipment for seismic vulnerabilities; relating these vulnerabilities to the earthquake hazard and determining the probable extent of damage; and then, evaluating the probable losses resulting from this damage.

The *Asset Manager*, using guidelines presented in this *Toolkit*, can conduct the initial reviews of buildings, structures, and equipment for seismic vulnerability. However, detailed evaluation of earthquake vulnerability and the process of predicting damage should be performed by structural engineers or other professionals knowledgeable and experienced in earthquake performance assessment. In order to perform assessments of the seismic hazard this professional will typically require the services of a geotechnical engineer, seismologist, or earth scientist. Some structural engineering consulting firms can offer these geo-hazard assessment services directly; however, most will wish to retain specialty geo-hazard consultants.

Given that certain damage is expected to occur, the *Financial Officer* can best perform the assessment of losses. The *Financial Officer* should also be assisted by those members of your staff who are most familiar with the needs of your operations and the ability to continue to operate, given that certain facilities are damaged or unavailable for use.

Since the comprehensive seismic review of all structures and equipment can be a significant undertaking (i.e., expensive), *screening* techniques have been developed to make this effort more reasonable. Specifically, screening consists of an initial, simple review of buildings and/or equipment, for the purpose of cost-effectively identifying those buildings or equipment, which are likely to perform satisfactorily in an earthquake. Many *Asset Managers* will be able to perform this screening with their own staff, using procedures described in this chapter. Buildings or equipment, which cannot be screened out, must be reviewed in a more detailed manner to identify key seismic vulnerabilities. It will typically be necessary to retain an engineering consultant to do this.

Once key vulnerabilities have been identified, there are usually several alternatives available for addressing these vulnerabilities. The basic process is shown in Figure 3-1, and consists of:

- **Identification of the Assets at Risk** – The *Risk Manager*, with the concurrence of the *Decision-Maker*, must identify the facilities and assets that may be affected, and potentially damaged or destroyed, by an earthquake. In addition to identifying these facilities, the *Risk Manager* and *Decision-Maker* must make some basic decisions as to the desired *performance objective* for each facility – should it be functional following the earthquake, be allowed to sustain a moderate degree of repairable damage, or simply prevented from collapse? The primary asset at risk is the safety of personnel and the public, and the minimum performance level typically desired for this asset is preservation of life-safety.

- **Assessment of Facilities** – The *Risk Manager* should work with the *Asset Manager* to obtain evaluations for each building, equipment item, and systems component identified as an important asset. As mentioned above, several screening techniques (such as FEMA-154 for buildings and MCEER 99-0008 for equipment) can be used to perform initial evaluations.

  Once screening is completed, more detailed evaluations must be performed, typically relying on technical consultants. Part of this process involves establishing the seismic hazard for each facility – that is, the likely intensity of shaking (taking into account the site-specific soils), as well as the potential for soil failure. At several steps in this process, the facility may be found to "pass" – that is, the expected performance is satisfactory, and the assessment process is terminated for that facility.

- **Alternatives** – Working with the *Asset Manager* and technical consultants, the *Risk Manager* should identify and evaluate mitigation alternatives, for facilities where the expected seismic performance is not satisfactory. This is discussed further below.

The remainder of this chapter discusses this process in more detail.

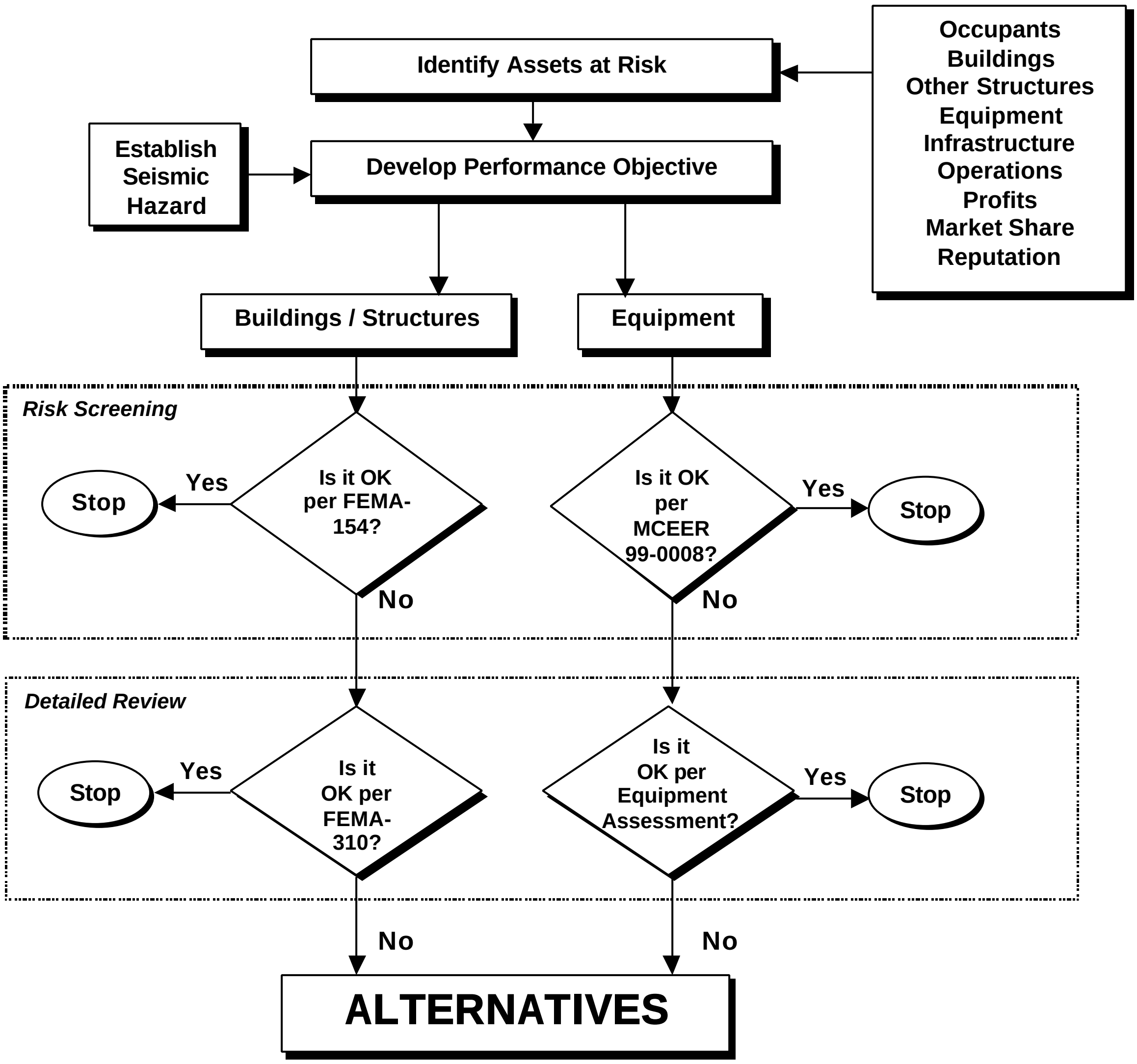


Figure 3-1: Earthquake Risk Assessment

3.3 Identifying the Assets at Risk

Earthquake mitigation starts by defining the problem, that is, what are the assets at risk? As a general rule of thumb,

whatever a Decision-Maker
is responsible for,
is what is at risk from earthquakes.

This is at least true from the pragmatic viewpoint that the *Decision-Maker* can only affect what he or she is responsible for.

The *Risk Manager* should start the process by developing a catalog of the assets at risk. Tables 3-1 and 3-2 provide a sample catalog of the typical assets that are at risk from earthquakes. Table 3-1 focuses on the private sector, and lists not only the assets at risk, but also the threats that earthquakes pose to these assets and, generally but not exhaustively, the mitigation alternatives available for countering each of these threats.

Table 3-2 provides similar information for the public sector enterprise. In government, typically no one *Decision-Maker* will be responsible for everything. Schools, water utilities, and other public services may be the responsibility of special service districts, independently elected. Even the mayor of a large city or the city council is not typically responsible for public utilities such as telephones. However, this mayor or city council, or state governor, will be expected to act to protect the public interest if and when breakdowns occur in any arena and are not remedied in a timely manner. While perhaps not legally or literally responsible, high public officials will be held accountable if things go wrong for too long. In other words, the public sector has the responsibility for protecting the public health and safety, even if others must ultimately be relied upon to provided the needed services.

Therefore, it is often in the best interest for all public *Decision-Makers* to provide local and regional leadership for a wide, if not full, earthquake mitigation program. For example, a mayor and mayoral staff should attempt an exhaustive identification of the assets at risk in their community, including public and private assets, as the first step towards earthquake risk mitigation. This can then be pruned back, via regional coordination with the responsible agencies and private owners, to those assets that are the *Decision-Maker's* direct responsibility, or can be directly influenced, by the city government.

Since the mitigation alternatives available to the private sector tend to be the same as those presented in Table 3-1, Table 3-2 simply catalogs the impacts rather than listing mitigation alternatives.

Table 3-1

PRIVATE SECTOR ASSETS AT RISK

Asset / Loss	Earthquake Threat	Mitigation Alternatives
❑ People/ death and injury	♦ Building damage/collapse, via ground shaking, fault rupture, or other earthquake hazard	▪ Strengthen the building ▪ Base isolate the building ▪ Provide supplemental damping ▪ Provide ground or foundation improvements, if ground failure is the issue ▪ Replace the building (i.e., move, or new construction)
	♦ Building contents damage	▪ Inventory all contents and brace or otherwise reduce damage
	♦ Equipment malfunction	▪ Identify and review critical equipment for continuity of functionality during and after and earthquake (e.g., check for relay chatter, backup power, water, fuel etc) ▪ Assure equipment will not be damaged (i.e., brace etc) ▪ Provide redundant equipment ▪ Develop emergency plans and procedures for equipment malfunction
	♦ Offsite threats	▪ Identify and review neighborhood for earthquake hazards (e.g., tsunami, landslide) and threats (e.g., nearby hazardous operations, such as a chemical process plant) ▪ Develop Emergency plans and procedures, including possible warning mechanisms ▪ Build protective barriers ▪ Acquire protective equipment and training (e.g., fire brigades) ▪ Modify offsite threat (e.g., earthmoving, for a landslide; or buy out nearby hazardous operation; or move)
❑ Building, equipment damage/ financial loss	♦ Same as above ♦ Inventory	▪ Same as above, plus ▪ Emergency plans and procedures to minimize damage (e.g., recovery of inventory; quick shut-down of broken sprinklers) ▪ Earthquake insurance
❑ Function/ BI, loss of revenue, market share	♦ Same as above plus loss of infrastructure (e.g., transportation), loss of vendors	▪ Contingency planning for loss / replacement or recovery of facilities (e.g., backup sites or suppliers, rapid recovery via pre-arranged inspection and repair contractors) ▪ Financial planning for loss of revenue ▪ Earthquake / Loss of profits insurance ▪ Planning for alternative production / transportation to maintain market share

Table 3-2

PUBLIC SECTOR ASSETS AT RISK

Asset / Loss	Earthquake Threat	Impacts
❑ People/ death and injury	♦ Structure damage/collapse, via ground shaking, fault rupture, or other earthquake hazard ♦ Building contents damage ♦ Equipment malfunction	▪ Residential – single family dwellings, apartments, hotels, dormitories ▪ Commercial – offices, stores, factories, restaurants ▪ Public facilities – schools, correctional facilities, offices ▪ Public assembly – theaters, halls, stadiums ▪ Essential facilities – hospitals, police / fire stations ▪ Lifelines – power, water, sewer, gas and liquid fuels, highways, ports, airports, railroads, telephone and other communications ▪ Hazardous Facilities – dams, industrial facilities
❑ Structure, equipment damage/ financial loss	♦ Same as above	▪ For public sector, portion of repair costs not reimbursed by state / federal aid
❑ Function/ BI, loss of revenue, market share	♦ Same as above	▪ Employment – private sector loss of jobs (closed factories, loss of tourism, …) ▪ Tax base / revenues (sales, real estate, …)
❑ Reputation	♦ Lack of timely recovery	▪ Loss of population ▪ Existing business decides to rebuild elsewhere ▪ Loss of new investment, development, tourism… ▪ Breakdown in political process – squabbling as to best path to recovery … ▪ Loss of political office

3.4 Determine Acceptable Risk

Before beginning a seismic evaluation, the *Risk Manager* should establish its limits. This helps focus the risk-management effort on the information the *Decision-Maker* needs. In the present situation, the most important aspect of decision framing is determining the *Decision-Maker*'s policy toward facility performance, and to establish the order in which risk-mitigation decisions will be made. Therefore, the *Risk Manager* should begin the risk analysis by creating a *decision hierarchy*, which separates decisions into three groups: policy, strategy, and tactical.

- *Policy decisions* will be resolved first, before beginning the seismic risk evaluation. As an example, an organization must decide to attempt to reduce earthquake losses to acceptable levels, and determine what "acceptable" means. Policy decisions, like all decisions, often require additional information to be finalized, and may go through several cycles of consideration, additional information required, etc. While the *Decision-Maker* must ultimately make policy decisions, the *Risk Manager* will usually have to support the process and must ultimately work within the framework of these policy decisions.

- *Strategic decisions* are the real point of the present seismic risk analysis. That is, the *Risk Manager* will gather information on the seismic risk to facilities for the purpose of facilitating strategic decisions. An example of a strategic decision is that an office complex must remain operational immediately following an earthquake or, alternatively, that it can sustain damage, since its functions are not immediately needed.

- *Tactical decisions* are made after the strategic decisions. These are the detail decisions that can be dealt with later, and can perhaps be delegated. An example of a tactical decision is that backup power must be available for an office complex, if its required remain operational immediately following an earthquake. If the strategic decision is that the office complex can sustain damage, since its functions are not immediately needed, then the tactical decision is that no backup power is required.

This section leads the *Risk Manager* through the various steps necessary to establish policy on seismic performance. This policy is established by setting performance objectives for each facility.

A performance objective is a specification of the level of performance (limiting amount of damage) desired for various potential earthquake scenarios. Generally, large destructive earthquakes occur infrequently, while moderate, less destructive earthquakes can be expected to occur more often. Typically, the *Decision-Maker* will be willing to accept poorer performance (more damage, increased hazard to life, increased service, and economic loss) in large, infrequent events than they are for moderate, more frequent earthquakes.

In this *Toolkit*, we suggest that the *Risk Manager* set performance objectives for two different levels of earthquake. These are defined as follows:

- **Maximum Probable Earthquake (*MPE*).** – This level of hazard is representative of a severe earthquake that may occur one time during the life of a facility. We define the *MPE* as having a mean return period of approximately 500 years. In any 50-year period, there is, on average, approximately a 10% chance that ground motion of this intensity will be exceeded.

  For sites located adjacent to major active faults, the *MPE* can be taken as that intensity of ground shaking likely to occur (50% probability of exceedance) given that a characteristic event occurs on the nearby fault. The California Building Code (CBC) requires that new buildings be designed to resist this level of earthquake without endangering life safety.

- **Likely Earthquake (*LE*).** – This level of hazard is representative of the intensity of ground shaking likely to be experienced one or more times during the facility's life. We define the *LE* as having a mean return period of approximately 100 years. In any 50-year period, there is, on average, approximately a 40% chance that such shaking will be exceeded.

In addition to the *MPE* and *LE*, some *Decision-Makers* may elect to protect certain critical facilities for the most severe earthquake effects that could ever occur. There is great uncertainty in the definition of such an event. For the purposes of this *Toolkit*, we recommend that the *Upper Bound Earthquake* (*UBE*) defined in the California Building Code be taken as representative of such an event. The *UBE* is defined as that intensity of ground shaking having a mean return period of 1,000 years. In any 50-year period, on average, there is approximately a 5% chance that such shaking will be exceeded.

It is the *Decision-Maker's* responsibility to select an appropriate performance objective for each facility class for these various earthquake events. This is a key and difficult aspect of the entire earthquake risk management process. Examples of performance levels, which are typically selected, are provided in the Table 3-3, as a guide. Table 3-4 describes the damage to building structures and nonstructural components for each of the performance objectives described in Table 3-3.

Table 3-3

EXAMPLES OF TYPICAL PERFORMANCE OBJECTIVES FOR VARIOUS FACILITY-TYPES

Facility-type	Earthquake Event UBE (1,000-Year)	MPE (500-Year)	LE (100-Year)
Essential public facilities, • Hospitals • Police stations • Fire stations • Emergency communication centers	LS[1]	IO	O
Public facilities with vulnerable occupants • Schools • Correctional Facilities	CP	LS	IO
Other public facilities	CP	LS	-
Private commercial – emergency response	LS	IO	O
Private commercial with hazardous materials	LS	IO	O
Private commercial – essential operations	LS	IO	O
Private commercial – ordinary operations	CP	LS	-
Other private commercial facilities	CP	LS	-
Multi-family residential buildings	CP	LS	IO
Single-family residential buildings	CP	LS	-
Historic buildings	CP	LS	-

[1] Legend (refer to Table 3-4 for more detailed information):
CP – Collapse Prevention
LS – Life Safety
IO – Immediate Occupancy
O – Operational

Table 3-4

POST-EARTHQUAKE PERFORMANCE OBJECTIVES[1]

Objective	Structural Performance		Nonstructural Performance	
Operational (O)	S-1	Structure is essentially undamaged and retains nearly all of its pre-earthquake strength and stiffness. Any minor damage sustained can be repaired at convenience. Structure is safe for occupancy.	N-A	Nonstructural components are essentially undamaged and all equipment, systems and utilities essential to normal operations are functional, though utility service may be supplied from emergency sources. Building is suitable for use in normal occupancy and to fulfill its primary function.
Immediate Occupancy (IO)	S-1	Structure is essentially undamaged and retains nearly all of its pre-earthquake strength and stiffness. Any minor damage sustained can be repaired at convenience. Structure is safe for occupancy.	N-B	Nonstructural components essential to life safety are including fire protection systems, emergency lighting and egress means are functional. Other non-structural components may sustain minor damage and may or may not function, but do not pose a threat to life safety. Utility service may or may not be available. Though the building is suitable for occupancy, it may not be available for use in its normal occupancy before some cleanup and repair is accomplished. Interruption of service is expected to be limited
Life Safe (LS)	S-3	Structure has sustained some damage and has experienced a loss of both stiffness and potentially strength. However, neither total nor partial collapse has occurred, and the building retains some additional capacity to resist additional lateral loading, e.g. from after shocks. The building may not be safe for re-occupancy until temporary shoring or repairs are conducted. Permanent repair is feasible, though they may potentially be quite expensive and time consuming	N-C	Extensive damage to nonstructural components, systems and equipment. Utility service is generally not available and many systems would not function even if service were available. Extensive damage due to water leakage from broken piping. Substantial toppling and sliding of light components, however, no major hazards occur due to falling debris and egress ways are not blocked. Interruption of service may be long term.
Collapse Prevention (CP)	S-5	Structure experiences extensive damage with a substantial loss of both stiffness and strength. Although neither local nor global collapse has occurred, marginal additional loading, as from aftershocks could credibly cause such collapse. The building is not safe for occupancy and may not be economically or technically feasible to repair.	N-E	Widespread disarray and damage to contents including toppling and sliding of many items of contents and equipment. Access and egress ways may be impaired by debris. Though individual large items may topple or fall, major non-structural components that could pose a hazard to many people, such as large suspended ceilings do not fall.

[1] Performance Objective descriptions adapted from ***FEMA-273: NEHRP Guidelines for Seismic Rehabilitation of Structures***

Two worksheets are provided to assist the *Risk Manager* in setting performance objectives for the enterprise (see Appendix G for extra blank worksheets). These are the Decision Hierarchy worksheet (Worksheet 1-A), and the Facility–type Definition worksheet (Worksheet 1-B). The Decision Hierarchy worksheet is used to guide the process of strategic decision-making, including the establishment of the scope of the risk assessment and the definition of specific risk-management objectives. Working with the *Decision-Maker*, The *Risk Manager* should use this worksheet to do the following:

1. First, choose a performance objective for the *MPE* and *LE* events for each of the several facility types. Five performance options are offered: Operational (O), Immediately Occupancy (IO), Life Safe (LS), Collapse Prevention (CP) or Not Considered (N). These options are defined in Table 3-4. For each class of facility listed on the worksheet (and for which the enterprise is responsible) circle the appropriate performance objective for both earthquakes.

2. Next, for each class of facility (except those with a performance objective of *Not Considered* for both earthquakes) determine whether the performance objectives are to be required (common for public facilities and high-risk private facilities) or encouraged (common for moderate- to low-risk private facilities).

***Risk Manager*: What you should do**

Edit Worksheets 1-A and 1-B to match your circumstances. When considering policy options, confer with legal counsel to ensure that potential alternatives meet local laws and regulations. When considering facility types, confer with zoning officials (public agency) or asset management (private) to ensure conformity with standard facility-use categories.

Present both worksheets to your *Decision-Maker*, along with copies of performance objectives and earthquake event definitions. The purpose is to introduce them to the decisions you will ask them to make, and the order in which you intend to do so.

Ask the *Decision-Maker*:

(1) To approve the facility-type classification system of Worksheet 1-B,

(2) To approve the decision hierarchy, that is, the nature and order of the decisions shown in Worksheet 1-A, and

(3) To resolve the policy decisions in the top section of Worksheet 1-A.

Then begin gathering the proper information for making strategic decisions.

Following completion of the Decision-Hierarchy worksheet, the *Risk Manager* should complete the Facility-type Definition worksheet. This worksheet lists the same facilities types included on the Worksheet 1-A.

The *Risk Manager* should assign each of the assets to be included in the risk assessment to one of these categories. Use Column C of Worksheet 1-B to list the assets placed in each facility class. Public agencies may do this by associating each facility type with local zoning or use codes, or in some cases with a list of specific addresses. Private entities may wish to begin with a list of enterprise operations and then determine the addresses at which these operations occur. Attach additional pages if Column C does not provide enough room.

Taken together, the Decision Hierarchy worksheet and Facility-type Definition worksheet unambiguously define the earthquake performance objectives for the enterprise.

Worksheet 1-A: Decision Hierarchy

POLICY DECISIONS – MADE BEFORE RISK ASSESSMENT

Decision-Maker: For each facility-type and earthquake event, choose and circle the appropriate performance objective: Operational (O), Immediate Occupancy (IO), Life Safe (LS), Collapse Prevention (CP) or Not Considered (N). Also choose and circle a corresponding enforcement alternative: required (R) or encouraged (E). For precise definitions of facility-types, see Worksheet 1-B for examples. For precise definitions of performance objectives, see Table 3-4.

Facility type	MPE (500 year)	LE (100 year)	Mandate
Essential public facilities	O IO LS CP N	O IO LS CP N	R E
Public facilities with vulnerable occupants	O IO LS CP N	O IO LS CP N	R E
Other public facilities	O IO LS CP N	O IO LS CP N	R E
Private commercial - emergency response	O IO LS CP N	O IO LS CP N	R E
Private commercial with hazardous materials	O IO LS CP N	O IO LS CP N	R E
Private commercial – essential operations	O IO LS CP N	O IO LS CP N	R E
Private commercial - ordinary operations	O IO LS CP N	O IO LS CP N	R E
Other private commercial	O IO LS CP N	O IO LS CP N	R E
Multi-family residential	O IO LS CP N	O IO LS CP N	R E
Single-family residential	O IO LS CP N	O IO LS CP N	R E
Historic	O IO LS CP N	O IO LS CP N	R E

STRATEGIC DECISIONS – MADE AFTER RISK ASSESSMENT

The Risk Manager will collect information on all facilities with a performance objective other than "N" in the table above. With the aid of the Asset Manager and engineering consultants, the Risk Manager will evaluate each facility to determine if it is capable of meeting the selected performance objective. For those facilities that do not meet these objectives, the Risk Manager, assisted by the Asset Manager and engineering consultants, will recommend mitigation alternatives and select the alternative that best meets the stated objective. The Risk Manager will provide the Decision-Maker with cost and benefit information necessary to evaluate the recommendation and make the final decision.

Worksheet 1-B – Facility-type Definition

Risk Manager: Unambiguously define each facility-type you will use (e.g., by zoning or use code, by exact address, etc.) to prevent misunderstanding on the category of any particular facility. Decision-Maker: Adjust or endorse this classification system.

(A) Facility-type	(B) Examples; notes	(C) Zoning or use codes, addresses
Essential public facilities	Fire & police stations, hospitals, emergency operation & communication facilities, water supply facilities	
Public facilities with vulnerable occupants	Schools, non-emergency medical facilities, correctional facilities, nursing homes	
Other public facilities	Libraries, office buildings, public works equipment yards, local vehicular bridges, wastewater treatment facilities	
Private commercial - emergency response	Telephone switching facilities, private ambulance services, private medical facilities	
Private commercial - hazardous materials	Chemical and gas manufacturers and distributors, industrial facilities	
Private commercial - essential operations	Bank data processing centers, customer service centers, manufacturing facilities in certain high-tech industries	
Private commercial - ordinary operations	Research & development facilities, warehouses, retail, wholesale, service, transportation, construction facilities	
Other private commercial facilities	Other facilities	
Multi-family residential	Apartment buildings, condominium associations	
Single-family residential[1]	Detached or attached single-family dwellings.	
Historic	Local, state, or national historic registry	

[1] Public agencies rarely examine seismic risk for single-family residences, except in the case of unreinforced masonry (URM) buildings.

Moderate and Large Earthquakes

Performance objectives discussed in this Toolkit refer to earthquake size and probability. Two earthquake sizes are considered: a large, rare event, and a moderate and more likely event. Think of the 1906 San Francisco earthquake as the former and the 1994 Northridge earthquake as the latter.

The large earthquake is conventionally used to plan for earthquake life safety. This event has a 10% probability of being exceeded in 50 years, or about 0.2% per year. Its mean return period (average time between events) is roughly 500 years (average is emphasized, since actual intervals between events can vary substantially). This is the MPE event.

Planning for business operations more commonly considers a 5- to 10-year period. The moderate event considered herein is one with 10% chance of exceedance in 10 years, or about 1% annual probability of exceedance, or a mean return period of approximately 100 years. This is the LE event.

The figure shown at right illustrates the mathematical relationship:

$$T = \frac{1}{1-(1-P)^{1/t}}$$

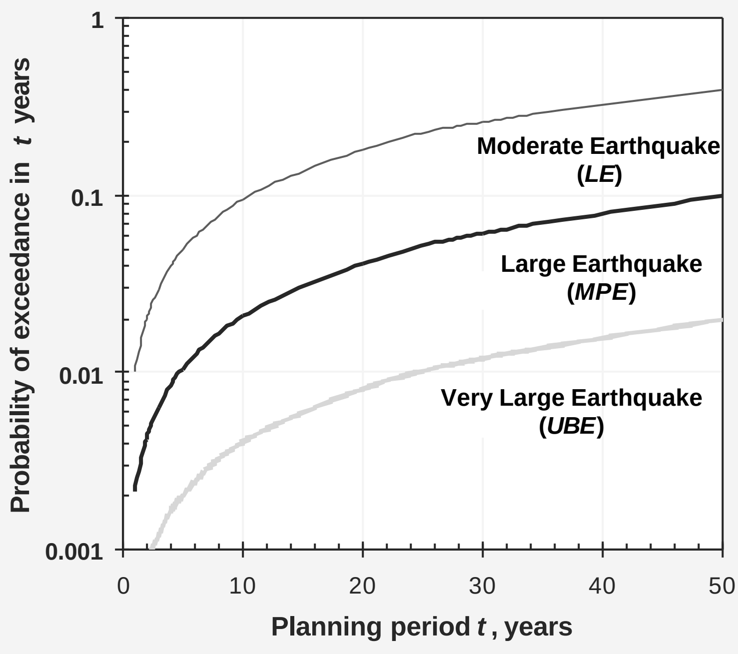
or

$$P = 1-\left(1-\frac{1}{T}\right)^{t}$$

where,

T is the mean return period in years, and

P is the probability of exceedance within the planning period, t (in years).



Some highly hazardous facilities plan for an earthquake with 5% exceedance probability in 50 years; this is the very large earthquake in the figure or the UBE event.

3.5 Data Collection

After identifying the assets at risk, and determining the acceptable level of risk, gather sufficient data on the facilities, population, and assets at risk to estimate the baseline risk.

Information Gathering - During this phase, the *Risk Manager* gathers data on the hazard and vulnerability of each facility, and the costs and benefits of various potential risk-mitigation options. Data-gathering tasks and their associated level of effort are listed in Table 3-5.

Risk Managers performing this process for a large number of assets will want to use Facility Task List worksheet (Worksheet 2). This simple form allows identification of the individuals responsible for providing the required information for each asset, and can also be used as a checklist to track progress in gathering this information. To use Worksheet 2, list each of the facilities identified on Worksheets 1-A and 1-B as requiring seismic examination (performance objectives O, IO, LS, or CP for either of the two earthquake levels). As an individual is identified to perform steps in the information gathering for each facility, list the contact information for this individual on the form, under the appropriate category and line.

There are three steps to the informational phase:

1. *Risk Screening*. As a first step, we recommend that all facilities be subjected to a *rapid screening*. This is a first examination of the facilities in order to identify those that are clearly adequate. This will allow the *Risk Manager* to focus remaining resources on facilities that pose the greatest risk.

   Rapid screening should be performed for both building structures and important equipment and systems. Sections 3.6 and 3.8, respectively, provide detailed technical guidance on how to perform this task for buildings and equipment. The *Asset Manager* should perform this screening with support from technical staff. Some enterprises may need to retain consultants for this task. The screening exercises will identify, on a preliminary basis, those facilities likely to fail their performance objectives under as-is conditions, as well as the probability for this failure.

2. *Detailed Risk Assessment and Options Review*. Facilities identified in risk screening as unlikely to meet the selected performance objectives should be reviewed by qualified structural and mechanical engineers. The engineers must estimate, for each of the earthquake event, the probable casualties, damage costs, and duration of facility outage. When these detailed evaluations confirm that probable performance does not meet the goals, the engineers should suggest practical seismic mitigation options and estimate their effectiveness in reducing probable casualties, damage and facility outage duration.

   In addition to engineering solutions, the *Risk Manager* should also examine the costs and benefits of non-engineering risk-mitigation options such as insurance, facility relocation, and emergency outsourcing options. The *Risk*

Manager will need to engage the assistance of the *Financial* and *Asset Managers* in estimating the financial losses associated with loss of use, including relocation costs and temporary loss of market share.

3. *Benefit-Cost Analysis.* The *Risk Manager* will tabulate in a worksheet the costs and benefits of risk-mitigation options examined in Step 2. Options that do not help a facility meet a performance objective will be screened out. Remaining options will be sorted in order of decreasing benefit-to-cost ratio, and the top contenders proposed to the decision makers for consideration.

Ensure Information Quality - Note that at each stage, information should be obtained from those best qualified to provide it (e.g., building department or facility manager for age and type of construction, and chief financial officer for cost of capital). All information should be carefully documented and filed for later retrieval and review.

Whenever parties with whom the *Decision-Makers* are unfamiliar provide data, it is important to document that party's qualifications and, in case of doubt, get the *Decision-Makers'* buy-in on those qualifications. It is generally better to pay more for information that the *Decision-Makers* will trust than to try to convince them of its adequacy after the fact.

In some cases, definitive information, such as the year in which a particular facility was built, will be available. In other cases, experts will have to provide an estimate.

It is important to separate actual information from expert preferences. They may inadvertently color their information to favor a particular outcome. The *Decision-Makers*' preferences, informed by expert information, should guide the decision. For that reason, the *Risk Manager* should be involved in each step and remain on the alert for potentially biased information.

Table 3-5

DATA-GATHERING TASKS

Worksheet Number	Worksheet Title	Facilities Covered	Worksheet Completed by	Estimated Effort per Facility
2	Facility Task List	All (one worksheet)	*Risk Manager*	5 to15 minutes total
3	Rapid Building Screening[1]	All buildings	*Asset Manager* or structural engineer	1 or 2 ph[2]
4	Building Assessment	Buildings with rapid screening score ≤ 2.0	structural engineer	8 to 24 ph
-[3]	Equipment Screening	All equipment	*Asset Manager* or mechanical engineer	8 to 24 ph
5	Equipment Assessment	Equipment items with screening score ≤ failing score	mechanical engineer	16 to 48 ph
6	Loss-of-Use Analysis	Worksheet 4 facilities and Worksheet 5 equipment items	*Risk Manager* aided by *Asset Manager* and *Financial Manager*	4 to 8 ph
7	Benefit-cost Analysis	All (one worksheet)	*Risk Manager*	4 to 8 ph total

[1] Worksheet 3 adapted from ***FEMA-154: Rapid Visual Screening for Potential Seismic Hazards – A Handbook***.

[2] ph = person hour of effort, by appropriate professional. These estimates are very approximate and will vary by specific facility-type. They are offered here as a rough guide for planning purposes only.

[3] Individual worksheets for specific equipment-types can be found in ***MCEER 99-0008: Seismic Reliability Assessment of Critical Facilities – A Handbook, Supporting Documentation, and Model Code Provisions***.

Worksheet 2 – Facility Task List

Risk Manager: For each facility, assign a unique identifier into Column A. Fill this in together with the facility address or location into Column B. From Worksheet 1-B, enter the facility-type into Column C. In Columns D and E, circle the performance objectives for the MPE and LE events, respectively. For Columns F and G, enter the name and contact information for the persons performing the building and equipment screenings, respectively. Columns H and I are only needed if the screening exercise results in recommendation for more detailed evaluation.

(A) ID	(B) Facility Address or Location	(C) Facility-Type	(D) MPE Objective	(E) LE Objective	(F) Building Screening	(G) Equipment Screening	(H) Building Assessment	(I) Equipment Assessment
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*

(Use additional sheets as necessary)

3.6 Building Screening

3.6.1 Purpose of Building Screening

Building screening determines whether a facility represents a significant enough risk to warrant more detailed evaluation. Although this can be done in a number of ways, we recommend the use of the method described in:

> ***FEMA-154: Rapid Visual Screening of Buildings for Potential Hazards - A Handbook.***

This method provides a convenient, standardized approach to building screening that can be implemented with minimum effort.

Using the FEMA-154 methodology, calculate a structural risk screening score (typically on the order of 0.0 to 6.0 for high seismic areas like California) for all buildings under consideration. FEMA-154 provides worksheets to assist in this calculation (see Worksheet 3). This scoring system is based on a rapid visual inspection and on important features such as construction materials, site soil conditions, and building configuration. A typical screening takes about 15 minutes or so to perform for each facility, plus travel time and approximately ½ hour to gather preliminary information that may not be apparent at the site.

Buildings with a structural risk screening score of about 2.0 or less are typically deemed to represent a significant life safety risk and therefore should be subjected to a detailed building evaluation. If Immediate Occupancy (IO) or Operational (O) performance is desired for a facility, we suggest a minimum score of 3.0 be employed as "passing" the screening process. Buildings scoring between 2.0 and 3.0 may not present a significant life safety risk; however, these structures may sustain sufficient damage to be out of operational for some period of time after an earthquake.

The Structural Risk Screening Score

The structural risk screening score, **S**, developed in the FEMA-154 rapid visual screening procedure is an initial measure of building earthquake adequacy, and is based on the probability of major damage that may occur. Major damage in FEMA-154 are repairs that would cost approximately 60 percent of the building replacement value (not including land and site improvements). At this level of damage, it was judged that occupant life-safety begins to become a concern.

A screening score of S=1 indicates that the probability of major damage for a particular building is 1 in 10, given the occurrence of expected ground shaking. S=2 corresponds to a probability of 1 in 100, S=3 is 1 in 1000, and so on. A high S score is good or "passing", while a low S denotes probable poor earthquake performance.

In general, if S is less than 2.0, it was judged that the seismic performance of that building may not be adequate, and may possibly represent a life-safety hazard. If Occupancy (IO) or Operational (O) post-earthquake performance is desired, a higher cut-off score, such as 3.0, may be appropriate.

3.6.2 *Gather Preliminary Information*

Before performing a visual examination, the inspector charged with the screening should obtain three basic pieces of information: structure type, year of construction, and soil profile.

Structure Type – For structure type, consult an experienced building department official or a structural engineer. FEMA-154 uses a classification system of 12 structure types, detailed in Table 3-6. A structural engineer or highly experienced building official with access to construction drawings can determine structure type definitively. Structure type can be ascertained visually with less confidence.

Year Built – Year of construction is typically available from the building department or from the senior facility manager. Use the age of the oldest significant portion of a building. The evolution of building codes in California is such that within given eras, buildings of certain construction types are likely to have common deficiencies and vulnerabilities. The years when building code regulations changed significantly, resulting in substantially reduced vulnerability, are commonly termed benchmark years. Table 3-6 shows basic benchmark years for typical California buildings designed to the Uniform Building Code (UBC). Benchmark year is used as a modifier in the FEMA-154 methodology, as discussed below.

Soil Profile – Soil type is an important aspect of shaking intensity and, for a particular address, is often available from the building department or from a local geotechnical engineer. The structural engineer or possibly the architect who designed the building may have a copy of the original geotechnical report on file. If no specific information is available, estimate a soil type based on general geologic data, such as maps published by the California Department of Mines and Geology (CDMG) and the United States Geologic Survey (USGS). Determine the soil classification from one of these sources in accordance with Table 3-7. Acquire a copy of the documentation used to determine the soil profile in anticipation of the building assessment.

Table 3-6

FEMA-154 STRUCTURE TYPES

Code	Meaning	Benchmark Year
W	Wood frame	1949
S1	Steel moment resisting frame	1997
S2	Steel braced frame	1988
S3	Light metal frame	-[1]
S4	Steel frame with concrete shear wall	1976
C1	Concrete moment-resisting frame	1976
C2	Concrete shear wall	1976
C3/S5	Steel or concrete frame with masonry infill	-
PC1	Tilt-up	1973
PC2	Precast frame	-
RM	Reinforced masonry	1976
URM	Unreinforced masonry	-

[1] No benchmark year – buildings of this type do not receive a positive age modifier.

Table 3-7

FEMA-154 SOIL PROFILES

Soil Profile	Description
SL1	Rock or still clay less than 200 feet thick overlying rock
SL2	Cohesionless soil or still clay greater than 200 feet deep
SL3	Soft or medium stiff clay 30 or more feet deep

3.6.3 Performing Rapid Screening

As noted above, rapid screening of buildings can be performed using appropriate techniques. The FEMA-154 methodology is currently the most widely used and is recommended here. It requires completion of a one-page form, reproduced here as Worksheet 3. Refer to FEMA-154 for additional information. Copies of FEMA-154 are available directly from the Federal Emergency Management Agency (FEMA):

FEMA Distribution Center
P.O. Box 2012
Jessup, Maryland 20794
PHONE: (800) 480-2520
FAX: (301) 497-6378

Any rapid screening procedure will typically follow the same basic steps: the inspector completes the identification section of the form, draws a scale drawing of the facility footprint, attaches a photograph of the facility, and circles the structure type indicated by the structural drawings. If structural drawings are not available, the inspector must judge the possible structure types and circle all of them. The inspector then circles modifiers relevant to the building (in FEMA-154, these are high rise [8+ stories], plan irregularity, etc.). The inspector then sums the basic score for each possible structure type with the modifiers below it.

Setting up a Building Screening Task

If the inspectors or engineers have not performed a rapid screening before, arrange for a training session. This is typically a 4- to 8-hour session and may require two days of an instructor’s time, who should be an earthquake engineer or structural engineer familiar with the FEMA-154 rapid screening methodology.

Locate the structural drawings and the geotechnical (or soils) report for each facility to be screened. Identify the person who will provide access to the facility to those charged with performing the screening. Provide this information, along with copies of Worksheet to the screeners. For each building reviewed, one copy of Worksheet 3 should be filled out.

Compile screening records afterwards, along with all structural drawings and geotechnical reports. Identify the facilities with “failing” structural risk screening scores (S) as well as those with potential nonstructural falling hazards. Contract with a licensed structural engineer to perform a detailed building assessment for these potentially vulnerable facilities.

Worksheet 3 – Rapid Building Screening[1]

FEMA 154 **(NEHRP Map Areas 5,6,7 High)**

Sketch of Building

Scale:

Facility ______________________

Address ______________________

No. Of Stories ______________________

Year Built ______________________

Total Floor Area ______________________ (sq.ft.)

Building Use ______________________

Inspector ______________________

Date ______________________

INSTANT PHOTO or DIGITAL IMAGE

OCCUPANCY

Residential	No. Persons
Commercial	
Office	0-10
Industrial	11-100
Pub. Assem.	100+
School	
Govt. Bldg.	
Emer. Serv.	
Historic Bldg.	

Non Structural Falling Hazard

DATA CONFIDENCE

* = Estimated, Subjective, or Unreliable Data

DNK = Do Not Know

STRUCTURAL SCORES AND MODIFIERS

Building Type	W	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	C1 (MRF)	C2 (SW)	C3/S5 (URM INF)	PC1 (TU)	PC2	RM	URM
Basic Score	4.5	4.5	3.0	5.5	3.5	2.0	3.0	1.5	2.0	1.5	3.0	1.0
High Rise	N/A	-2.0	-1.0	N/A	-1.0	-1.0	-1.0	-0.5	N/A	-0.5	-1.0	-0.5
Poor Condition	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Vert. Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-0.5	-0.5	-1.0	-1.0	-0.5	-0.5
Soft Story	-1.0	-2.5	-2.0	-1.0	-2.0	-2.0	-2.0	-1.0	-1.0	-2.0	-2.0	-1.0
Torsion	-1.0	-2.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0	-1.0
Pounding	N/A	-0.5	-0.5	N/A	-0.5	-0.5	N/A	N/A	N/A	-0.5	N/A	N/A
Large Heavy Cladding	N/A	-2.0	N/A	N/A	N/A	-1.0	N/A	N/A	N/A	-1.0	N/A	N/A
Short Columns	N/A	N/A	N/A	N/A	N/A	-1.0	-1.0	-1.0	N/A	-1.0	N/A	N/A
Post Benchmark Year	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	N/A	+2.0	+2.0	+2.0	N/A
SL2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
SL3	-0.6	-0.6	-0.6	-0.6	-0.8	-0.6	-0.8	-0.6	-0.6	-0.8	-0.6	-0.8
SL3 & 8 to 20 Stories	N/A	-0.8	-0.8	N/A	-0.9	-0.9	-0.9	-0.9	N/A	-0.8	-0.8	-0.9

COMMENTS

Detailed Evaluation Required?

Yes No

[1] Adapted from FEMA-154 Rapid Visual Screening and Data Collection Form

3.7 Building Assessment

Buildings that received a "failing" screening score represent a significant potential for life-threatening damage and/or a significant potential for loss of function (depending on the policy decision made). Buildings with nonstructural falling hazards also represent a risk of life loss. All such facilities should be subjected to detailed evaluations to estimate probable losses including life loss, repair costs, and likely period of closure. Contract with a licensed structural engineer to perform these evaluations.

The evaluation should estimate the losses for the existing facility for both a *LE* and *MPE* (baseline risk). In addition, the evaluation should include identification of potential mitigation measures, *rough order of magnitude*[1] estimates of their potential implementation costs, and an estimate of the potential losses if the mitigation is implemented (residual risk). The engineer should complete Worksheet 4 for each building evaluated.

The engineer should recommend upgrade alternatives that seem most appropriate, given the existing facility vulnerability and the performance goals selected by the *Decision-Maker*. The following publications provide useful information on common retrofit and upgrade strategies:

> ***FEMA-273 and FEMA-274: NEHRP Guidelines for Seismic Rehabilitation of Buildings and Commentary***,
>
> ***SSC 96-01: Seismic Evaluation and Retrofit of Concrete Buildings (California Seismic Safety Commission)***, and
>
> ***FEMA-172: NEHRP Handbook for Seismic Rehabilitation of Existing Buildings***.

The FEMA-273 and SSC 96-01 reports, though intended for design of seismic upgrades, also may be used for evaluation of probable building performance. However, these methodologies are quite detailed and are intended primarily for use in the upgrade design process. Generally, it will be more cost-effective to perform evaluations of probable seismic performance using the following publication:

> ***FEMA-310: Handbook for the Seismic Evaluation of Buildings – A Prestandard.***

FEMA-310 is a recent publication and supercedes FEMA-178 (also termed ATC-22), with which many engineers may be more familiar (see Appendix B). The FEMA-310 evaluation methodology is a two-tiered process, as shown in Figure 3-1. The Tier 1 evaluation process is shown in Figure 3-2 and consists of responding to a series of Basic Structural Checklists, one per building type. The Tier 2 process, if required, relies on more detailed structural analyses.

[1] rough order of magnitude or ROM is a term commonly employed in construction estimating (Means, 1996) to indicate preliminary or initial cost estimates, which have an accuracy of perhaps + or -20%. Note that ROM differs from the scientific term *order of magnitude*, which is a range of magnitude extending from some value to ten times that value.

It is important to emphasize to the engineer that the purpose of the analysis is to develop approximate estimates and schematic retrofit options. The engineer need not do detailed structural analyses or design of seismic retrofits. These steps will be undertaken only if the *Decision-Makers* choose to perform a retrofit.

The *Decision-Maker* should be aware that retrofit costs based on preliminary evaluations could be excessively low or high. If many facilities are being evaluated, this variation should not be a significant concern as, on the average, the estimated costs should be adequate. However, on an individual building or facility basis, costs estimated through rapid analyses can be substantially off. Detailed evaluations, such as those conducted in accordance with FEMA-273 or SSC96-01 should be performed early in the retrofit design process to confirm budget allocations and to allow any necessary adjustments to be made.

This step is for information purposes, not for the detailed preparation of design drawings. The level of effort to provide approximate analyses will vary, but may range from 24 to several hundred hours per facility.

Setting up a Building Assessment Task

Contract with a licensed structural engineer to complete Worksheet 4. One such worksheet is required for each facility whose FEMA-154 structural risk screening score (S) was 2.0 or less. For facilities with a building score greater than 2.0, but identified as having a nonstructural falling hazard, contract with a structural engineer to assess risk from the falling hazard only.

Provide the engineer with the soil report and structural drawings acquired in preparation for the building screening. If possible, provide the engineer with all the construction drawings, including architectural and mechanical drawings. Arrange for the engineer to have access to inspect the building. Ensure that the engineer understands the level of detail required.

The structural engineer will benefit from the assistance of a licensed geotechnical engineer. Hire one geotechnical engineer for all the building assessments, or allow the structural engineer to select the geotechnical engineer.

Compile Worksheet 4 from all building assessments after the assessment is complete. Use these in the benefit-cost analysis to follow in Chapter 4.

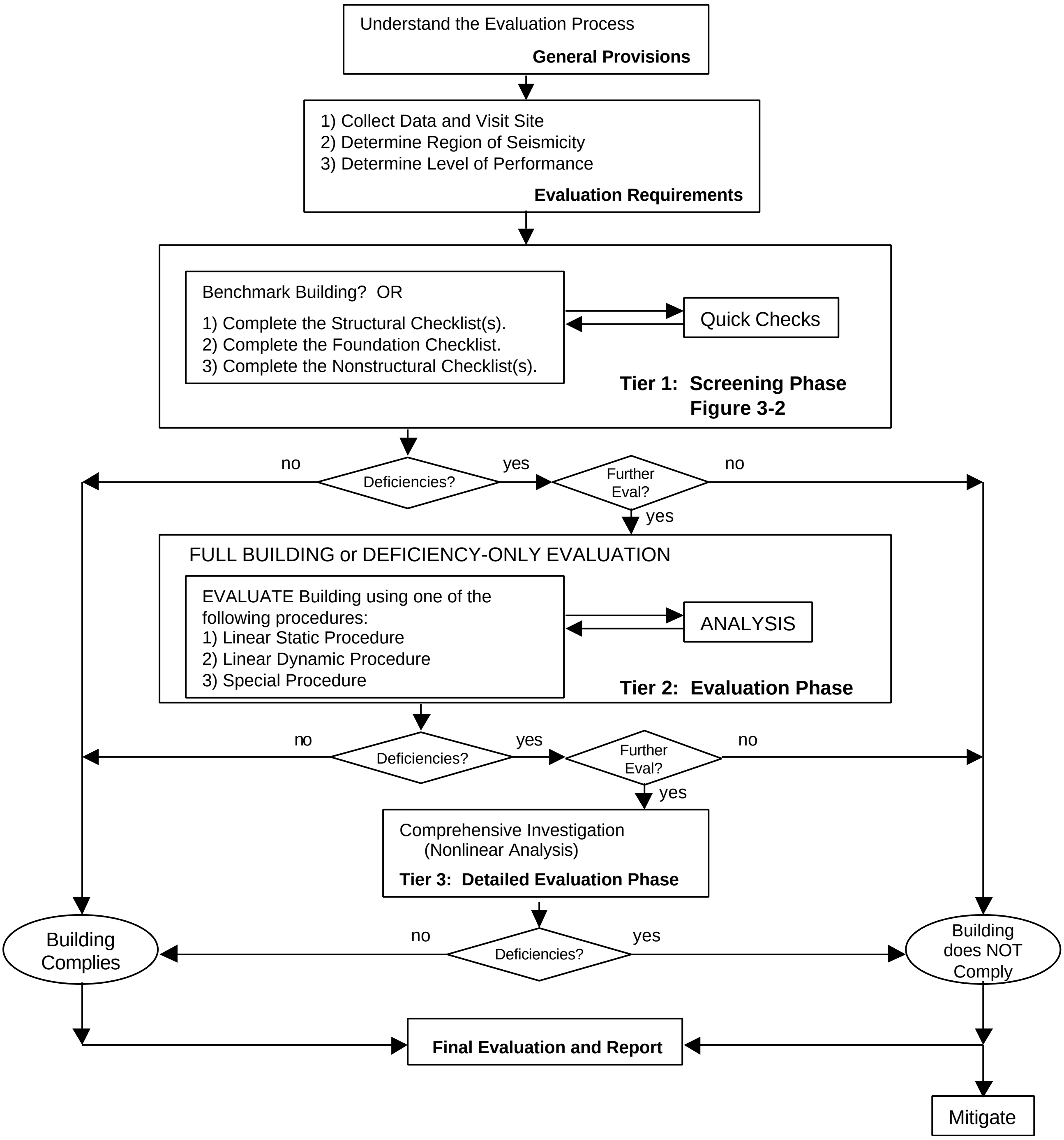


Figure 3-1: FEMA-310 Evaluation Process

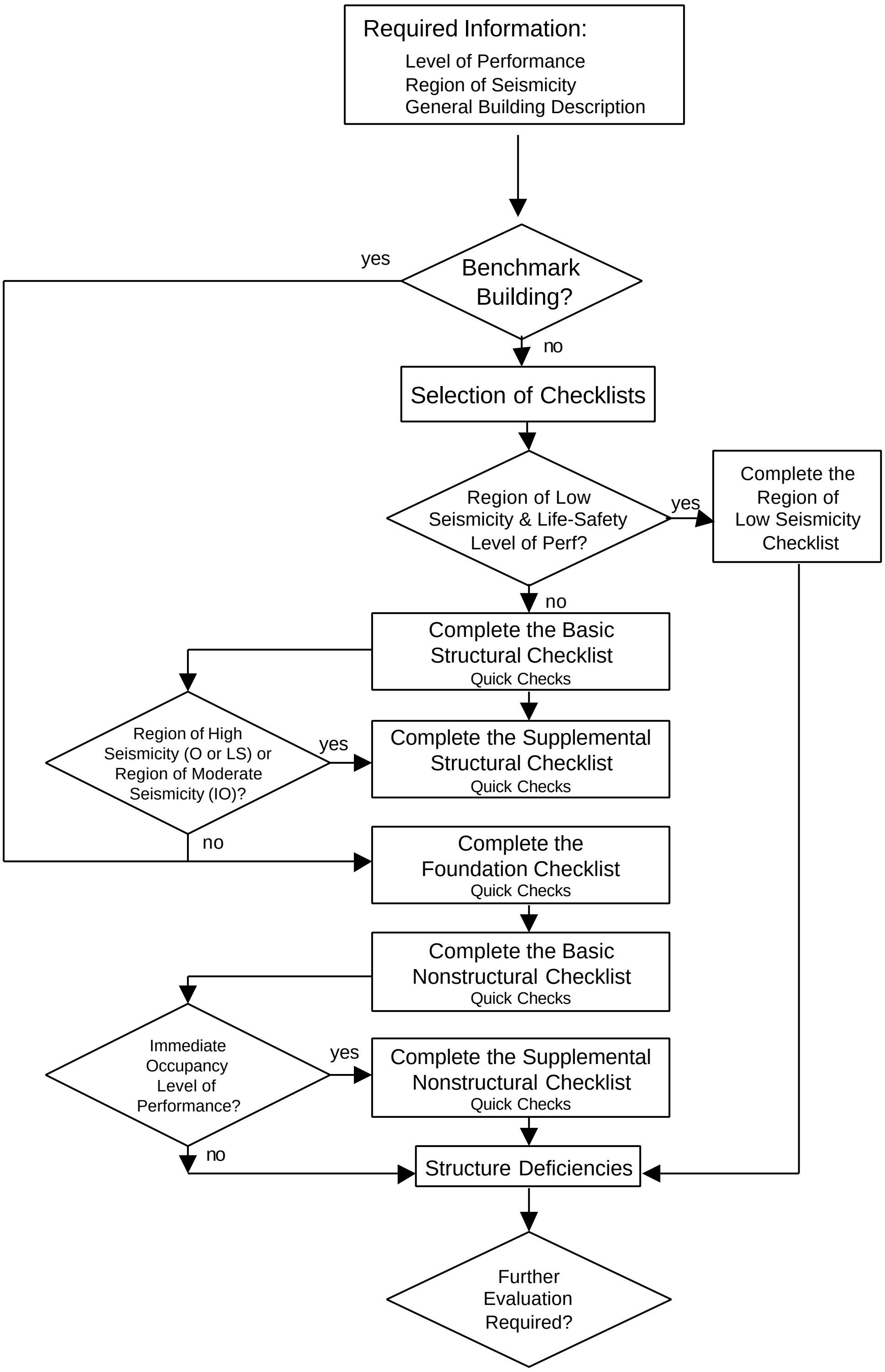


Figure 3-2: FEMA-310 Tier 1 Evaluation Process

Worksheet 4 – Building Assessment

Facility: ____ Date: __________

Engineer: ______________________________ Interest Rate Employed:__________

PRESENT VALUE OF RETROFIT COSTS

Retrofit Option	Best Estimate ($)	Contingency[1] ($)	Duration[2] (months)
Do Nothing (As-is Conditions)	-	-	
Option 1 (describe): ____________________			
Option 2 (describe): ____________________			
Option 3 (describe): ____________________			

[1] Contingency is an amount held in reserve to account for unforeseen conditions.

[2] Duration is an indication of the amount of time required to implement the retrofit.

LOSS ESTIMATES

Retrofit Option	Loss Item	MPE (500-Year)		LE (100-Year)	
		Best[3]	High[3]	Best	High
As-is Conditions	Repair Cost				
	Loss-of-Use[4]				
Option 1	Repair Cost				
	Loss-of-Use[3]				
Option 2	Repair Cost				
	Loss-of-Use[3]				
Option 3	Repair Cost				
	Loss-of-Use[3]				

[3] The “best” estimate is the engineer’s estimate of the most probable outcome. There should be roughly a 50% chance that the actual outcome would be either higher or lower than this estimate. The “high” estimate represents the engineer’s estimate associated with a high confidence of non-exceedance. Engineers familiar with the performance of Probable Maximum Loss estimates will associate this “high” estimate with a PML.

[4] Loss-of-Use is the duration (measured in days or months) of the time that the facility will not fulfill its normal function.

3.8 Equipment Screening

3.8.1 Purpose and Summary of Equipment Screening

Equipment screening determines whether there is a significant risk that the facility will be inoperative or pose a threat to life safety because of equipment failure. Similar to the process described above for building screening, this is done by calculating a risk score (typically ranging from 0.0 to 6.0). If the performance goal for *either* the *LE* or *MPE* is operational (O) or Immediately Occupiable (IO), one risk score is calculated for operational equipment, one for life-safety equipment. Otherwise, only life-safety equipment must be screened.

Operational equipment includes all components necessary to support normal operation of the facility. Life-safety equipment includes all components necessary to support life safety, as well as any components that would jeopardize life safety if they failed. For example, emergency lighting systems are considered life safety equipment because they are needed to protect people from injury when exiting a building. A cylinder containing flammable gas is also considered life safety equipment because, if it were to fail, it could cause a fire or explosion and jeopardize safety.

Each equipment system screened will be assigned a risk score by the equipment inspector. The *Risk Manager* must determine whether these scores are adequate, using the passing scores listed in Table 3-8.

Equipment systems with a failing score represent a significant risk of either operational or safety-related failure, and therefore should be subjected to a detailed evaluation of risk-mitigation measures.

The score sheets used for this process are analogous to those used in FEMA-154, and were developed as part of a new system-reliability assessment technique documented in:

> ***MCEER 99-0008: Seismic Reliability Assessment of Critical Facilities: A Handbook, Supporting Documentation, and Model Code Provisions.***

MCEER 99-008 is available from the Multidisciplinary Center for Earthquake Engineering (MCEER) at:

MCEER
Red Jacket Quadrangle
State University of New York at Buffalo
Buffalo NY, 14260, USA
Phone: (716) 645-3391
FAX: (716) 645-3399
http:\\mceer@buffalo.edu.

Table 3-8

PASSING SCORES FOR EQUIPMENT SCREENING[1]

Facility Occupancy	Life-safety Equipment		Operational Equipment	
	MPE	LE	MPE	LE
Emergency response or vulnerable population	4	3.5	3	2.5
All others	3	2.5	2	1.5

[1] Passing scores for the large event are documented in ***MCEER 98-0016: Appropriate Seismic Reliability for Critical Equipment Systems – Recommendations Based on Regional Analysis of Financial and Life Loss***. Passing scores for the moderate event are 0.5 lower than for the large event, based on the observation that typical equipment systems are 2 to 4 times less likely to fail in a 100-year earthquake than in a 475-year earthquake, equating with a logarithmic decrement of 0.5 in failure probability.

Setting up an Equipment Screening Task

If the equipment inspectors have not used the MCEER 99-0008 methodology before, arrange a training session. This is typically a 4- to 8-hour session and may require two days of an instructor's time. The training should be given by an earthquake engineer or a mechanical engineer experienced in using the methodology.

Find mechanical, electrical, and plumbing drawings as well as a geotechnical (or soils) report for each facility to be screened. If an outside engineer is to be used, arrange with an experienced facility engineer to assist and provide access. Provide these data to the equipment inspectors, along with a copy of the MCEER manual.

If the facility has a performance objective of operational (O) or immediate occupancy (IO) for either earthquake event, instruct the inspectors to screen the facility for both life-safety and operational equipment. Otherwise, instruct the inspectors to screen the facility only for life-safety equipment.

Compile screening records afterwards, along with all drawings. Identify facilities with any equipment system with a failing risk score. Instruct the same engineers to perform a detailed equipment assessment, as described in Section 3.9. If all scores are passing, the equipment may be left as-is.

Example: Equipment Screening

The city office building being screened houses personnel from the Parks and Recreation Department and the city Controller's Office. City policy for the *LE* (moderate earthquake) event is that this type of facility shall remain Operational (O). Policy for the *MPE* (large earthquake) event is that the facility remains Life Safe (LS).

The life-safety systems (fire detection and alarm equipment) within the building were screened and given a score of 3.3. The operational equipment score was 1.2. What do you do?

Solution:

Determine occupancy. First, the building does not house emergency personnel or vulnerable populations (schoolchildren, elderly) so occupancy in Table 3-8 is "All others."

Consider life-safety equipment. This system scored 3.3. It must be available in the large event, because policy for the large event is that the facility must remain life safe. A passing score for the large event is 3.0. So the life-safety equipment is adequate and may be left as-is.

Consider operational equipment. These need not remain available for the large event, since the large-event performance requirement is life safe only. But they must be available after the moderate-event, since the facility must remain operational after the moderate event. A passing score is 1.5 for operational equipment in ordinary-occupancy facilities in the moderate event. The operational equipment here scored 1.2, a failing score. The *Risk Manager* should therefore submit the operational equipment at this facility for detailed assessment, but allow the life-safety equipment to remain as-is.

3.8.2 Performing the Equipment Screening

The equipment reliability screening process has four steps: (1) identify critical equipment systems and components; (2) assess the reliability of individual components using score sheets; (3) assess system reliability using a modified fault tree analysis; and, if necessary, (4) perform risk management to improve system reliability to tolerable levels.

The following material summarizes these steps for the inspectors. It is copied here, with permission, from MCEER 99-0008, Chapter 2. A summary is provided for information purposes, but the inspector performing the equipment screening should use the complete methodology documented in the MCEER report.

Step 1: System and Component Identification

What You Will Do:	*Look at the services your facility needs to provide, which equipment items and support services are really necessary to provide that function, and how the various items are tied together.*
How You Will Do It:	*Use checklists to help identify critical systems and components. Sketch logic diagrams to illustrate how systems are tied together and where you have backup system and equipment components. [Sample checklists are presented in Figures 3-3 and 3-4. Sample logic diagrams for the entire facility, the life-safety system, and a fire detection and alarm sub-system are presented in Figures 3-5, 3-6, and 3-7, respectively.]*
What This Does For You:	*Identifies possible "weak links" in your system and ultimately helps to ensure fixes are limited to the most important items.*

A facility may have specific functionality requirements during or after an earthquake, as specified by federal law or federal, state, or local regulators. For example, hospital performance requirements for critical care may be specified in a state-issued license; data processing requirements for banks may be specified in federal law. In addition, a facility owner may determine that a function is essential if it is deemed financially important for continued operation or business recovery.

A critical system is one that is required to provide either (1) the essential facility function, as defined above, or (2) life-safety protection as required by other laws or regulations. A component of a critical system could be either a particular equipment item, a portion of a system such as piping or ducting, or a human action that is required to provide function of the critical system.

The handbook describes how critical systems and critical components can be identified for a facility. A method is provided for systematically reviewing important systems and the impact of their failure on each other. A means is provided to incorporate special considerations, such as emergency plans, personnel actions, and known maintenance problems.

Step 2: Assessment of Individual Components

What You Will Do:	*Assign "scores" to individual items indicating reliability to continue functioning after an earthquake. A higher score means more reliability.*
How You Will Do It:	*Do a mostly visual review of each component. Use data sheets in Handbook Appendix B to calculate scores. [A sample data sheet is presented in Figure 3-8.] You will review for all items on the data sheets, assigning scores applying rules in the Handbook.*
What This Does For You:	*Helps identify weaknesses in individual equipment items.*

The handbook presents a method for rapidly evaluating individual equipment components and incorporating those evaluations into a system evaluation. That method uses assessment techniques based on historical earthquake performance of similar equipment items. Assessments are made of specific items that have been known to be causes of damage in past earthquakes, or known to be seismically vulnerable for other reasons.

Score sheets are provided for individual components, and a method for assigning scores is presented, based on the design and installation of the component, the location within a building and geographically, and other factors. Higher scores indicate higher seismic reliability.

Step 3: Assessment of System Reliability

What You Will Do:	*Assign "scores" to systems and the entire facility indicating reliability to continue functioning after an earthquake. A higher score means more reliability.*
How You Will Do It:	*Use the score from Step 2 with the graphical description of the system from Step 1. A set of simple rules to calculate the score is provided.*
What This Does For You:	*Provides the information you need to make decisions on what changes will increase reliability.*

This handbook provides a method for rapidly, but systematically evaluating the reliability of critical systems in an earthquake. A system scoring system is provided to quantify the relative reliability of systems and components. This method can be used by an individual to identify and prioritize vulnerabilities on a system and facility basis.

For each of the major systems identified, a system evaluation should be performed. The methodology described in this handbook makes use of the system and component information developed for each system and the scores for individual components.

Step 4: Risk Management

What You Will Do:	*Make decisions about actual system modifications, more detailed analyses, or other steps to take (e.g., emergency plans) to increase the reliability of your facility operating following an earthquake.*
How You Will Do It:	*Use the results from Steps 1, 2, and 3. Review how scores may change if certain steps are taken.*
What This Does For You:	*This is the reason for doing the entire assessment: to make sure that money spent for risk reduction is being put to its best use. This gives you a basis for deciding on various options, such as structural modifications, system changes, operational or procedural changes, or other reasonable ways of reducing risk.*

The results of the screening provide a basis for making risk management decisions. The review of critical electrical and mechanical systems and their components provides the information necessary to create a specific plan for improving a facility's post-earthquake functionality.

The component and system evaluations described in this recommended practice are part of a screening assessment. It highlights important system components, their interactions, and their impact on system function. It is not the only indicator of where upgrades or repairs should be made, but it provides a consistent method for identifying obvious vulnerabilities and prioritizing risk management implementation.

Mitigation is not limited to physical repairs to equipment or systems, but can be achieved through upgrades, analyses, and emergency response procedures. All mitigation efforts as defined in this handbook are intended to improve overall system reliability.

Critical Systems Identification List (Extract)

System / Sub-System	Life Safety	Business Operations	Not Critical	Not Applicable
Fire Response:	☐	☐	☐	☐
Requirements of system: ________				
Sub-Systems:				
Detection and alarm	☐	☐	☐	☐
Suppression	☐	☐	☐	☐
Air duct fire and smoke barriers	☐	☐	☐	☐
Smoke purge	☐	☐	☐	☐
Other: ________	☐	☐	☐	☐
________	☐	☐	☐	☐
Gas Shutoff:	☐	☐	☐	☐
Requirements of system: ________				
Sub-Systems:				
Other: ________	☐	☐	☐	☐
________	☐	☐	☐	☐
Elevator Safety:	☐	☐	☐	☐
Requirements of system: ________				
Sub-Systems:				
Detection/control	☐	☐	☐	☐
Other: ________	☐	☐	☐	☐
________	☐	☐	☐	☐
________	☐	☐	☐	☐
Building/Evacuation Egress:	☐	☐	☐	☐
Requirements of system: ________				
Sub-Systems:				
Alarm/indication	☐	☐	☐	☐
Available routes	☐	☐	☐	☐
Other: ________	☐	☐	☐	☐
________	☐	☐	☐	☐

Figure 3-3: Extract of MCEER 99-0008 Critical Systems Identification Checklist

Critical System Component ID Worksheet (Extract)

SYSTEM: FIRE RESPONSE

Description: ______________________________

SUB-SYSTEM: Detection And Alarm

	Criticality (circle one) E-essential R-redundant N-non-essential			Redundant Component List redundant item number	Support System Required List function (i.e., power, cooling water, etc.)
A. Detection					
A.1 Area/Spot Smoke Detectors	E	R	N	______	______
A.2 Line Smoke Detectors	E	R	N	______	______
A.3 HVAC/Plenum Smoke Detectors	E	R	N	______	______
A.4 Heat Detectors	E	R	N	______	______
A.5 Sprinkler Flow Sensors	E	R	N	______	______
A.6 Pull Stations	E	R	N	______	______
A.7 Other (define)______	E	R	N	______	______
B. Alarms					
B.1 Bell/Siren Alarms	E	R	N	______	______
B.2 Speakers	E	R	N	______	______
B.3 Strobe Lights	E	R	N	______	______
B.4 Remote Alarm Monitors (specify)	E	R	N	______	______
B.5 Other (define)______	E	R	N	______	______
C. Detection/Alarm Interface					
C.1 Computer System	E	R	N	______	______
C.2 Fire Communication Center	E	R	N	______	______
C.3 Alarm Panel(s)	E	R	N	______	______
C.4 Cabling/Conduit	E	R	N	______	______
C.5 Other (define)______	E	R	N	______	______

D. General Items

D.1 Is operator intervention required for operation of any of the above equipment? Y N
If yes, is the area expected to be accessible?

____

(Note: if the area is not accessible, equipment requiring manual operation should not be credited.)

D.2 Based on experience, has any of the identified equipment required an above average amount of maintenance or been inoperable or degraded for a significant amount of time due to failures? Y N
If yes, explain:

____

(Note: if the equipment is highly unreliable, it should not be credited except as a possible redundancy.)

Figure 3-4: Extract of MCEER 99-0008 Critical System Component ID Worksheet

KEY		
SYMBOL	NAME	MEANING
	AND GATE	Component above gate functions if all components below function
	OR GATE	Component above gate functions if any component below functions

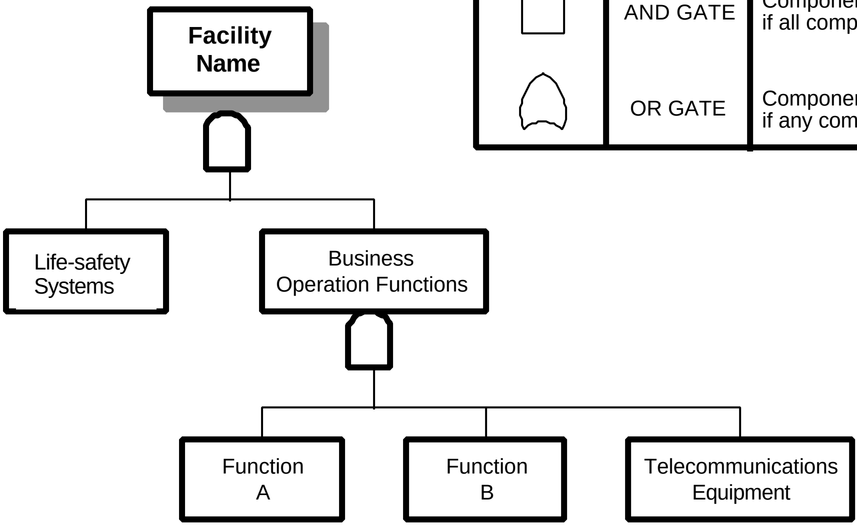


Figure 3-5: Facility Logic Model

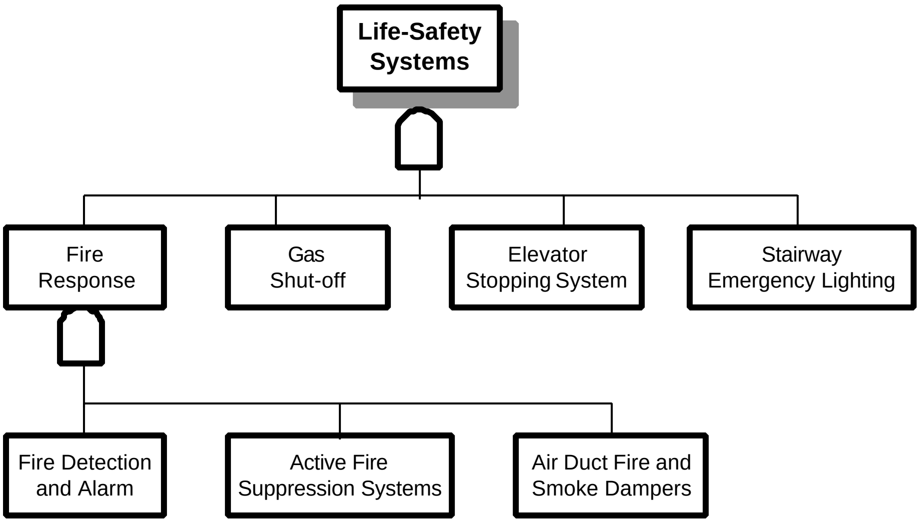


Figure 3-6: Life-safety System Logic Model

KEY		
SYMBOL	NAME	MEANING
	AND GATE	Component above gate functions if all components below function
	OR GATE	Component above gate functions if any component below functions

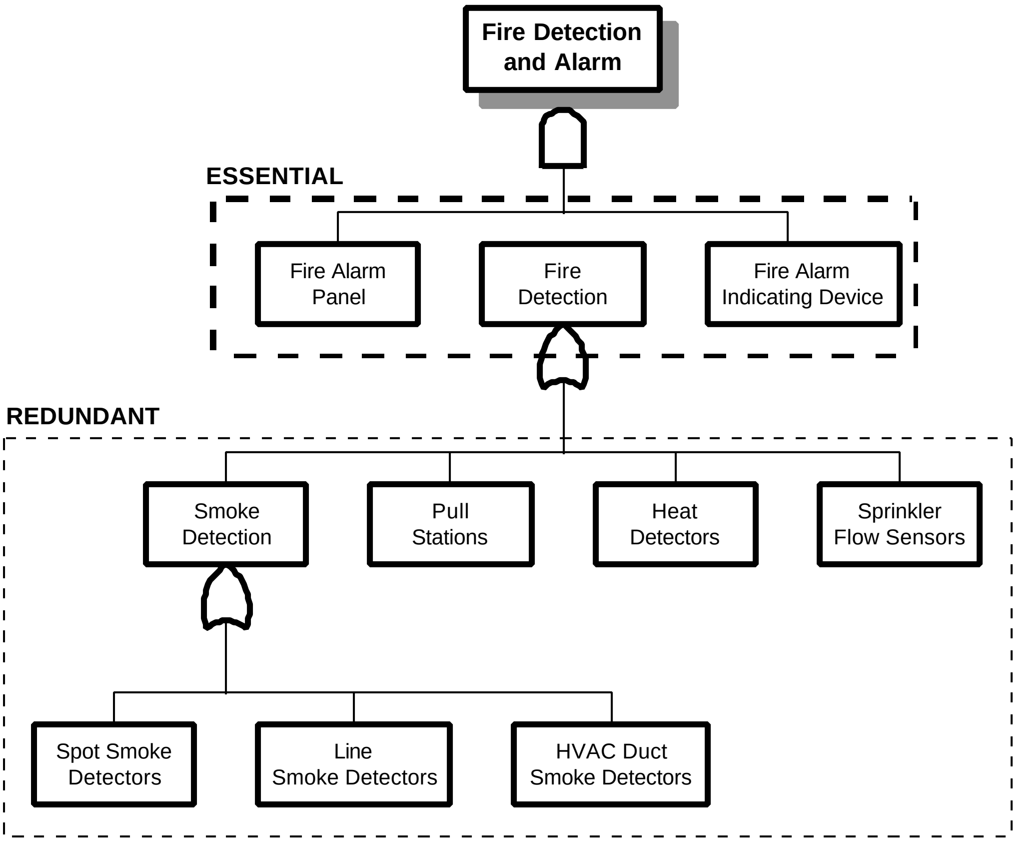


Figure 3-7: Fire Detection and Alarm Sub-system Logic Model

Batteries and Racks

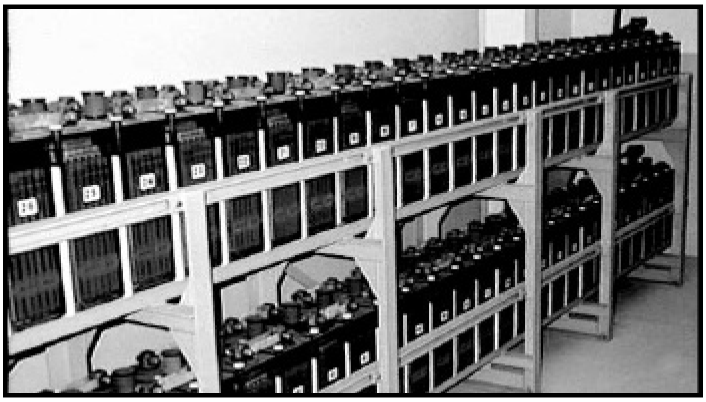
Component ID:

____

Location:

____

____



Comments:

____

____

Earthquake Load Level (circle one letter)

			Location in Building		
	NEHRP	**UBC**	**Bottom Third**	**Middle Third**	**Top Third**
Z	1-3	1	A	A	A
O	4-5	2	A	B	C
N	6	3	B	C	D
E	7	4	C	D	E

Scores and Modifiers - Batteries and Racks

(circle a Basic Score and **all** PMFs that apply - use the column indicated by the Earthquake Load Level above)

	Description	**A**	**B**	**C**	**D**	**E**
	Basic Score →	5.3	4.4	3.9	3.5	3.2
	1. No anchorage	1.5	1.5	1.5	1.5	1.5
	2. "Poor" anchorage	1.3	1.3	1.3	1.3	1.3
P	3. No battery spacers	0.7	0.7	0.7	0.7	0.7
M	4. No cross-bracing	0.9	0.9	0.9	0.9	0.9
F	5. No battery restraints	2.0	2.0	2.0	2.0	2.0
	6. Interaction concerns	0.5	0.5	0.5	0.5	0.5
	7. Other:______________________					
	Final Score = Basic Score – **highest applicable** PMF					

Note that this is a screening process and is inherently conservative. If there is any question about an item, note it and select the appropriate PMF. See the following page for PMF guidelines.

Figure 3-8: Sample MCEER 99-0008 Component Scoresheet: Batteries and Racks

Explanation of Performance Modification Factors (PMFs)

1, 2 If there are no anchor bolts at the base of the frame, select PMF 1. If the anchors appear to be undersized, if there are not anchors for every frame of the rack, or if the anchorage appears to be damaged, select PMF 2.

3 Look for stiff spacers, such as Styrofoam, between the batteries that fit snugly to prevent battery pounding. If there are none, select PMF 3.

4 The rack should provide restraints to assure that the batteries will not fall off. The photo above shows a rack with no restraints, while the photo to the left shows a rack with restraints. Select PMF 4 if adequate restraint is not provided.

5 Racks with long rows of batteries need to be braced longitudinally as shown in the photo to the left. Select PMF 5 if no cross-bracing is present.

6 If large items such as non-structural walls could fall and impact the battery racks, select PMF 6.

7 For other conditions that the reviewer believes could inhibit battery function following an earthquake (e.g., a history of problems with this piece of equipment), assign a PMF value relative to the existing PMFs in the table. Add a descriptive statement for the concern.

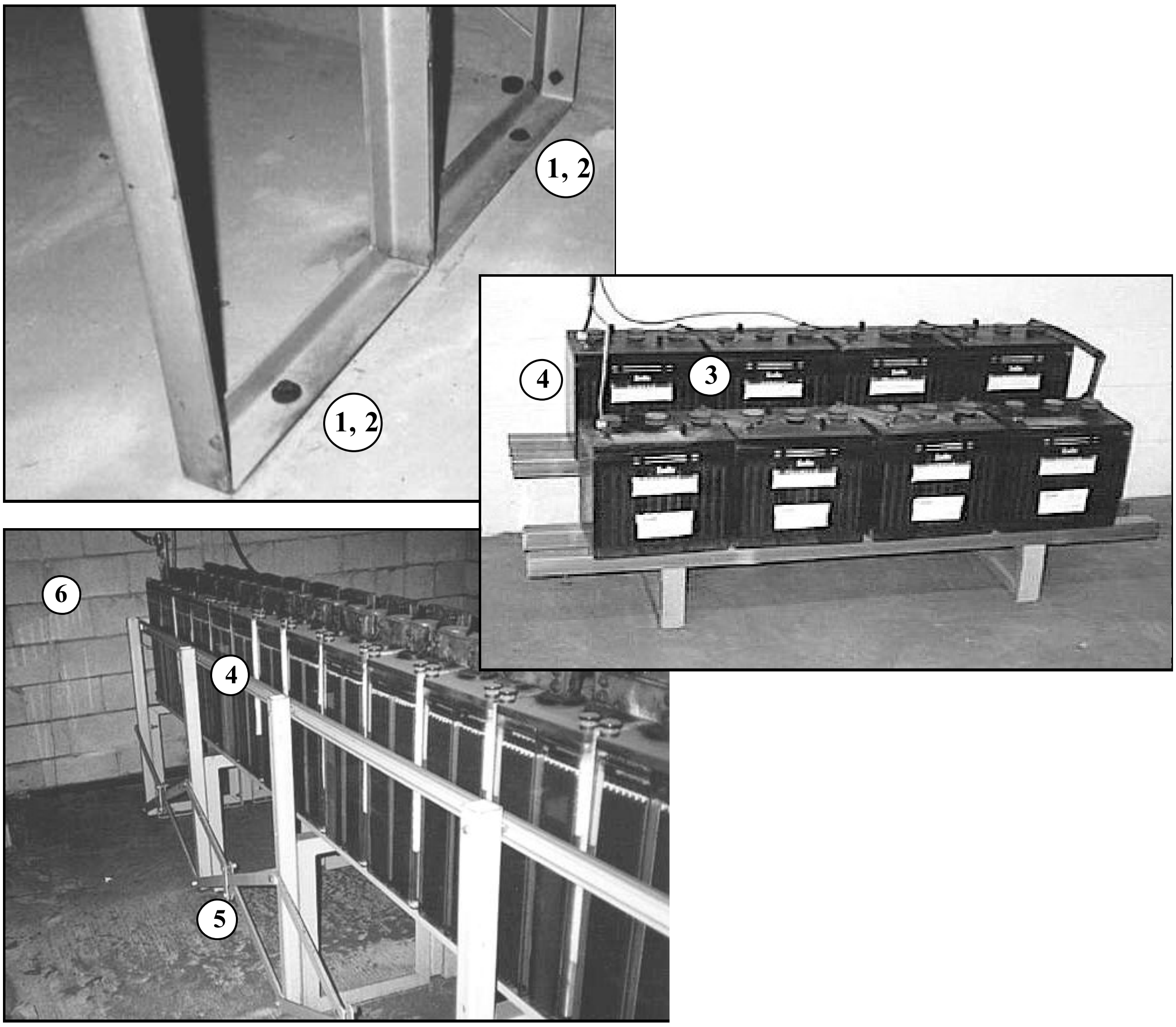


Figure 3-8 (continued): Sample MCEER 99-0008 Component Scoresheet: Batteries and Racks

3.9 Equipment Assessment

Facilities with equipment systems that received a failing MCEER risk score represent potential operational failure or risks to life-safety. All such equipment systems should be examined to estimate the failure probabilities and losses under the *MPE* and *LE* events, as well as to identify mitigation alternatives.

The equipment inspector (EI) should propose various retrofit alternatives, such as those detailed in MCEER 99-0008, and reevaluate the probability of system failure under the various mitigation alternatives. The inspector should estimate the cost to implement the mitigation measures, as well as any associated downtime.

The precise data required are listed in Worksheet 5. The equipment inspector should only fill out rows labeled "*By EI*" in the right-hand column. Other rows will be filled in by the *Asset Manager* and *Financial Manager* as described below.

It is important for the equipment inspector to keep in mind that the analysis needs only develop approximate estimates and schematic retrofit options. The inspector need not prepare detailed design of seismic retrofits. These steps will be undertaken only if the *Decision-Maker* chooses to perform a retrofit.

The level of effort to provide approximate analyses will vary, but may range from $2,500 to $20,000 per facility, depending on complexity.

Risk Manager: What You Should Do

Ask the equipment inspector (EI) to examine equipment systems that failed the screening score. The EI should estimate the cost to repair the damaged equipment as well as the duration of loss of use, assuming failure occurs. The EI should also propose one or more mitigation options that reduce the system risk scores to acceptable levels depending on the earthquake event considered. The costs to implement these options should also be provided. The EI's estimates should be recorded in Worksheet 5. Use one Worksheet 5 form per facility per system examined.

Compile Worksheet 5 forms from each equipment system reviewed. Pass life-safety equipment assessment forms to the life-safety operational expert (LSOE) or *Asset Manager* for loss-of-use assessment. Pass BI equipment assessment forms to the *Financial Manager*. Loss-of-use assessments are described further in Section 3-10.

Worksheet 5 – Equipment Assessment

Equipment System: ______________________ Type (circle one): Damage / Life-safety / BI

Inspector: ______________________________ Date: ______________________

Mitigation Option	Risk Score *S*	Best Estimate	High Estimate	
As-is (do nothing):		-	-	*By EI*
Option 1:				*By EI*
Option 2:				*By EI*

Loss-of-use Costs for Failure (from Worksheet 6)

UGF (1 hr)______ *UGF* (1 week)_______ *UGF* (1 day)_______ *UGF* (1 month)______

Case	Loss Items	MPE (500-year)	LE (100-year)	
As-is	Repair Cost, *R* (Best $ Estimate):			*By EI*
	Duration Units (circle one):	hour day week month	hour day week month	*By EI*
	Loss-of-Use Duration, *LUD:*			*By EI*
	Loss-of-Use Cost (Given Failure), *UGF:*			
	Loss-of-Use Cost, $U = 10^{-S} \times UGF$:			
Opt. 1	Repair Cost, *R* (Best $ Estimate):			*By EI*
	Duration Units (circle one):	hour day week month	hour day week month	*By EI*
	Loss-of-Use Duration, *LUD:*			*By EI*
	Loss-of-Use Cost (Given Failure), *UGF:*			
	Loss-of-Use Cost, $U = 10^{-S} \times UGF$:			
Opt. 2	Repair Cost, *R* (Best $ Estimate):			*By EI*
	Duration Units (circle one):	hour day week month	hour day week month	*By EI*
	Loss-of-Use Duration, *LUD:*			*By EI*
	Loss-of-Use Cost (Given Failure), *UGF:*			
	Loss-of-Use Cost, $U = 10^{-S} \times UGF$:			

Maximum repair cost R_{max} (from *Risk Manager* or *Asset Manager*): $__________________

3.10 Loss-of-Use Assessment

Operational failure can result in financial losses; in the insurance industry, this is termed Business Interruption, or BI. This section addresses the estimation of financial operational risk, or BI.

3.10.1 Financial Operational Assessment

Complete one Worksheet 6 for each facility. This worksheet should be filled out by the *Financial Manager***.** The *Financial Manager* must estimate the cost associated with losing the use of each facility for various periods of time.

These time periods, or "durations," should be estimated by the engineers who perform the building and equipment assessments and can be obtained from Worksheets 4 and 5. Rather than providing these individual estimates, it may be easier for the *Financial Manager* to estimate losses for operational interruptions of one hour, one day, one week, and one month. The *Risk Manager* can then develop appropriate estimates for the actual period of interruption estimated by the engineers using this data. Worksheet 6 provides a line for tabulating these estimates.

The costs associated with loss of use will vary by the type of facility under consideration. A school, for example, will have loss-of-use costs associated with renting temporary facilities and moving computers and administrative supplies to the temporary facilities and back again. Total loss should be the sum of all potential sources of financial loss. Typical financial losses include the following:

U_1 = Difference in rent between damaged facility and temporary (or new) facility

U_2 = Moving expenses to and from temporary facilities

U_3 = Lost productivity during moves

U_4 = Lost profit associated with outsourcing services or manufacturing previously done in-house

U_5 = Lost profit from temporary loss of market share

U_6 = Extra costs to regain market share (e.g., extra advertising and overtime costs)

In addition to the losses associated with arbitrary interruption periods, the *Financial Manager* should also determine the maximum loss-of-use cost, U_{max}. This is the cost associated with permanent loss of the facility.

Complete Worksheet 6 for each facility with performance goals of O or IO for either the *MPE* or *LE events*. Transfer the totals from each Worksheet 6 to the corresponding Worksheet 5. For each loss-of-use duration in Worksheet 5, note the total average loss costs resulting from that duration, in the field marked *Loss-of-Use Cost (Given Failure), UGF.* For each retrofit option, calculate the loss-of-use cost for the *MPE* and for the *LE* events.

$$\text{Expected loss-of-use cost} = 10^{-S} \cdot UGF$$

Where S is the risk score obtained from the equipment or building evaluation methodologies (i.e., FEMA-154 or the MCEER 99-0008), see the Example: Loss-of-Use Calculation sidebar.

Example: Loss-of-Use Calculation

From Worksheet 6, the sum of the dollar costs resulting from the facility being out of operation for a week is found to be UGF = $100,000 (e.g., from lost production).

From the MCEER methodology, suppose that only one equipment item is found to be vulnerable to earthquake damage – the main electrical transformer for the plant, which is unbolted to its foundation pad (the As-Is condition). Due to the lack of anchorage, it is determined that this transformer will slide and be damaged, with a score S=1.5. Under a large earthquake, it is determined that a replacement transformer will require one week to be located and installed. Therefore, the LUD = 1 week. Repair Cost, R, for the transformer (i.e., replacement) = $20,000. Therefore, the Loss-of-Use Cost, U, is:

U = $10^{-1.5}$ x ($100,000 + $20,000 = $120,000) = $3,795.

Mitigation Option 1 is to have maintenance personnel shut down the transformer on a Saturday (overtime is involved) and bolt the transformer down. Materials are a negligible cost item, and the labor for two mechanics to work one-day overtime is $480 per person, or a total of about $1,000.

Mitigation Option 2 is to insure for the damage and/or BI. The insurance company offers an insurance policy for BI due to loss-of-power from *any* cause (including earthquake), with a one-day deductible and a premium for this plant of $2,000 per year. If the postulated earthquake occurs, the losses due to the transformer damage would therefore be $20,000 replacement + $20,000 (the one-day deductible, taken as 20% of the week's lost production), or $40,000. Given the same time-discount as above (i.e., 3.795/120 = 0.0316), the expected value of the uninsured loss is $1,265.

The plant risk manager discusses electrical utility response in recent earthquakes, with his electric utility account executive, and is informed that only parts of Los Angeles or San Francisco lost power for more than a day, in recent earthquakes such as the 1994 Northridge or 1989 Loma Prieta events.

Based on a comparison of the expected costs:

As-is: $3,795 weighted average of no earthquake and earthquake occurs
$0 if no earthquake
$120,000 loss if an earthquake

Option 1: $1,000, with no risk due to earthquake

Option 2: $2,000 per year for insurance + $1,265 weighted average of EQ / no EQ
$40,000 loss if an earthquake
(but also covered for loss of power due to other reasons than earthquake)

The risk manager decides for Option 1.

Worksheet 6 – Loss-of-Use by Facility

Expert(s): ____ Date: ___________

Facility: ____

Financial Manager: Provide best estimates of dollar costs resulting from this facility being out of operation for various durations. Assume the building is safe to enter to remove documents and equipment, but elevators, electric power, water, etc., are unavailable. Total UGF = sum of column

$ Units (circle one) = dollars / hundreds / thousands / millions

	Loss-of-Use Duration			
Cost Item	**1 hour**	**1 day**	**1 week**	**1 month**
Extra Rent:	0	0		
Movers:	0	0		
Production Losses:				
Outsourcing Costs:	0			
Loss of Market Share:	0	0		
Extra Marketing:	0	0		
Overtime:	0	0		
Other:_______________				
Total *UGF*				

3.11 Alternatives

Mitigation Alternatives were summarized in Chapter 2 and are discussed in detail in Appendix D. They can be broadly categorized as:

- **Buildings** can be *strengthened* with the addition of braced frames or shear walls. Additionally, building seismic vulnerability can be enhanced by *mass-reduction,* that is, reducing weight by removing a few top floors, replacing a heavy roof slab with light-weight concrete, moving heavy equipment from the roof to the basement, or by introducing an atrium into a few upper floors. Techniques attractive when continued operation is required following a large earthquake include *base-isolation* (which introduces compliant bearings beneath the building columns, allowing the building to displace without damage), and *energy dissipation systems* (which function akin to automobile shock absorbers in dissipating the energy imparted to a building during a large earthquake).

- **Equipment** can also be strengthened or braced in a variety of ways, which in many cases is very cost-effective. Often, this is simply a matter of bolting the equipment to a floor or wall.

- **Emergency planning** is a recommended practice, even when buildings and equipment have been mitigated, since unforeseen circumstances can always arise, for which it is wise to be prepared.

- **Insurance** purchase is also a recommended practice. However, bear in mind that insurance is only a financial risk transfer mechanism; it does not protect lives. Significant risk is often most cost-effectively mitigated by strengthening or otherwise improving structures and equipment against earthquake effects. Employment of insurance is for the *residual risk* – the damage accepted by the *Decision-Maker* after going through the process outlined in this chapter.

3.12 Baseline Risk

The previous sections have presented methods for screening and focusing on the greatest contributors to earthquake risk. Several points are worth noting here:

- The **total earthquake risk** for a community or organization is the aggregate of the constituent elements. That is, the total lives which may be lost is approximately equal to the summation of the lives lost in all the buildings, in all the fires, and in all the hazardous materials spills. Similarly, the total financial impact of an earthquake will be the summation of the total repair costs of all the facilities, plus the total value of disrupted economic activity, due to all causes traceable to the earthquake. Note that "double-counting" should not occur; the expected loss due to shaking should not be added to the expected loss due to fire following earthquake, for the same facility.[2]

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[2] In the insurance industry, this is known as 'burning the rubble.'

- There is uncertainty associated with each estimate of lives lost, cost of repair, or other estimates of loss. This uncertainty should be taken into account in determining the total losses due to an earthquake. The rigorous mathematical procedures for needed to do this are beyond the scope of this *toolkit*, and we simply note that they exist and should be employed. The *Risk Manager* and *Decision-Maker* should be aware that uncertainty exists and there are methods for dealing with it (e.g., Benjamin and Cornell, 1970; Ang and Tang, 1975). They should require a proper treatment and accounting of uncertainty, by the specialists involved.

- Losses can be estimated on either a *scenario*, or *annualized*, basis. This is an important point, and the distinction should be clearly understood:

- *Scenario* losses are those that accrue due to a specific event, such as a magnitude 7 earthquake on the San Andreas fault. Scenario losses are valid for a given event only, and are independent of the probability of that event.

- *Annualized* accrue on a probabilistic basis from all possible events that can occur, taking into account the probability for each of these events in a given year. Annualized losses are expressed as the average losses expected per year, taken over a period of many years. In insurance terms, annualized losses are the pure premium, that is, they are the approximate equivalent of the insurance premium, before it is loaded with insurance company overhead, profit, taxes and other expenses. For an organization that elects to self-insure, the annualized loss is the amount of money that should be set aside, on an annual basis, to cover losses that will eventually occur.

- In decision-making, both scenario and annualized losses should be considered. The *Decision-Maker* should grasp what losses may result from a specific large earthquake event (i.e., the scenario loss), and the loss cost per year of earthquakes (i.e., the annualized loss). The *Decision-Maker* can compare scenario losses against the maximum tolerable loss, and can compare annualized losses against other losses, such as the number of persons killed in automobile accidents, or the annual expected losses due to fire.

- The uncertainty associated with all these losses should be taken into account. Not only should the mean (i.e., 'average') or median (i.e., 50th percentile) losses be reported and considered, but so also should upper fractiles, such as the 90th percentile loss (that is, the loss which has a 10% probability of being exceeded). This consideration of upper fractiles can get very complex, and difficult to understand for the *Decision-Maker* and the lay person. Examples include:

1. *90th percentile scenario loss*--equal to the loss for the scenario event which will not be exceeded with 10% probability (can be thought of as the loss which will not be exceeded for 9 out of 10 repetitions of the same scenario event, all else being equal).

2. *90th percentile annualized loss*--equal to the annualized loss which will not be exceeded with 10% probability (can be thought of as the loss which will not be exceeded for 9 out of 10 years, all else being equal).

3. *90th percentile loss in 50 years*--equal to the loss which will not be exceeded with 10% probability in 50 years (can be thought of as the loss expected to occur about once in 500 years, all else being equal).[3]

3.13 Summary

This chapter has summarized methodologies for assessing earthquake risk and alternatives.

- **Identify the Assets at Risk** – from a *Decision-Maker's* viewpoint, this is property and lives for which the *Decision-Maker* is responsible. Section 3-2 tabulated a broad spectrum of assets at risk, for both the private and public sectors.

- **Determine Acceptable Risk** – this consists of making some initial policy and strategic decisions concerning the required level of seismic reliability for various classes of facilities, and determining whether the programs for mitigation are going to be mandated or voluntary.

- **Data Collection** – once the assets at risk have been identified, and certain basic decisions made, collect data on all the facilities. This is a basic step in earthquake risk management, and it can be a costly effort. Mitigating the data collection cost is the recognition that the data, once collected and if maintained, can form the basis for efficient facility management.

- **Building and Equipment Screening** – to examine everything in detail is expensive and not necessary. Therefore, screening methods have been developed for buildings and equipment which can be employed to quickly focus on the greatest risks.

- **Building Assessment** – FEMA-310 provides a standard methodology for examining those buildings that pose a significant risk.

- **Loss-of-Use Assessment** – Loss of use is an important element of earthquake risk, leading to loss of revenues and potentially even loss of life, as in

[3] If a poisson model is assumed, the annual probability of exceedance for this case is 1/475 per annum, and this is more accurately referred to as the '475' year loss, rather than the '500' year loss, to which it is sometimes rounded for lay persons.

the case of a hospital rendered inoperable. Therefore, it is vital to assess loss of use due to structural and equipment deficiencies. There is no standardized methodology for this, but an approach has been provided in this chapter. Since loss of use is so critical to the overall operations of an organization or community, this assessment should be performed by a team comprised of seismic experts and persons familiar with the specific operations of the organization or community.

Following these steps should provide a good assessment of the risk to an organization or community, including the constituent elements of the risk. This chapter has not dwelt on the details of the many possible mitigation alternatives, since they are very numerous and really best identified by technical specialists. Nevertheless, as the constituents of risk are identified and assessed, many mitigation alternatives will become readily apparent. Choosing among them is the subject of the next chapter.

Primary Interest:
Risk Managers

Secondary Interest:
Decision-Makers

4. Deciding What To Do

4.1 Introduction

In the previous section, we presented methods for determining the *baseline risk;* the risk under existing or as-is conditions. The decision about whether that risk is acceptable should be based on two fundamental criteria:

- What loss would be tolerable, should it occur?, and
- How easy (i.e., at what cost) would it be to reduce the loss?

In general, significant risk of structural collapse[1] is not tolerable in California today. In that sense, some aspects of the decision-making may be easy: if the baseline risk assessment indicates likely collapse or other significant risk to life-safety, then that risk must be reduced. The problem we discuss here is how to determine an appropriate program of mitigation beyond protection of life safety. This chapter provides an overview of the many methods available for making that decision[2].

4.1.1 Maximization (benefit-cost) or Minimization (total cost)

The most common decision method is maximization, which forms the core of the well-known benefit-cost method. With this method, the *Decision-Maker* quantifies the net benefits of each alternative method (i.e., benefit minus cost associated with the alternative, where the benefit is the reduced loss), and selects that alternative that has the maximum net benefit.

The corollary of this is the minimization of the total cost, where the total cost is the expected loss plus the cost of mitigation. This is shown in Figure 4-1, where Point A is the least total cost. (Note that Point A does not necessarily correspond to Point B, the crossing of the expected loss curve with the mitigation cost curve.)

In order to apply these rules, each alternative must be associated with a single value that represents benefits. When uncertainty is ignored, applying the maximization rule is straightforward and expresses the *Decision-Maker's* simple desire for more of a good thing.

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[1] Or other risks to life-safety, such as major releases of hazardous materials in an earthquake.

[2] See Dames & Moore, 1994 or AIChE, 1995 for excellent discussions of the available methods.

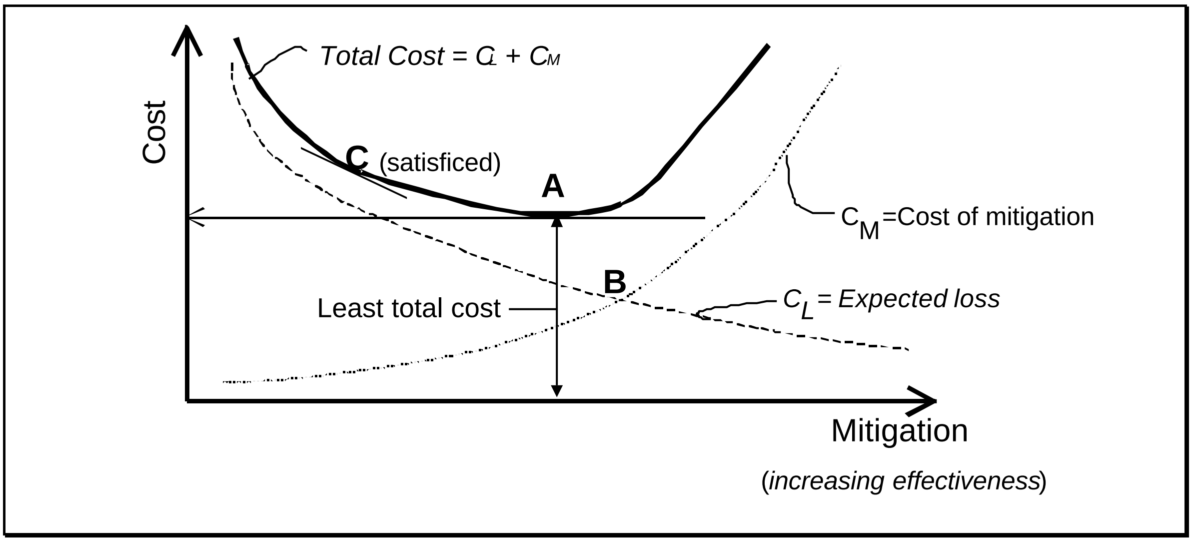

Figure 4-1: Typical Cost of Mitigation Curve

When considering uncertainty, the usual procedure for applying the maximization rule is to determine the likelihood of the possible outcomes of an alternative, and compute an expected value for each alternative. The expected value is the weighted sum of values for each possible outcome, with the weights determined by the likelihood (probability) of these outcomes.

In order to apply these rules, each alternative must be associated with a single value that represents benefits. When uncertainty is ignored, applying the maximization rule is straightforward and expresses the *Decision-Maker's* simple desire for more of a good thing. When considering uncertainty, the usual procedure for applying the maximization rule is to determine the likelihood of the possible outcomes of an alternative, and compute an expected value for each alternative. The expected value is the weighted sum of values for each possible outcome, with the weights determined by the likelihood (probability) of these outcomes.

4.1.2 Maximin and Maximax

Another common decision rule is the maximin rule ("maximize the minimum"). It can be applied in situations where multiple outcomes are possible, but with likelihoods that are not known. Using this rule, the *Decision-Maker* takes each decision and associates it with the value resulting from the worst possible outcome under that alternative. The alternative that provides for the highest value under its worst possible outcome is selected. The maximin rule is truly a pessimist's rule, for it ensures that the *Decision-Maker* avoids choosing alternatives that could lead to the worst possible outcomes, even if these alternatives could yield attractive outcomes as well.

The opposite approach is the maximax rule ("maximize the maximum"). Using this rule, the *Decision-Maker* selects the alternative whose return under the most favorable circumstances is the greatest. In this case, the *Decision-Maker* is "going for broke" by ignoring all possible downsides to each alternative, and focusing only on the possible benefits (AIChE, 1995).

4.1.3 Minimum Regret

After a loss, a *Decision-Maker* may be criticized by others for having selected an inappropriate alternative on the grounds that a different one would have led to a better outcome under the circumstances. For example, a plant manager chooses to delay seismic retrofit due to its high cost and a judgment that there is an extremely small chance of a major earthquake in the next five years. An earthquake occurs soon after this decision, and causes a 30-day interruption of operations. Though the decision was in fact a wise one given the decision maker's understanding of the costs and risks, the plant manager is criticized for not choosing the alternative that would have yielded the best outcome. The regret rule minimizes the risk to the *Decision-Maker* of being confronted in hindsight. For each possible future scenario, the *Decision-Maker* assesses the difference in value between each alternative and the best alternative if the scenario were to occur. This difference is referred to as the "regret." Regret represents the "cost" of not having perfect foresight and selecting the best decision. This rule applies a minimax rule, selecting the decision in which the maximum regret is the least.

4.1.4 Minimum Uncertainty

Most *Decision-Makers* are risk-averse: they prefer to avoid choosing alternatives for which the outcomes are uncertain. When outcomes are presented to a *Decision-Maker* in terms of the probability for each of the possible resultant values, a decision rule called minimum uncertainty can be employed. Minimum uncertainty may also be referred to as minimum risk, where risk refers not to physical or financial risks, but to aversion to uncertainty, as described above. With outcomes quantified by a probability distribution, extremely risk-averse *Decision-Makers* may wish to select an alternative that gives them the most certainty about future rewards by minimizing the variance on possible outcomes. Alternatively, some *Decision-Makers* choose to account only for those outcomes associated with the most likely future event. A minimum uncertainty rule can lead the *Decision-Maker* to reject attractive but uncertain alternatives, and choose a safer alternative with smaller potential rewards.

4.1.5 Satisficing

Not all decision rules yield a single best alternative. Many organizations are concerned with meeting many, sometimes contradictory, goals. Satisficing is a decision rule that is used to find one or more alternatives that can satisfy all (or most) of the organization's goals. When using a satisficing decision rule, a minimum level of achievement on each of several goals is set. For example, a safety goal may be to "reduce the risk of death below "10^{-7} per year" and "spend less than $100,000." All alternatives that meet these goals would be considered satisfactory.

An example of satisficing is shown in Figure 4-1, at Point C, which is not the least cost, but where the marginal cost of mitigation is a set ratio to the expected loss. Since many total cost curves are rather "flat," a near-minimum total cost can be achieved at a cost of mitigation far below the cost of mitigation corresponding to the true minimum Point A.

Any of the above methods can be employed in decision-making. In the next sections, we employ and illustrate an approach, which combines elements of decision analysis and benefit-cost analysis.

4.2 Decision Analysis

Benefit-cost analysis is one method for deciding among alternative mitigation measures. This approach has been adapted from decision analysis (DA). DA represents a set of convenient and powerful principles to help make difficult decisions in an orderly, rational manner. Oil companies use DA to decide whether to bid on a development field and how much to bid; high-tech firms use it when deciding which research projects to fund. DA can be used to help make life-and-death medical decisions. The DA process, adapted here, is generally best used when:

1. an organization faces a high-value decision,

2. the decision has many uncertainties, and

3. no single individual or small group in the organization has all the expertise and information necessary to make the decision. A related criterion is that the organization is complex and buy-in must be obtained from a diverse group before a decision can be carried out effectively.

For the application to earthquake risk mitigation, we have divided the approach into a series of 13 sequential tasks, shown in Table 4-1. Also shown in the table is a final task, development of post-earthquake response plans. This is not specifically a part of the decision method, but is a very important earthquake risk management element; it should be included in the process.

The “done by” column of Table 4-1 is important for maximizing decision quality, and for obtaining buy-in from stakeholders in the decision. The *Risk Manager* must involve all-important stakeholders in identifying as complete and creative a set of alternatives as possible, and in gathering the best information available. As described below, the *Financial Manager* will be called upon to estimate financial consequences of facility outage. Legal counsel may be asked early on to identify legal obligations that could limit retrofit alternatives. Other stakeholders should also be invited to participate in the process. This will improve the quality of the information upon which the decision is based and help to ensure that the decision is accepted by the enterprise.

Table 4-1

RETROFIT DECISION PROCESS

Task	*Toolkit* Section	Done by	Aided by
1. Define Acceptable Risk	*3.4*	*Decision-Maker*	*Risk Manager*
2. List Facilities	*3.4*	*Risk Manager*	Various
3. Task-out Screenings	*3.4*	*Risk Manager*	Various
4. Building Screening	*3.6*	*Asset Manager*	Structural engineer
5. Building Assessment	*3.7*	Structural engineer	*Asset Manager*
6. Equipment Screening	*3.8*	*Asset Manager*	Structural engineer
7. Equipment Assessment	*3.9*	Mechanical engineer	*Asset Manager*
8. Loss-of-Use Assessment	*3.10*	*Risk Manager*	Structural engineer Mechanical engineer *Asset Manager* *Financial Manager*
9. Benefit-Cost Analysis	*4.3*	*Risk Manager*	*Financial Manager*
10. Recommend retrofit strategy	*4.4*	*Risk Manager*	Structural engineer
11. Decide retrofit strategy	*4.4*	*Decision-Maker*	*Risk manager*
12. Perform and maintain retrofit	*5.3*	*Asset Manager*	Structural engineer
13. Enact emergency plans	*5.6*	*Risk manager*	*Asset Manager*

4.3 Benefit-Cost Analysis

4.3.1 *Introduction*

Retrofit options should be screened based on the performance goals that have been selected; any alternative that does not satisfy the desired performance goal should be rejected. For example, the *Decision-Maker* has set a policy for Facility A that it shall remain life-safe in the event of an *MPE*. The *Asset Manager* performed building screening using FEMA-154 and calculated a score for Facility A of S=0.5. Therefore, a structural engineer was retained to assess the building in greater detail.

The engineer confirmed that the building could not reliably protect life safety for an *MPE* event. Three possible retrofit options (A, B, and C) were proposed. Options B and C were judged capable of providing for life safety if the facility experienced *MPE* ground shaking, while option A still left a non-negligible chance of collapse. The do-nothing option and option A should both be rejected for failing to meet the life-safety performance goal selected by the *Decision-Maker*. Options B and C are both acceptable and should be examined to determine which one is most cost-effective.

The benefit-cost analysis method consists of the following steps:

1. Each facility is evaluated to determine its probable earthquake performance (ability to protect life-safety, likely damage repair costs, and potential duration of loss-of-use). Chapter 3 provided guidelines for this aspect of the process.

2. Facilities that represent an unacceptable risk to life safety are targeted for retrofit (or other alternatives such as replacement) which reduce the life-safety risk to an acceptable level.

3. Facilities that pose an acceptable life-safety risk but have significant potential to result in financial loss due to damage, loss of occupancy or function are evaluated to identify alternative retrofit (and other mitigation measures) which can reduce the financial risk to acceptable levels:

   (a) The implementation cost for each alternative is estimated and amortized over an appropriate planning period.

   (b) Probable costs resulting from damage and loss of use are estimated and converted to an annualized basis, considering all possible event sizes and their associated probabilities. This is the present annualized loss (PAL).

   (c) Calculation of annualized loss is repeated, assuming that each of the alternatives is implemented, exclusive of the other alternatives. In each case, the calculated value is the residual annualized loss (RAL).

   (d) The annualized benefit-cost ratio for each alternative is computed as:

$$BCR = \frac{PAL - RAL}{Cost} \qquad (4\text{-}1)$$

   (e) A computed benefit-cost ratio of less than 1.0 indicates that it costs more to implement an alternative than the probable savings in avoided loss.

Benefit-cost ratios that exceed 1.0 indicate that the probable savings resulting from future avoided losses exceed the cost of the mitigation. Alternatives with the largest benefit-cost ratio are the "best" choice.

While a benefit-cost ratio of less than 1.0 indicates that the cost of mitigation exceeds the probable benefits to be obtained, this should not, in itself, be interpreted to indicate that mitigation should not be performed.

Inherent in this method of analysis is an assumption that the earthquake that causes damage is equally likely to occur in any year, and may not actually occur until many years in the future. If it is assumed that the damaging earthquake will actually occur in the near future, which is a possibility, then the benefit of performing the mitigation would be much more attractive relative to the cost. Therefore, while benefit-cost analysis is an appropriate method to choose among mitigation alternatives, it may not be an appropriate model upon which to base a decision to mitigate.

4.3.2 *Screen Out Unacceptable Options*

Any alternative that fails to meet the performance goals determined in Worksheet 1A should be eliminated.

4.3.3 *Estimate Amortized Retrofit Cost*

First, the appropriate planning period, **T**, must be determined. The *Risk Manager* should determine this in consultation with the *Financial Manager*.

- For a private organization: T is usually taken on the order of 5-0 years.
- For a public agency: T may be longer, perhaps on the order of 30-50 years.

In consultation with the *Financial Manager*, determine the cost of funds, **i** [3].

For each retrofit option, determine the expected value of construction cost, **C**, and the amortized retrofit cost (i.e., the retrofit costs per annum), C_{pa} using the equation:

$$C_{pa} = \frac{Ci}{\left(1 - \frac{1}{(i+1)^T}\right)} \tag{4-2}$$

Use the engineer's best estimate for retrofit cost C (alternatively, an organization may wish to use a weighted average of the engineer's best estimate, and the contingency, for conservatism).

4.3.4 *Estimate Annualized Damage Costs*

For each mitigation alternative (including the case of no mitigation), determine the

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[3] This is the cost of retrofit capital. Theoretically, this is the *real interest rate*, which is the market interest rate minus the inflation rate [this is because the funds accrue interest at the market rate, but the capital and interest are paid back with future *inflated* dollars]. In practice, many public and private agencies use the market interest rate as the cost of funds (e.g., the U.S. government OMB mandates that the market rate for Treasury bonds be used) – the effect of this is to require projects to be more beneficial than their theoretical return.

expected annualized value of damage repairs due to future earthquakes. In practice, this is most often determined using computer programs, which analyze the damage due to all possible earthquakes, and multiply its cost by the probability per year that each earthquake may occur.

The following procedure may be used as a rough approximation of this more rigorous approach.

(a) determine the annual expected cost to repair damage due to the *MPE* as:

$$\frac{D_{MPE}}{500}$$

where D_{MPE} is the expected cost of damage repair if the *MPE* actually occurs.

(b) determine the annual expected cost to repair damage due to the *LE* as:

$$\frac{D_{LE}}{100}$$

where D_{LE} is the expected cost of damage repair if the *LE* actually occurs.

(c) determine the total annual expected cost to repair damage due to all possible future earthquakes as:

$$E[D\ pa] \cong 4\left[\frac{D_{LE}}{100} + \frac{D_{MPE}}{500}\right] \quad (4\text{-}3)$$

where E[D pa] is the expected Damage per annum

This approximation is empirically based, and may be appropriate only for the high seismicity areas of California. In other areas, it may not be appropriate, and a more accurate computer program-based approach should be used[4].

4.3.5 *Estimate Annualized Loss-of-Use Costs*

For each facility and each retrofit option, determine the expected value of loss of use costs for the *MPE* and *LE* earthquake, using the *Financial Manager's* best estimates of loss-of-use cost U, from Section 3.2.

U_{MPE} = best estimate of loss-of-use cost for the large event

U_{LE} = best estimate of loss-of-use cost for the moderate event

Then, calculate E[U pa], the expected annualized loss of use cost for each mitigation alternative (as well as the alternative of no mitigation) as:

$$E[U\ pa] \cong 4\left[\frac{U_{LE}}{100} + \frac{U_{MPE}}{500}\right] \quad (4\text{-}4)$$

4.3.6 *Benefit-Cost Analysis*

You now have all the data required to perform a benefit-cost analysis using the Benefit-Cost Analysis worksheet (Worksheet 7). Next steps:

[4] As noted, Equation 4-3 is an empirically based approximation. The multiplicative constant 4 provided in empirically ranges between 3 and 5, so that there may be significant uncertainty. This approximation has not been thoroughly peer reviewed and is only the opinion of the authors.

- List the facilities (Column A), retrofit options (Column B), performance goals (Column C, *MPE* and *LE* events), and occupancy class (Column D), grouping mitigation alternatives together for each facility. Remember to include the "no mitigation" alternative in this list.

- For each facility and each mitigation alternative, enter the expected retrofit cost (Column E), and amortized retrofit cost per Equation 4-2 (Column F), expected *LE* damage repair cost (Column G), expected *MPE* damage repair cost (Column H), expected annual damage repair cost, E [D pa] per Equation 4-3 (Column I), expected *LE* loss of use cost U_{LE} (Column J), expected *MPE* loss of use cost U_{MPE} (Column K), and the annual expected loss of use cost, E[U pa] per Equation 4-4 (Column L).

- Enter the sum of the values from Columns I and L in Column M. This is the annualized loss cost.

- Calculate the annualized benefit for each alternative as (M for no mitigation option) – (M for the mitigation alternative), and enter in Column N.

- Calculate benefit-to-cost ratio for each option, that is, as (Column N)/(Column M).

- For each facility, recommend the option with the greatest benefit-to-cost ratio.

Worksheet 7 - Benefit-Cost Analysis

Column A Facility	B Retrofit Option	C Perf. Obj.	D Occup. Class	E Retrofit Cost, C	F C_{pa} *Eqn. 4-2*	G D_{IF}	H D_{MPE}	I E[D pa] *Eqn. 4-3*	J U_{LL}	K U_{MPE}	L E[U pa] *Eqn. 4-4*	M E[D pa] + E[U pa]	N Benefit, B	O B/C_{pa}
1	A - *As-is*													
	B													
	C													
	D													
2	A - *As-is*													
	B													
	C													
	D													
3	A - *As-is*													
	B													
...	...													

4.4 The Retrofit Decision

With the Benefit-Cost Analysis worksheet (Worksheet 7) completed, the *Decision-Maker* has a clear set of choices, balancing expected losses with costs of mitigation. As noted in Chapter 2, additional information and analyses may be required at this point. However, eventually enough alternatives will have been examined to present a clear set of choices, from which a decision can be made according to the methods outlined above.

Once a decision is made, it is typically subject to outside review for several reasons. Not everyone can be involved in the decision process, and this is a common source of objections to seismic mitigation programs. It is important to recognize the potential for this and eliminate it, as it typically leads to fractious and counter-productive defense of the decision after it has been made.

The best way to eliminate this problem is to identify all stakeholders in the earthquake mitigation program early, and to keep them informed of the decision-making process from the beginning. Given the opportunity to comment on the process, stakeholders may offer valuable insights and suggestions and, at least, are not deprived of their voice in the process.

4.5 Olive Grove High School Example

The following example illustrates the decision process. Olive Grove is a fictitious school campus with several buildings.

STEP 1: POLICY GOALS AND ASSETS AT RISK

The fictional city of Olive Grove lies in Central California. In a resolution, the Olive Grove High School Board of Trustees instructs the superintendent to develop a seismic risk management plan, with these goals:

1. Safeguard lives of school students and employees;
2. Control damage to high school property if the benefits justify the costs.

The school includes four buildings:

1. Gymnasium (14,000 square feet; built 1925; unreinforced masonry)
2. Science Building (15,000 square feet; built 1950s; reinforced concrete frame construction)
3. Foundation Building (6,000 square feet; original school house built in 1911 and now used for administrative offices; wood frame)
4. Liberal Arts Building (25,500 square feet; built 1985; braced steel frame construction)

All four buildings are regularly occupied during school hours, with a total student, staff, and faculty population of 250.

STEP 2: LIFE-SAFETY EVALUATION AND MITIGATION

The school district contracts with "I.M. Abel Structural Engineers" to perform a seismic evaluation of the campus. After completion of a Tier-2 evaluation using the FEMA 310 methodology, the engineers' report indicates that the gymnasium and science building pose collapse hazards for the *MPE* earthquake. The administration and liberal arts buildings have some seismic problems, but are unlikely to collapse or pose a serious life-safety threat. The district directs Abel Engineers to respond to the life-safety threat posed by the gym and science buildings. The engineer recommends the gym and science building be assessed for retrofit according to the California Code of Building Conservation (California Building Standards Commission, 1998), with the following results:

Gymnasium: The gymnasium is an unreinforced masonry building with a wood bowstring truss. The vulnerability that can lead to collapse is an inadequate connection of the trusses to the pilasters supporting them. In the design basis earthquake, the trusses will pull off the pilasters, dropping the trusses and roof into the gym area. Two alternatives are possible:

(i) The best retrofit involves (a) installing a new roof diaphragm by installation of diagonal steel members in the plane of the bottom chord of the trusses (this avoids ripping off the existing roofing); (b) strengthening the truss connection to the pilasters (i.e., adding some steel plates from the truss bottom chord which tie to a new beam); (c) installing a new steel beam running along the top of the unreinforced masonry wall at the level of the bottom of the trusses (this beam braces the wall and serves as a chord of the new roof diaphragm); and (d) installing a new mesh of steel reinforcing bars on the exterior walls, and shotcreting several inches of new concrete to the exterior walls, to strengthen and contain the existing brick walls. The total cost for this retrofit is estimated to be $250,000, or about $18 per square foot (sq. ft.).

(ii) The other alternative is to build a new gymnasium at a cost of about $125 per sq. ft., or a total cost of $1.75 million.

Science Building: The Science Building is a two-story reinforced concrete frame building with one-way floor slabs. The vulnerability that can lead to collapse is inadequate ductility of the concrete columns. In the design basis earthquake, the columns will fail in shear, resulting in a "pancake" type collapse. Two alternatives are possible:

(i) One retrofit involves replacing several of the interior classroom partitions (which are nonstructural) with structural concrete shear walls. Because of an interior corridor (with classrooms along both sides), the shear walls can be placed in a regular pattern so as to take virtually all of the seismic lateral forces, without requiring significant strengthening of the second floor and roof slabs. This work can be accomplished in one summer recess, and is estimated to be $200,000, or about $13 per sq. ft.

After painting, the new shear walls will be virtually indistinguishable from the old partition walls.

(ii) The other alternative involves partially demolishing partitions around many of the columns, and reinforcing the columns. Several alternatives are available for reinforcing the columns, including adding new lateral ties and concrete cover, steel jacketing, or carbon fiber wrapping. Because this will have to be done for almost all the columns, many partitions will be partially demolished, which makes this a more expensive alternative.

The best alternatives are retrofits estimated to cost approximately $250,000 for the gymnasium, and $200,000 for the science building. These retrofits are believed to provide margin against collapse, that is, they will provide a reasonable degree of life safety, although they will not prevent all damage in a strong earthquake.

In light of the life-safety threat to faculty, staff, and students, the superintendent recommends that the trustees take the engineer's advice and retrofit the gym and science buildings, at a total cost of $450,000. The superintendent estimates this option to be more economical than replacing both buildings, which would cost at least $4,000,000.

STEP 3: BENEFIT-COST ANALYSIS FOR FOUNDATION BUILDING

The engineer finds that the wood frame Foundation Building lacks foundation bolts and has weak cripple walls (cripple walls are short walls between the foundation and first floor). This situation does not pose a substantial life-safety hazard, but the building could shift from its foundation in a design basis earthquake, resulting in repair costs on the order of 40% of the building's replacement cost of $800,000, or $320,000. With repair design, fund allocation, and repairs, the building might be vacant for up to a year.

The superintendent estimates that if the Foundation Building were vacant up to a year, the high school would have to rent out nearby office space at a cost of $1.00 per square foot per month, for a total of $72,000 additional operating costs. Other expenses associated with moving out of the damaged building and back once repairs are completed could amount to $6,000 more, for a total **loss under the *MPE* of $398,000**, for the Foundation Building.

In a moderate event, the engineer's report goes on to state, damage to the Foundation Building could be 20% of replacement cost, with two months of lost use. This equates to $160,000 repair cost, $12,000 additional rent, and $6,000 moving and other costs. Thus between damage and loss of use, a ***LE* could cost $178,000.**

The engineer recommends a standard repair in such a situation: add foundation bolts and plywood sheathing to the inside of the cripple walls. Retrofitting the Foundation Building would cost approximately $20,000.

If the Foundation Building were retrofitted, the engineer estimates damage costs under the *MPE* of $60,000, but only a few days' loss of use. In the *LE*, damage might cost $20,000 and have negligible loss of use. It is now possible to perform a benefit-cost analysis for the Foundation Building.

The city's planning period T is 30 years. Special loans are available, making the school's cost of capital i = 6% pa.

Annualized retrofit costs are therefore as follows:

Annualized retrofit costs C_{pa}

Retrofit cost C = $20,000

$$C_{pa} = \frac{Ci}{\left(1 - \frac{1}{(i+1)^T}\right)}$$

$$= \frac{\$20{,}000 \times 0.06}{\left[1 - \frac{1}{1.06^{30}}\right]}$$

$$= \$1{,}453$$

"Do-nothing" annualized damage and loss-of-use costs.

D_{MPE} = $398,000
D_{LE} = $178,000;

$$E[D\ pa] = 4\left[\frac{D_{LE}}{100} + \frac{D_{MPE}}{500}\right]$$

$$= 4\left[\frac{\$178{,}000}{100} + \frac{\$398{,}000}{500}\right]$$

$$= \$10{,}304$$

Post-retrofit annualized damage and loss-of-use costs.

D_{MPE} = $60,000; D_{LE} = $20,000;

$$E[D\ pa] = 4\left[\frac{D_{LE}}{100} + \frac{D_{MPE}}{500}\right]$$

$$= 4\left[\frac{\$20{,}000}{100} + \frac{\$60{,}000}{500}\right]$$

$$= \$1{,}280$$

Annualized retrofit benefit B

B = E[D $_{pa}$] as-is – E[D $_{pa}$] retrofit

= $10,304 - $1,280

= $9,024

The benefit of retrofit in terms of reduced damage is $9,024, or almost six times the cost, making it very cost-effective. Furthermore, the retrofit cost of $20,000 is within budgetary constraints, so the superintendent recommends performing the retrofit on the Foundation building.

STEP 4: BENEFIT-COST ANALYSIS FOR LIBERAL ARTS BUILDING

The engineer examines the Liberal Arts Building and determines that it was built to a recent building code, and has no significant structural deficiencies. While the building may suffer some damage in an *MPE* event, the engineer does not recommend any structural retrofit.

The nonstructural component that poses substantial damage potential are the suspended light fixtures, which the engineer notes lack code-required braces. These could come down in a *LE* or *MPE*.

The engineer estimates that damage in an *MPE* might cost $500,000 to repair, and in a *LE*, $50,000. If the light fixtures came down, the debris could be removed, but some loss of use would occur. This is difficult to quantify; the duration would not be long enough to justify obtaining alternative classrooms. To add bracing as a seismic retrofit would cost approximately $200,000. This would limit damage in a large event to perhaps $5,000, and in a moderate event to a negligible amount.

Annualized retrofit costs C_{pa}

Retrofit cost C = $200,000

$$C_{pa} = \frac{Ci}{\left(1 - \frac{1}{(i+1)^T}\right)}$$

$$= \frac{\$200{,}000 \times 0.06}{\left[1 - \frac{1}{1.06^{30}}\right]}$$

$$= \quad \$14{,}600$$

Do-nothing annualized damage and loss-of-use costs.

D_{MPE} = $500,000; D_{LE} = $50,000;

$$E[D\ pa] = 4\left[\frac{D_{LE}}{100} + \frac{D_{MPE}}{500}\right]$$

$$= 4\left[\frac{\$50{,}000}{100} + \frac{\$500{,}000}{500}\right]$$

$$= \$6{,}000$$

Post-retrofit annualized damage and loss-of-use costs.

D_{MPE} = $5,000; D_{LE} = $1;

$$E[D\ pa] = 4\left[\frac{D_{LE}}{100} + \frac{D_{MPE}}{500}\right]$$

$$= 4\left[\frac{\$1}{100} + \frac{\$5{,}000}{500}\right]$$

$$= \$40$$

Annualized retrofit benefit B

B = E[D + U $_{pa}$]as-is – E[D + U $_{pa}$]retrofit
= $6000 - $40
= $5,960 = estimated annualized reduced damage

In this situation, the annualized benefit of retrofit is $5,960, while the annualized cost is $14,600. It is not worth retrofitting the light fixtures in the Liberal Arts Building from a financial perspective, but the performance of light fixtures in recent earthquakes indicates they have potential to inflict head injuries to students. Therefore, the superintendent recommends retrofit anyway.

The results for the Foundation and Liberal Arts Buildings are summarized in Table 4-2.

Table 4-2

EXAMPLE BENEFIT- COST WORKSHEET FOR OLIVE GROVE HIGH SCHOOL EXAMPLE

Column A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Facility	**Retrofit Option**	**Perf. Obj.**	**Occup. Class**	**Retrofit Cost, C**	**C_{pa}** *Eqn. 4-2*	**D_{LE}**	**D_{MPE}**	**E[D pa]** *Eqn. 4-3*	**U_{LE}**	**U_{MPE}**	**E[U pa]** *Eqn. 4-4*	**E[D pa] + E[U pa]**	**Benefit, B**	**B/C_{pa}**
Found. Building	A - *As-is*	IO	offices	-	-	160	320	8.96	18	78	1.344	10.34	-	-
	B – brace roof & walls	IO	Offi ces	20	1.45	20	60	1.28	-	-	-	1.28	9.024	9.02/1.45= 6.2
Liberal Arts Building	A - *As-is*	IO	school	-	-	50	500	6	-	-	-	6	-	-
	B – brace lights only	IO	schoo	200	14.6	-	5	0.04	-	-	-	0.04	5.96	5.96/4.6 = 1.3

Primary Interest:
Decision-Makers

Secondary Interest:
Risk Managers

5. Implementing the Earthquake Risk Mitigation Program

5.1 Introduction

This chapter provides guidance on some of the more practical aspects of implementing an earthquake risk management program: balancing earthquake risk against other needs; coordinating the program with other capital expenditures; funding the program; retention of professional services; risk transference; emergency response planning; and steps to take after an earthquake.

5.2 Earthquake Risk and Limited Resources

We introduced this *Toolkit* by acknowledging that **earthquakes are serious problems in California** and that **every one knows this**. Despite this wide knowledge, some *Decision-Makers* are reluctant to perform formal assessments of their earthquake risk. In some cases, this reluctance can be attributed to a belief that ignorance of existing risk is an excuse for inaction, or to the corresponding fear that once the level of risk is known, action must be taken to reduce or eliminate it. Since all *Decision-Makers* operate under the constraints of limited and often inadequate resources, there is an obvious bias towards avoiding "new" problems and demands for expenditure.

The perceived need to mitigate all risks once they are discovered relates to issues of potential liability. For example, once a building evaluation is performed and the *Decision-Maker* is informed that the building could collapse in an earthquake, the *Decision-Maker* must either inform the public and personnel who spend time in the building that this risk exists. Failing to do so makes the building owner subject to wrongful endangerment litigation in the event of an earthquake-induced collapse. However, some *Decision-Makers* think that personnel who are informed of the danger may refuse to work in the building, causing other obvious problems.

Since severe earthquakes affect a given region only infrequently, many *Decision-Makers* prefer to "bet" that damaging events will not occur during their term of office. Further, they believe that if an earthquake causes the building to collapse, it will be considered an act of God for which they will have no liability, particularly if no prior positive identification of the risk was available. Based on these beliefs, such *Decision-Makers* adopt an "ignorance is bliss" approach to risk management, avoid having positive knowledge of a risk, and believe they have limited potential liability as a result.

In California today, the validity of an ignorance-of-risk defense is highly questionable, particularly for public agencies. Since everyone knows that earthquakes are serious problems in California, *Decision-Makers* who are responsible for protecting the welfare of their enterprises and the public are now expected to understand the extent of this risk and to deal with it in a responsible manner.

"Dealing with risk in a responsible manner" does not mean pretending that the risk does not exist. Before a risk can be managed, it must be understood. Once the level of risk is understood, there is, at a minimum, a requirement to inform those who are at risk about the peril they may be in. However, if the risk is presented with acknowledgment of the consequences (e.g., the building may collapse) as well as the likelihood of occurrence (e.g., collapse is expected only for earthquakes that occur one time every 500 years), most personnel will accept the risk. In essence, disclosure of potential risk to personnel is an effective mechanism for risk transfer and is also fair.

Once an earthquake risk is understood, it is possible for the *Decision-Maker* to balance the potential losses and benefits gained from a mitigation program against other potential uses of the limited resources available. For example, should a community's limited capacity for bond indenture be limited to upgrade the wastewater processing system or used for earthquake risk reduction? It is impossible to answer such a question until the risks and potential benefits of both programs are defined and shared with all of the potential stakeholders.

Often, an enterprise will find that it can not afford to embark on a major program of earthquake retrofit, given the limited resources available and the competing uses for these resources. However, it is often possible to obtain incremental reduction in risk by performing limited mitigation as part of other programs. For example, if an existing fire station is going to be expanded to provide space for an additional company, seismic upgrade of the fire station can probably be accomplished concurrently, at little additional cost. Similarly, if a major asbestos reduction program is going to be pursued, it may be possible at very little additional expenditure to perform concurrent seismic upgrades. Until the extent of risk is understood, and priorities set for mitigating this risk, decisions to embark on such programs can not be made.

After a disaster occurs, *Decision-Maker* are often held responsible for having made the wrong decision, especially if losses are seen as unacceptably high and all stakeholders were not involved in the decision process. Steps to understand the risk and share the information with the affected stakeholders can help to minimize post-event backlash, even if no action to mitigate is ultimately taken. Once disclosure is made, the stakeholders will either acquiesce to the risk, essentially accepting the role of joint *Decision-Maker* themselves, or make it known that the risk must be addressed. In either event, the *Decision-Maker* that actively addresses earthquake risk and involves all stakeholders is better off than one who does not.

5.3 Coordinating the Program

It is very important to include earthquake risk mitigation measures with other facets of the asset management program. Key issues related to this are the following:

- Often by performing seismic upgrade work concurrently with other planned projects, it is possible to reduce the cost and disruption of the upgrade work. For example, a common requirement of seismic upgrade programs for low-rise buildings with wood roof structures is to increase the nailing of the plywood roof sheathing. This can only be done upon removal of the roofing. Clearly, if such upgrade work is performed concurrently with routine replacement of the roofing system, it will be far more economical.

- If an existing facility is assessed as incapable of providing adequate seismic performance for its current use, consider changing its mission to be more compatible with its seismic performance category. For example, if a critical care wing of a hospital is judged incapable of immediate post-earthquake occupancy, and there is simultaneous need to develop new outpatient care at the facility, the best choice may be to build new critical care space and convert the existing space to use for outpatient care.

- Consideration should be given to the length of time a facility is expected to remain in service. If a facility is scheduled for replacement or retirement in the near future, it makes little sense to invest in upgrade of the facility.

- Construction for seismic improvements to a facility will often trigger mandatory requirements to perform other types of upgrades such as disabled access improvements, hazardous material abatement, and fire/life safety improvements. These collateral upgrade requirements can have substantial impact on the implementation cost and, in some cases, the cost of collateral upgrades is higher than the seismic construction cost. It is important to account for these impacts when evaluating the cost of seismic mitigation.

Earthquake risk can not be effectively managed in a vacuum. The *Decision-Maker* and the *Risk Manager* must involve the *Asset Manager* in planning and implementing the mitigation program in order to assure that collateral issues are addressed and all capital improvements are coordinated. It also important to ask professional consultants, who may be retained to assist in quantifying risk and suggesting mitigation alternatives, to be mindful of these needs.

5.4 Funding the Program

Like all programs, earthquake risk management requires the investment of funds. The initial phases of the program, in which the risk is assessed and mitigation options explored, typically entails relatively modest cost. By spreading these tasks out over a period of one or two years, most enterprises will be able to accommodate these costs within their normal operating budgets. However, major programs of capital improvement will typically require extraordinary sources of funding.

The following sources should generally be considered when planning programs of seismic mitigation:

- **General Operating and Maintenance Funds** – Not all seismic upgrade projects are particularly costly and some seismic upgrades can be done at nominal cost. For example, most equipment items can be anchored or braced for seismic resistance at a cost of a few hundred dollars, or less. Many enterprises will be able to cover significant seismic upgrade activities out of their general operating and maintenance funds.
- **Bond Issues** – If a community understands its existing earthquake risk and is convinced that this is unacceptable, it may be willing to support additional bonded indebtedness as a means of raising the necessary funds. For example, the City of San Francisco obtained permission from its electorate to raise more than $100 million for earthquake safety retrofits of fire stations and other municipal buildings. From a strategic perspective, such bond measures are most successful in the period immediately following a major earthquake, when the public's attention is drawn to the issue of earthquake risk.
- **Special Use Fees** – In some cases, it may be possible to support the cost of seismic upgrade through the establishment of special use fees. As an example, the State of California raised tolls on bridges crossing San Francisco Bay as a means of funding seismic upgrades of these structures.
- **Hazard Mitigation Grants** – Occasionally, special grants become available from the federal and/or state government for partial funding of seismic mitigation work. These grants are may be offered as 1) seed money for demonstration projects, to encourage and attract other sources of funding; or 2) in order to reduce risk of damage in future earthquakes and to help communities become more self-sufficient. These grants are usually available only for public or non-profit enterprises and often are restricted to, or give preference to, certain types of projects. For example, using funding obtained under the Proposition 122 bond program, the State of California made limited mitigation funding available to cities, counties and similar agencies. Generally, projects to strengthen emergency response facilities such as fire stations, police stations, and city halls received priority over other types of projects.

  When mitigation grant programs are available, communities must typically apply for funding in competition with others. In addition, it is usually necessary for the enterprise to provide some co-funding of the project, often in the amount of 10% to 20% of total project costs.
- **Tax Preferences and Credits** – Certain tax credit and tax preference incentives are available for the rehabilitation of qualified historic landmarks. These incentives are typically applicable only to private, for-profit enterprises. In order to

qualify for these incentives, it is necessary to comply with certain historic preservation standards and to be subjected to a review and approval process for the design.

5.5 Retention of Professionals

Most enterprises will need to retain the services of specialty professional consultants to assist the *Risk Manager* in implementing portions of the earthquake risk mitigation program. Appendix G includes sample scope of work statements for professional consultation agreements related to the following services:

- Building Risk Screening
- Equipment Risk Screening
- Building Risk Assessment
- Equipment Risk Assessment
- Building Upgrade Design

Many organizations will be able to perform the Building Risk Screening and Equipment Risk Screening tasks with in-house technical personnel. However, should it be necessary to obtain consultant services for these tasks, we recommend professional structural engineering consultants as the most qualified persons to perform the Building Risk Screening task. Either professional mechanical or structural engineering consultants will be able to perform the Equipment Risk Screening task.

Most organizations will not have adequate staff with the necessary qualifications to perform the Building Assessment or Equipment Assessment tasks, and it will be necessary for them to retain consultants for this purpose. We recommend professional structural engineers as most qualified to perform the Building Assessment task and professional structural or mechanical or structural engineers to perform the Equipment Assessment task.

Today, there are a number of options for retaining services related to building upgrade design and construction projects. Some of the most commonly used approaches include the following:

- **Conventional Project Delivery – Architectural Lead** – This is how most building construction projects have been implemented in the past. In this method, the Owner advertises a desire to retain Architect/Engineer (A/E) teams to design the project and requests submittal of qualifications form interested providers of services. Typically, in this method of project delivery, an architect will be retained as the prime design professional. The architect will then retain a team of consultants including structural, mechanical, and electrical engineers, as well as other specialty consultants to develop different parts of the design. The architect manages the process and coordinates the team's efforts. The A/E team's deliverables include drawings and specifications that can be used to obtain contractor bids, building permits and to perform the work. General contractors can be selected to perform the work, either on a low-bid, lump sum basis; a negotiated cost-plus-fixed-fee basis; or negotiated total cost basis. The A/E team is typically retained to monitor construction progress, respond to contract requests for clarification of the documents and assist the owner in negotiating changes required to the basic contract as a result of changed conditions.

Many agencies find this form of project delivery advantageous when seismic upgrade work is performed concurrently with other major capital improvements such as general building renovation or building expansion. The advantages of this project delivery form are:

a) The architect is typically able to coordinate large teams in the design of complex projects, efficiently.

b) Construction scope can be well defined before retaining a contractor, allowing the construction cost to be fixed and change orders minimized.

This project delivery form also has some disadvantages, including:

a) Design of seismic upgrades requires special knowledge and skills that are not possessed by all structural engineers. The architect may not select the most qualified structural engineer for this work.

b) Because the architect may not be focused on the needs of the seismic upgrade program, it may become subordinated to other project goals, and result in a relatively ineffective upgrade design.

c) Since a contractor can not be retained until the design process is complete, the project may take a long time between initiation of design and completion of construction.

- **Conventional Project Delivery with Structural Lead** – This method of project delivery is very similar to that discussed above, except that the structural engineer acts as the prime design professional. This form of project delivery has been used for a number of major seismic upgrade projects, including some projects that had significant design components from disciplines other than structural engineering. However, it probably makes most sense for those projects where seismic upgrade is the primary and most important aspect of the project. Principal advantages of this project delivery method include:

  a) This approach allows direct selection of the structural engineer as the lead professional, based on qualifications of the engineer to perform the seismic upgrade design.

  b) This approach maximizes the probability that the project decisions will be made in the context of maximizing the effectiveness of the seismic upgrade, as opposed to other project aspects.

Although this project delivery approach has been used for some very large projects, such as the seismic upgrade of the San Francisco City Hall and Opera House, not all structural engineers are experienced in managing large multidisciplinary design teams. Therefore, if this approach is selected, it is important to ascertain that the prime professional has the necessary skills and knowledge to do the structural design and to handle management aspects of the project.

- **Conventional Project Delivery with Contractor Pre-Construction Services** – This approach may be conducted in a very similar manner to either of the two approaches previously described. The primary difference is that either a General Contractor or Construction Manner is retained at the same time as the design team to provide pre-construction services, rather than waiting for the design to be completed. These pre-construction services can include review of designs for constructability, value engineering, development of cost estimates, and construction schedules. Following completion of the design, the Owner can negotiate with the contractor to provide construction services; retain the contractor to act as a construction manager and perform the actual work by obtaining lump-sum, low bid subcontracts; or retain a new contractor to provide the required construction services.

  This approach has been found to be advantageous on projects where new technologies with unusual or special construction requirements are to be used, and on projects where construction is to be performed while the facility remains occupied during construction. The principal advantage of this approach is that the Contractor can help the design team to develop a design that is more practical to build and can provide more accurate estimates of required cost and schedule than most design professionals. A disadvantage is that this approach can sometimes be more expensive than the previous two.

- **Design-Build Delivery** - In this form of project delivery the Owner retains a general contractor to both design the project and construct it. The principal advantage of this approach is that the Owner need only deal with a single party, the general contractor. This reduces some of the management tasks the Owner must normally provide and, in addition, greatly reduces the potential for litigation between the Owner, contractor and design team in the event that there are problems in project execution. This project approach is coming into greater use in the public sector, particularly for the construction of new facilities. Although it has occasionally been used for renovation and upgrade work, this use is relatively rare because successful project execution requires that the Owner be very precise in specifying the project requirements, something that is frequently difficult to do in seismic upgrade projects.

We can not emphasize enough that design of seismic upgrade projects is a specialized area of practice. The building code requirements as well as the types of construction employed in such projects are often quite different from those used in typical projects for the construction of new facilities. Regardless of the type of project delivery system selected, we recommend that care be taken to select consultants with appropriate qualifications and demonstrated past success in design seismic upgrades.

5.6 Emergency Plans and Risk Transfer

After the seismic risk mitigation work has been completed, the risk associated with a facility will be greatly reduced from original levels. However, some residual risk will typically still remain. Prudent risk management suggests that effective steps be taken to further minimize the residual risk through the following steps:

- **Emergency Response Plan** – Even relatively minor damage to a facility can result in extended interruption of service, and loss of use, if no one knows what to do about assessing its condition, securing potentially hazardous contents and utilities, and conducting repairs so that service can be restored. Emergency response plans that designate the persons responsible for each of these actions, and specify how they can be contacted in an emergency can significantly reduce the amount of confusion and lost time when an earthquake actually occurs.

  In addition to basic information on who is responsible for specific emergency actions, Emergency response plans should include information on the critical equipment and systems within the building, the structural system, expected types and locations of damage, and checklists for specific post-earthquake actions. For critical facilities, the emergency plan can also include provision for alternative work spaces if damage is so severe that re-occupancy of the facility within the short term is not feasible.

- **Earthquake Insurance** – Earthquake insurance can be an effective method of guarding against the direct *financial* losses associated with an earthquake and is commonly used in the private sector for this purpose. Earthquake insurance is very effective in reimbursing a property owner for the direct costs related to repair of damage. It is less effective with regard to reimbursement for business interruption costs, as the quantification of these costs is often somewhat arbitrary and therefore subject to dispute. It is also important to note that most earthquake insurance policies include significant deductibles and will not cover upgrades to the facility that may be triggered by the building official as part of damage repair work. The cost of earthquake insurance is highly variable and depends as much on the global financial markets and health of the insurance industry as it does on the actual risk associated with a facility. In some years, insurance can be obtained at a fraction of its real value, at other times it may cost several times its actual value, or it may not be available at all. Thus, it is prudent not to rely on earthquake insurance as the sole means of risk management.

Recently, a new product on the financial markets--catastrophe bonds--has become available as an alternative to insurance. In essence, rather than purchasing insurance, an organization can transfer its risk by selling bonds. Rather than paying insurance premiums, the issuer of the bonds must pay interest to the bondholders. In the event that an earthquake loss occurs, the bondholders forfeit a portion of their interest and principal which may be used by the issuer to recover the costs of the loss. Out of practicality, bond issues must have a large financial value to be viable, so this approach is typically appropriate only for very large enterprises or for groups of enterprises that elect to pool their interests into a common surety.

For a number of years, the federal government, through the Federal Emergency Management Agency, has adopted a practice of providing a form of zero-premium disaster insurance for public agencies and certain not-for-profit organizations, through disaster assistance programs. In essence, FEMA has provided up to 90% of the cost of repair, and in some cases upgrade, of facilities damaged by disasters such as earthquakes, hurricanes, or tornadoes. As a result, purchase of insurance has not been necessary for most public agencies

It is *worth* noting that, historically, the actual funding provided by FEMA has been variable. Sometimes it has been more than sufficient to cover actual costs, while in other cases it has not been sufficient. As a result, some public agencies have elected to carry private earthquake insurance as a supplement to FEMA coverage. In addition, the federal government has recently come to the realization that these disaster assistance programs have served as a strong disincentive against mitigation. As a result, there have been several recent proposals to either terminate these programs or condition their availability on the community having taken substantive action to mitigate risk prior to the disaster. If such policies are adopted, this will make risk transfer through the private insurance and financial markets more attractive and important to public agencies.

- **Physical Redundancy and Geographic Dispersion.** One of the most effective techniques for mitigation of earthquake risk is to disperse operations into independent locations at different sties. Although the effects of earthquakes can be widely dispersed over a region of many square miles, the most extreme earthquake effects are typically limited to a small fraction of the affected region. If all of the physical facilities associated with an operation are concentrated at a single site or location, there may be significant potential for damage to completely interrupt operations for an extended period of time. However, if the physical facilities are dispersed to multiple locations, it becomes much less likely that all of them would be damaged to an extent that would limit operations at all of the locations. Thus, dispersion can become an effective tool to maintain at least partial operational capability following a major earthquake. To the extent that the dispersed facilities provide redundant capacity, it may be possible to have full operational capability even if some of the facilities become damaged.

- **Data Backup** – Redundant storage of critical records and data can be a highly effective risk mitigation technique. Following the 1989 Loma Prieta earthquake, the City of Oakland's Building Department was displaced from the severely damaged City Hall. The Building Department stored microfilm copies of original construction drawings for private buildings in archives within City Hall. The red-tagging of that building effectively made these records unavailable for many months following the earthquake, hampering the efforts of the community to assess and repair damage sustained by other buildings. Had a redundant set of microfilm records been maintained in an off-site location, access to both sets of data would probably not have been lost.

  Public agencies and private businesses can maintain their own offsite records storage, or they can rely on providers of this service. This may be particularly important for electronic records that are maintained on-line. There are a number of private data centers that provide stand-by electronic records storage, as well as data processing capability.

- **Retain Structural Engineers and Contractors** – Following the 1989 Loma Prieta earthquake, the City of San Francisco's Building Inspection Department found itself overwhelmed by the demand to perform post-earthquake safety inspections of public and private buildings in the city. Even with the assistance of many volunteer inspectors, it took months before all buildings were evaluated and their condition determined. During this period of time, building owners and tenants often did not know whether it was safe to reoccupy damaged buildings, leading to extensive economic losses.

  In order to avoid these problems in future earthquakes, the City of San Francisco later established the voluntary Business Occupancy Resumption Earthquake Inspection Program (BOREIP). Under the BOREIP, building owners can retain qualified structural engineers to perform future post-earthquake inspections of their buildings. These engineers must develop a post-earthquake inspection plan for the building, and be certified by the city as deputy building inspectors for the specific building. Under the program, BOREIP inspectors are obligated to perform post-earthquake inspections within 36 hours of an earthquake disaster. They then have the authority to post inspected buildings on behalf of the city.

Building departments can develop similar programs, to speed the post-earthquake recovery of their communities. In addition, even in the absence of such programs, individual public and private building owners and tenants can retain structural engineers to perform rapid post-earthquake assessments of buildings, to advise as to whether the buildings are safe for occupancy and to develop repairs in the event these are required. While these engineers would not have the power to officially "post" a building, they can provide assurance as the condition of its structure and appropriate recovery actions. It is often beneficial to develop retainer agreements with engineers before an earthquake. In the days and weeks immediately following a major earthquake, structural engineers are extremely busy and are unlikely to be available on short notice unless advance arrangements have been made.

It may also be beneficial to develop similar retainer agreements with general contractors, so that there is assurance that if repairs are needed, there will be construction capability to do them.

5.7 What To Do after an Earthquake

After search and rescue operations are initiated and the immediate threats to life-safety are addressed, the following actions should be undertaken following an earthquake.

- **Assess the Extent of Damage** – Following an earthquake it is necessary to assess the extent of damage. Determine *whether* physical facilities that are relied upon for operations are functional and safe, and estimate the amount of time they may be out of service. It is impossible to implement an effective response and recovery program until this information is known.

  For many public agencies, the responsibility for post-earthquake damage assessment may extend beyond the need to assess the performance of the physical facilities, and include an assessment of the extent of damage and loss community-wide. For example, if housing in a community is severely damaged, public agencies will be expected to provide for the temporary shelter and care of displaced families. If a number of buildings have collapsed, public agencies will be expected to assist in locating and extracting victims. In order to respond to such needs, it is necessary to be able to rapidly assess the likely extent of damage and loss. These assessments can be made by performing rapid post-earthquake reconnaissance, or by implementing one of several disaster simulation software packages that permit rapid estimation of losses.

  Regardless of the method an agency or business elects to pursue, a current emergency response plan and previously negotiated agreements with necessary engineering consultants and contractors can speed this phase of the recovery effort.

- **Implement Emergency Operations Procedures** – As soon as an assessment of damage is made, and the extent of impairment of ability to provide service and the need for these services is ascertained, recovery operations should commence. In the period immediately following the *earthquake*, individual public agencies and private businesses will have to rely on their own resources. An effective emergency response plan can help to smooth the difficult immediate post-event recovery period. Within days to weeks, outside assistance will begin to become available from such sources as the Federal Emergency Management Agency, the State of California Office of Emergency Services, the American Red Cross and other volunteer agencies. In extreme emergencies, military assistance may also be made available.

- **Restore Normal Operations** – Over a period of *days* to *weeks* and, in the worst disasters, perhaps a period of years, normal operations will be restored. The length of time necessary for restoration of normal operations will be directly dependent on the severity of the event, as well as the extent to which risks were identified and mitigated, and emergency response plans developed prior to the event.

  It many cases, what is deemed "normal operations" after the earthquake is not the same condition that existed before the event. Earthquakes can have broad economic and social impacts that can completely change the character of a community and the long-term profitability of individual businesses. For this reason, it is particularly important that public leaders view earthquake risk reduction not only as their responsibility with regard to protection of public facilities, but also as a responsibility that the entire community must share. One of the major benefits of risk mitigation on the part of a public agency is that it sets a leadership example for the community at large.

- **Assess the Lessons Learned** – An important, but often *overlooked* concluding step in the earthquake-recovery process is a carefully conducted review of the loss and recovery experience. No matter how well prepared a community or business is for an emergency, it will typically be found that unanticipated problems developed and that preparation could have been better. Although severe earthquakes are rare events, it is possible for some communities in California to have major damaging events more than once during a typical lifetime. The San Fernando Valley, for example, experienced large magnitude events in both 1971 and 1994. A careful assessment of what went wrong and what went right in the disaster can allow for better preparation for the next event. It will also serve as a valuable learning tool for other communities that have not yet been affected by their earthquake disaster.

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Appendix A: Glossary

acceleration: The rate of change of velocity of a reference point. Commonly expressed as a fraction or percentage of the acceleration due to gravity (g), where g = 980 cm/s^2.

active fault: An earthquake fault that is considered likely to undergo renewed movement within a period of concern to humans. Faults are commonly considered to be active if they have moved one or more times in the last 10,000 years, but they may also be considered active when assessing the hazard for some applications even if movement has occurred in the last 500,000 years. (see **fault**)

alluvium: A soil type consisting of loosely compacted gravel, sand, silt, or clay deposited by streams. Structures founded on alluvium can experience amplified ground shaking intensities.

Alquist-Priolo Fault Zoning Act: Passed in 1972 by the California Legislature, the Alquist-Priolo Earthquake Fault Zoning Act's main purpose is to prevent the construction of buildings used for human occupancy on a **fault trace**. Passage of the Act was a direct result of the 1971 San Fernando earthquake, which was associated with extensive surface fault ruptures that damaged numerous homes, commercial buildings, and other structures. The Act only addresses the hazard of surface fault rupture and is not directed toward other earthquake hazards. The Act also establishes so-called Alquist-Priolo Earthquake Fault Zones ("Special Studies Zones" prior to January 1, 1994), regulatory regions around active faults that average about ¼ mile wide where construction of buildings for human occupancy are controlled. Non-surface fault rupture hazards are addressed by the **Seismic Hazards Mapping Act.**   (see **seismic zonation**)

amplification: An increase in seismic wave amplitude as it propagates through certain soils.

annualized loss: The loss per annum due to earthquakes, calculated as the probabilistic loss contribution of all events. Annualized loss is expressed as a probability distribution of loss per annum. The expected annual loss is the expectation of this probability distribution of loss per annum, and under certain assumptions may be calculated as the probability-weighted average of loss due to all possible earthquake events.

attenuation: The rate at which seismic wave amplitude decreases with distance from its source.

baseline risk: The existing risk, under current or as-is conditions. (see Section 3.12)

base isolation: A structural design concept that reduces the magnitude of lateral response by preventing earthquake ground motion from being transmitted from the foundation into the building superstructure. Application is accomplished through the installation of isolator bearings at all of the connections between the structure and the foundation. The isolators are vertically stiff, capable of supporting vertical gravity loads, while being laterally flexible, capable of allowing large horizontal displacements. In effect, the ground is allowed to move back and forth under a base isolated building during an earthquake, while leaving the building to remain "stationary."

benefit-cost analysis: A risk management tool used to make decisions about accepting risk or using some other risk management technique. (see Section 4.3)

brittle failure: Describe the failure mode of a structural element or material that has undergone very little deformation with very little energy absorption**.**

business interruption (BI): Economic loss associated with loss of function of a commercial enterprise.

compaction: The uniform or differential settlement of loose soils or poorly consolidated alluvium as a result of ground shaking.

completeness: Homogeneity of the seismicity record.

cripple wall: A carpenter's term indicating a wood frame wall of less than full height, located between the foundation and the first floor framing.

damage: Physical disruption, such as cracking in walls or overturning of equipment (often used synonymously with **loss**).

damping: Represents the force or energy lost in the process of material deformation.

decision hierarchy: The priority in which decisions are required to be made (e.g., (1) whether to retrofit or not?, (2) whether to retrofit for collapse prevention or for no damage?, (3) whether to employ bracing vs. shear walls?, and so on).

deterministic methods: Refers to engineering and financial methods of calculating ground motions for hypothetical earthquakes based on earthquake-source models and wave-propagation methods that exclude random effects.

ductile detailing: Special requirements for the placement of the reinforcing steel within structural elements of reinforced concrete and masonry construction necessary to achieve ductile behavior (**ductility**). Examples of ductile detailing include close spacing of lateral reinforcement to attain confinement of a concrete core, appropriate relative dimensioning of beams and columns, 135 degree hooks on lateral reinforcement, and hooks on main beam reinforcement within the column.

ductility: The ability of a structural element or material to offer resistance, sustain large deformations, and absorb energy without **brittle failure**. Commonly quantified by the ratio of the total displacement (elastic plus inelastic) to the elastic (i.e., **yield**) displacement.

earthquake: Ground shaking and radiated seismic energy caused most commonly by sudden **slip** on a fault, volcanic or magmatic activity, or other sudden stress changes in the earth.

earthquake hazard: The potential for or occurrence of any physical phenomenon associated with an earthquake to produce adverse effects on human activities that might lead to loss (or damage). This includes ground shaking, fault rupture, landsliding, liquefaction, tectonic deformation, tsunami, and seiche and their effects on land use, manmade structures, and socioeconomic systems. A commonly used restricted definition of earthquake hazard is the probability of occurrence of a specified level of ground shaking in a specified period of time.

earthquake risk: (see **seismic risk**)

energy dissipation systems: Various structural devices that actively or passively absorb a portion of the earthquake energy in order to reduce the magnitude or duration (or both) of the building earthquake response. These devices include active mass systems, passive visco-elastic dampers, tendon devices, and **base isolation**, and may be incorporated into the building design.

epicenter: The projection on the ground surface directly above the **hypocenter** of an earthquake.

essential facilities: Structures whose ongoing performance during an emergency is required or whose failure could threaten many lives. May include (1) structures such as nuclear power reactors or large dams whose failure might be catastrophic; (2) major communication, utility, and transportation systems; (3) involuntary- or high-occupancy buildings such as schools or prisons; and (4) emergency facilities such as hospitals, police and fire stations, and disaster-response centers.

fault: A fracture along which there has been significant displacement of the two sides relative to each other parallel to the fracture. *Strike-slip faults* are vertical (or nearly vertical) fractures along which rock masses have mostly shifted horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral. *Dip-slip faults* are inclined fractures along which rock masses have mostly shifted vertically. If the rock mass above an inclined fault is depressed by slip, the fault is termed normal, whereas if the rock above the fault is elevated by slip, the fault is termed *thrust* (or reverse). *Oblique-slip faults* have significant components of both slip styles.

fault rupture: A concentrated, permanent deformation that occurs along the **fault trace** and caused by **slip** on the fault.

fault scarp: A step-like linear landform coincident with a **fault trace** and caused by geologically recent **slip** on the fault.

fault trace: An intersection of a fault with the ground surface; also, the line commonly plotted on geologic maps to represent a fault.

fragility: The probability of having a specific level of damage given for a specified level of hazard.

frequency: Number of cycles occurring in a given unit of time.

fundamental period: The longest period for which a structure shows a maximum response (the reciprocal of **natural frequency**).

ground failure: A general reference to fault rupture, liquefaction, landsliding, and lateral spreading that can occur during an earthquake.

ground fault rupture: (see **fault rupture**)

ground shaking: General term referring to the qualitative or quantitative aspects of movement of the ground surface from earthquakes. Ground shaking is produced by **seismic waves** that are generated by sudden slip on a fault and travel through the earth and along its surface.

hazard: The potential for or occurrence of any physical phenomenon to produce adverse effects on human activities and might lead to loss**.** (see **earthquake hazard**).

hypocenter: The location of initial radiation of **seismic waves**.

intensity: A subjective numerical index describing the severity of an earthquake in terms of its effects at the ground surface and on humans and their structures. Several scales exist, but the two most commonly used in the United States are the **Modified Mercalli Intensity (MMI)** and the Rossi-Forel (RF) scales.

isoseismal: Refers to a line on a map bounding points of equal ground shaking intensity for a particular earthquake.

lateral force-resisting system: A structural system for resisting horizontal forces due to earthquake or wind (as opposed to the **vertical force-resisting system**, which provides support against gravity forces).

landsliding: The abrupt downslope movement of soil and/or rock in response to gravity. An earthquake or other natural causes can trigger landslides. Undersea landslides can cause tsunamis.

lateral spreading: The landsliding of gentle, water-saturated slopes with rapid fluid-like flow movement caused by ground shaking and liquefaction.

lifelines: Structures that are important or critical for urban functionality. Examples include roadways, water distribution systems, pipelines, power transmission lines, sewers, communications, and port facilities.

Likely Earthquake (*LE*): An earthquake [as defined by various parameters, such as **PGA** or **response spectra**] representative of the intensity of ground shaking likely to be experienced one or more times during the facility's life. The *LE* is defined as having a mean return period of 100 years. In any 50-year period, there is approximately a 40% chance that such shaking will be exceeded.

liquefaction: A process by which water-saturated soil temporarily loses shear strength due to a build-up of pore pressure and acts as a fluid.

loss: The human or financial consequences of **damage**, such as human death or injury, cost of repairs, or disruption of social or economic systems.

loss of market share: A reduction in market stature or economic position associated with loss of function of a commercial enterprise.

magnitude: A unique measure of an individual earthquake's release of strain energy, measured on a variety of scales, of which the moment magnitude M_w (derived from **seismic moment**) is preferred. (see **Richter Scale**)

mass-reduction: A structural mitigation concept where the weight (or mass) of the building is reduced, in turn reducing the lateral earthquake response and the corresponding forces. This mitigation measure is generally considered impractical since it usually requires the demolition of a significant portion of the subject building.

Maximum Probable Earthquake (*MPE*): A severe earthquake [as defined by various parameters, such as **PGA** or **response spectra**] that may occur one time during the life of a facility. The *MPE* is defined as having a mean return period of roughly 500 years. In any 50-year period, there is approximately a 10% chance that ground motion of this intensity will be exceeded. The California Building Code (CBC) requires that new buildings be designed to resist this level of earthquake without endangering life-safety.

mean: The average value in a distribution.

median: The value in a distribution where 50% of the distribution values are greater than or less than the median value.

Modified Mercalli Intensity (MMI) scale: A qualitative scale for measuring the severity of earthquake ground shaking at a site through the evaluation of the way people react to it and its effects on typical types of structures, such as chimneys and masonry buildings. The MMI scale is the most commonly used intensity scale in the United States and is shown in Table C-1.

meizoseismal: The area of strong shaking and damage.

natural frequency(ies): The discrete frequency(ies) at which a particular elastic system vibrates when it is set in motion by a single impulse and not influenced by other external forces or by damping. It is the reciprocal of **fundamental period**.

non-ductile frames: Frames lacking **ductility** or energy absorption capacity due to lack of **ductile detailing**. Ultimate load is sustained over a smaller deflection (relative to ductile frames) and for only a fewer cycles before a generally **brittle failure**.

pancake collapse: A structural collapse-mode typical of multi-story, concrete-frame buildings, where the columns fail and the floors slabs collapse under gravity, resting in a pile of tightly packed layers, similar to a stack of pancakes.

peak ground acceleration (PGA): The maximum amplitude of recorded acceleration (also termed the ZPA, or zero period acceleration).

performance objectives: A range of limiting structural damage and functionality states for a facility given a specific earthquake event. (see Table 3-4)

pounding: The collision of adjacent buildings during an earthquake due to insufficient lateral clearance.

probabalistic methods: Refer to engineering and financial methods of calculating ground motions for hypothetical earthquakes based on earthquake-source models and wave-propagation methods that take into account the randomness and uncertainty associated with the natural phenomena and associated structural and societal response.

probability of exceedence: A measure (expressed as a percentage or ratio) of estimation of the chance that an event will meet or exceed a specified threshold (e.g., magnitude, intensity, or loss).

probability of occurrence: A measure (expressed as a percentage or ratio) of estimation of the chance that a specific event will occur.

ranking: A process of establishing the order or priority.

recurrence interval: The average time span between events (such as large earthquakes or ground shaking exceeding a particular intensity) at a particular site (also termed return period).

redundancy: (see **structural redundancy**)

residual risk: The remaining risk after risk management techniques have been applied.

response spectrum: A plot of maximum amplitudes (**acceleration**, velocity or displacement) of a single degree of freedom oscillator (SDOF), as the natural period of the SDOF is varied across a spectrum of engineering interest (typically, for natural periods from 0.03 to 3 or more seconds, or frequencies of 0.3 to 30+ hertz).

return period: (see **recurrence interval**)

Richter Scale: A system developed by American seismologist Charles Richter in 1935 to measure the strength (or **magnitude)** of an earthquake, indicating the energy released in an event.

risk: The potential for loss. Risk can be expressed in absolute terms such as 'the risk of collapse', or in probabilistic terms, such as 'the risk per year is $1,000'.

risk acceptance: A risk management technique that allows management to weigh the cost of managing the risk versus the benefits of reducing the risk.

risk assessment: The identification of risk, the measurement of risk, and the process of prioritizing risks for a specific hazard.

risk transference: A risk management technique to remove risk from one area to another or one party to another. Insurance transfers risk of financial loss from insured to insurer.

sand boils or **mud volcanoes**: Ejecta of solids (i.e., sand or silt) carried to the ground surface by water, due to excessive pore pressure associated with liquefaction.

satisficing: A risk management decision technique that is used to find one or more alternatives that can satisfy all (or most) of the organization's goals rather than determining the best alternative for a single goal.

scenario event: An earthquake for which all initiating event natural phenomena parameters are specified (e.g., epicentral location, magnitude, length of fault rupture, fault displacement, etc.). Dependent natural phenomena, such as amount and location of liquefaction, are determined from the initiating event parameters.

scenario loss: The loss due to a specific **scenario event**.

seiche: The movement of water in a lake, reservoir, or other enclosed body of water produced by a local or distant earthquake.

seismicity: The geographic and historical distribution of earthquakes.

seismic hazards: The phenomena and/or expectation of an earthquake-related agent of damage, such as vibratory ground motion (i.e., ground shaking), inundation (e.g., tsunami, seiche, dam failure), various kinds of permanent ground failure (e.g. fault rupture, liquefaction), fire or hazardous materials release.

Seismic Hazards Mapping Act: Passed in 1990 by the California Legislature, the Seismic Hazards Mapping Act addresses non-surface fault rupture earthquake hazards, including liquefaction and seismically induced landslides. Surface fault rupture is addressed by the **Alquist-Priolo Fault Zoning Act.**

seismic moment: A measure of the size of an earthquake based on the area of fault rupture, the average amount of slip, and the shear modulus of the rocks offset by faulting. Seismic moment can also be calculated from the amplitude spectra of seismic waves.

seismic risk: The product of the hazard and the vulnerability and equals the probability of social or economic consequences of an earthquake. (see **risk**)

seismic wave: An elastic wave generated by an earthquake impulse. Seismic waves may propagate either along or near the ground surface (for example, Rayleigh and Love waves) or through the interior of the earth (P and S waves).

seismic zonation: Geographic delineation of areas having different potentials for hazardous effects from future earthquakes. Seismic zonation can be done at any scale - national, regional, or local. California has two Seismic Zones as identified in the California Building Code (CBC), "Zone 3" and "Zone 4." Zone 3 is the less seismically active area and is located in the northern-central valley of the State extending from the northern border to Bakersfield, plus a portion of the desert area east of the San Bernardino Mountains. This is a large portion of the State and includes Sacramento. Zone 4 is the most seismically active area and is located along the western coast of the State extending from Eureka to San Diego. This is a large portion of the State and includes most all of the inland area from Bakersfield to the southern border. (also see **Alquist-Priolo Fault Zoning Act**)

seismotectonic model: A mathematical model representing the **seismicity**, **attenuation,** and related environment.

site amplification: (see **amplification**)

slip: The relative displacement of formerly adjacent points on opposite sides of a fault, measured on the fault surface.

slip model: A kinematic model that describes the amount, distribution, and timing of slip associated with a real or postulated earthquake.

slip rate: The average rate of displacement at a point along a fault as determined from geodetic measurements, from offset man-made structures, or from offset geologic features whose age can be estimated.

soft story: A story of a building significantly less stiff than adjacent stories (that is, the lateral stiffness is 70% or less than that in the story above, or less than 80% of the average stiffness of the three stories above [BSSC, 1994]).

soil: In earthquake engineering, all unconsolidated material above bedrock.

soil profile: The vertical arrangement of soil horizons down to the parent material or to bedrock.

source: The geologic structure that generates a particular earthquake.

Special Studies Zones: (see **Alquist-Priolo Fault Zoning Act**)

spectrum amplification factor: The ratio of a response spectral parameter to the ground motion parameter (where parameter indicates **acceleration**, velocity or displacement).

strike: The approximate direction of the intersection of a fault and the surface of the earth, usually measured from North (e.g., the fault strike is N 60^{o} W).

structural redundancy: The method of design where load resistance of a structure is supplied by more than one load path.

subduction: Refers to the plunging of a tectonic plate (e.g., the Pacific) beneath another (e.g., the North American) down into the mantle, due to convergent motion.

surface waves: Seismic waves transmitted within the surficial layer of the earth, and are of two types: horizontally oscillating Love waves (analogous to S-body waves) and vertically oscillating Rayleigh waves.

tsunami: An impulsively generated sea wave of local or distant origin that results from large-scale seafloor displacements associated with large earthquakes, major submarine slides, or exploding volcanic islands.

Upper Bound Earthquake (*UBE*): An earthquake [as defined by various parameters, such as **PGA** or **response spectra**] representative of the most severe ground shaking that could ever occur at a specific site. The *UBE* is defined as that intensity of ground shaking likely to be experienced at least one time every 1,000 years. In any 50-year period, there is approximately a 5% chance that such shaking will be exceeded.

vertical force-resisting system: A structural system for resisting vertical forces due to gravity (as opposed to the **lateral force-resisting system**, which provides support against earthquake and wind forces).

vulnerability: The expected damage given a specified value of a hazard parameter.

yield: The point at which a structural element or material begins to loose its ability to resist any additional applied load. The transition point between elastic and inelastic behavior.

Appendix B: Resources

There is a variety of information and resources readily available on various aspects of earthquake risk management, which we catalog below.

B.1 Internet Resources

Site	URL	Contains
Applied Technology Council (ATC)	www.atcouncil.org	ATC site contains information about the council's mission and organization; recent news releases; newsletters; recent reports, briefs, and training manuals; databases; seminars and workshops; and other ATC products.
Association of Bay Area Governments (ABAG)	www.abag.org	Maps of seismicity for the San Francisco Bay Area; information on building vulnerability.
California Division of Mines and Geology (CDMG)	www.consrv.ca.gov/dmg	CDMG has primary responsibility for work in the geosciences in California, including hazard mapping, earthquake scenarios, a strong motion instrumentation program, and policy implementation.
California Seismic Safety Commission (CSSC)	www.seismic.ca.gov	CSSC Web site provides information about the commission, its publications, pending legislation relevant to seismic hazards in California, and a table of significant California earthquakes.
California Universities for Research in Earthquake Engineering (CUREe)	www.curee.org	CUREe is a consortium of eight universities to coordinate work on earthquake research problems: California Institute of Technology, Stanford University, University of California at Berkeley, UC Davis, UC Irvine, UCLA, UC San Diego, and USC.
Disaster Research Center (DRC)	www.udel.edu/DRC	DRC is the first social science research center in the world devoted to the study of disasters.

Site	URL	Contains
Earthquake Engineering Research Center (EERC)	www.eerc.berkeley.edu/eea	Earthquake Engineering Abstracts covers the world literature in earthquake engineering since 1971. Contents include selected technical reports, conference papers, monographs, and journal articles. Most materials are available for loan from the PEER library (University of California at Berkeley).
Earthquake Engineering Research Institute (EERI)	www.eeri.org	N\EERI is the de facto US national society for earthquake engineering – contains useful information and links.
EQNET	www.EQNET.org	Excellent database of Earthquake Information Sources on the Web.
Federal Emergency Management Agency (FEMA)	www.fema.gov	FEMA web site has many free publications of high caliber, useful information.
Multidisciplinary Center for Earthquake Engineering Research (MCEER)	www.mceer.buffalo.edu	MCEER bibliographies, literature and research guides, and list of FEMA and NEHRP guidelines and handbooks for earthquake resistant construction and design. The latter category includes Seismic Safety of Lifelines, Seismic Safety of Existing Buildings, and Seismic Safety of New Buildings.
Natural Hazards Research and Applications Information Center (NHRAIC)	www.colorado.edu/hazards/litbase/litindex	HazLit is an excellent on-line index that provides bibliographic access only to that collection of NHRAIC at the University of Colorado at Boulder. While Hazlit is not a full-text database, and the Hazards Center Library does not loan its holdings to the public, this is an excellent resource.

Site	URL	Contains
Pacific Earthquake Engineering Research (PEER) Center	www.peer.berkeley.edu	PEER is a consortium of earthquake engineering research universities in the Western U.S. – the web site has their reports, much useful information.
Southern California Earthquake Center (SCEC)	www.scec.org	SCEC is a Science and Technology Center of the National Science Foundation. Home Page contains background information about SCEC and links to its many member academic institutions. Both the SCEC newsletter and SCEC publications list are available from this site. Also, check out the Earthquake Hazard Analysis Map--a map of probable future Southern California earthquakes.
Structural Engineers Association of California (SEAOC)	www.seaoc.org	SEAOC's site is useful for keeping up with research specific to structural engineering, esp. buildings, and with the practice.
University of Washington earthquake page	www.geophys.washington.edu/seismosurfing	Excellent general site, with directory to many other sites related to earthquakes.
United States Geological Survey (USGS) Earthquake Information	www.quake.wr.usgs.gov	Excellent source of earthquake information for many aspects.

B.2 Seismic Safety Commission

The Seismic Safety Commission of California publishes a variety of documents related to earthquakes and earthquake safety. Listed below are the Commission's current publications related to earthquake risk management.

- SSC 86-01 *The Commission's Role in Seismic Research* (Committee Report)
- SSC 87-03 *Guidebook to Identify and Mitigate Seismic Hazards in Buildings with Appendix* (Commission Report)
- SSC 87-02 *Financial and Social Impacts of Unreinforced Masonry Building Rehabilitation* (Commission Report)
- SSC 88-01 *California at Risk: Steps to Earthquake Safety for Local Governments* (Commission Report)

- SSC 90-05 *Earthquake Hazard Identification and Voluntary Mitigation: Palo Alto's City Ordinance* (Commission Report)
- SSC 90-06 *Report to the Governor on Executive Order D-86-90* (Commission Report)
- SSC 90-07 *Damage to Unreinforced Masonry Buildings in the Loma Prieta Earthquake of October 17, 1989* (Rutherford & Chekene Consulting Engineers)
- SSC 90-08 *Earthquake Emergency Preparedness and Response* (Commission Report)
- SSC 91-02 *Planning for the Next One* (Transcripts of Hearings on the Loma Prieta Earthquake of Oct. 17, 1989)
- SSC 91-05 *Breaking the Pattern: A Research and Development Plan to Improve Seismic Retrofit Practices for Government Buildings* (Charles Thiel, et al.)
- SSC 91-06 *Loma Prieta's Call To Action* (Janice R. Hutton)
- SSC 91-09 *A California Business Owners' Earthquake Insurance Program* (Committee Report)
- SSC 91-10 *Architectural Practice & Earthquake Hazards* (A Report of the Committee on the Architect's Role in Earthquake Hazard Mitigation)
- SSC 92-03 *The Right to Know: Disclosure of Seismic Hazards in Buildings*
- SSC 93-01 *The Commercial Property Owner's Guide to Earthquake Safety*
- SSC 93-02 *Proposed Maps for NEHRP's Recommended Provision*
- SSC 93-03 *Creating a Seismic Safety Advisory Board: A Guide to Earthquake Risk*
- SSC 94-01 *California at Risk: 1994 Status Report*
- SSC 94-02 *Provisional Commentary for Seismic Retrofit, Product 1.1*
- SSC 94-03 *Review of Seismic Research Results for Existing Buildings, Product 3.1*
- SSC 94-04 *The Tsunami Threat to California: Hearings before the California Seismic Safety Commission*
- SSC 94-05 *Seismic Risk Management Tools, Product 2.1*
- *SSC* 94-06 *Northridge Buildings Case Studies Project, Product 3.2*

- SSC 94-07 *Northridge Earthquake Hearings: Draft Transcripts of Hearings Held February 10 & 11 and March 2 & 3, 1994*
- SSC 94-08 *A Compendium of Background Reports on the Northridge Earthquake (January 17,1994) for Executive Order*, W-78-94
- SSC 94-10 *Research and Implementation Plan Earthquake Risk Reduction in California*
- SSC 94-11 *Northridge Earthquake, January 17,1994: The Hospital Response* (Donald H. Cheu, M.D.)
- SSC 95-01 *Northridge Earthquake: Turning Loss to Gain.* Seismic Safety Commission Report to Governor Pete Wilson, Governor's Executive Order, W-78-94
- SSC 95-02 *A Reconnaissance Report to the Seismic Safety Commission on the Hyogo-ken Nanbu Earthquake, (Neisei Nana Nen) The South Hyogo Prefecture near Kobe, Japan, January 17, 1995* (L. Thomas Tobin, Executive Director, Seismic Safety Commission)
- SSC 95-03 *Public Safety Issues from the Northridge Earthquake of January 17,1994*
- SSC 95-04 *1995 Recommended Model Ordinance for the Seismic Retrofit of Hazardous Unreinforced Masonry Bearing Wall Buildings*
- SSC 95-05 *1995 Status of California's Unreinforced Masonry Building Law*
- SSC 97-01 *The Homeowner's Guide to Earthquake Safety*,1998 Edition
- SSC 97-02 *California Earthquake Risk Reduction Plan, 1997-2001*
- 1990 SB 1250: *Seismic Retrofit Cost Estimates for State Owned Buildings* (Commission Report)
- *Draft Commentary to the Structural Engineers Association of California & California Building Officials, Joint Recommended Unreinforced Masonry Building Seismic Safety Provisions* (Wiss Janny Elstner Associates)

How to Order: SSC publications can be order from:

Seismic Safety Commission
1755 Creekside Oaks Drive, Suite 100
Sacramento, California 95833
PHONE: (916) 263-5506
FAX: (916) 263-0594

Quantity discounts for orders of more than five copies of any one publication are also available.

B.3 California Governor's Office of Emergency Services

The California Governor's Office of Emergency Services (OES) publishes a variety of documents related to earthquakes safety and earthquake risk management. Listed below are some of OES's current publications available for order.

- *Emergency Planning Guidance for Local Government.* This document addresses emergency planning at the city and county level. It has evolved from the insight and experience gathered from past disasters and the cooperation between OES staff and local government emergency managers. This guidance document is divided into three volumes, as described below:

  Volume I - The Emergency Planning Guide contains examples from sections of local plans from jurisdictions throughout California. This volume is intended to be a "cookbook" describing the elements and processes needed to develop critical parts of any emergency plan.

  Volume II & Volume III - The local government and the operational area emergency plan examples are represented as Santa Luisa Del Mar and Santa Luisa County, respectively. These "model" plans are included to provide an overall example of the content and structure of SEMS based disaster plans. The tables, checklists and functional organizations depicted are examples and are not intended to represent a single specific model of how jurisdictions should incorporate SEMS into their emergency plan.

- *Emergency Planning Guidance for Public and Private Water Utilities*. This document is intended to assist water utilities of all sizes comply with the requirements of the State Department of Health Services and the Standardized Emergency Management System, and improve coordination among water utilities and other emergency response agencies. Compliance with the guidance may also assist investor owned utilities in cost recovery of damages and as an aid in reducing potential liability.

How to Order: OES publications can be obtained by contacting any regional OES office:

COASTAL REGION (OAKLAND)
1300 Clay Street, Suite 408
Oakland, CA 94612
PHONE: (510) 286-0895

INLAND REGION NORTH
2395 N. Bechelli Lane
Redding, CA 96002
PHONE: (916) 224-4835

INLAND REGION SOUTH
2550 Mariposa Mall, Room 181
Fresno, CA 93721
PHONE: (209) 445-5672
FAX: (209) 445-5987

SOUTHERN REGION (LOS ALAMITOS)
11200 Lexington Drive, Bldg.283 Los
Alamitos, CA 90720-5002
PHONE: (562) 795-2900
FAX: (562) 795-2877

SOUTHERN REGION (SAN DIEGO)
1350 Front Street, Suite 2041
San Diego, CA 92101
PHONE: (619) 525-4287

SOUTHERN REGION (SANTA BARBARA)
117 W. Micheltorena Street, Suite D
Santa Barbara, CA 93101
PHONE: (805) 568-1207

B.4 Federal Emergency Management Agency

The Federal Emergency Management Agency (FEMA) publishes a variety of documents related to earthquake safety, preparedness, risk management, and mitigation. Listed below are some of FEMA's current publications available for order.

- *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook* (FEMA-154, 1988, 185 pages) and *Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation* (FEMA-155, 1988, 137 pages). Prepared by the Applied Technology Council, Redwood City, CA.

  The Handbook presents a method for quickly identifying buildings posing risk of death, injury, or severe curtailment in use following an earthquake. The methodology, "Rapid Screening Procedure (RSP)," can be used by trained personnel to identify potentially hazardous buildings on the basis of a 15 to 30 minute exterior inspection, using a data collection form included in the Handbook. Twelve basic structural categories are inspected, leading to a numerical "structural score" based on visual inspection. Building inspectors are the most likely group to implement an RSP, although this report is also intended for building officials, engineers, architects, building owners, emergency managers and interested citizens. The Supporting Documentation reviews the literature and existing procedures for rapid visual screening.

- *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* (FEMA-178, 1992, 227 pages). Prepared by the Building Seismic Safety Council, Washington, D.C.

  The Handbook presents a nationally applicable method for engineers to identify buildings or building components that present unacceptable risks in case of an earthquake. Four structural subsystems in which deficits may exist are identified: vertical elements resisting horizontal loads; horizontal elements resisting lateral loads; foundations; and connections between structural elements or subsystems. Fifteen structural categories are defined for the evaluation of buildings by engineers. The Handbook is formulated to be compatible with *NEHRP Handbook of Techniques for the Seismic Rehabilitation of Existing Buildings* (FEMA-172, 1992).

- *NEHRP Handbook of Techniques for the Seismic Rehabilitation of Existing* Buildings (FEMA-172, 1992, 197 pages). Prepared by the Building Seismic Safety Council, Washington, DC.

  This handbook presents techniques for solving a variety of seismic rehabilitation problems. Intended for engineers concerned with seismic rehabilitation of existing buildings, the handbook identifies and describes seismic rehabilitation techniques for a broad spectrum of building types and building components (both structural and nonstructural). Most techniques are illustrated with sketches, and the relative merits of the techniques are discussed. Designed to be compatible with the *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* (FEMA-178, 1992), this publication is based on a preliminary version prepared by URS/John A. Blume and Associates, *Techniques for Seismically Rehabilitating Existing Buildings* (FEMA-172, 1989).

- *Typical Costs for Seismic Rehabilitation of Existing Buildings: Volume 1: Summary, Second Edition* (FEMA-156, 1994, approx. 70 pages); *Volume 2: Supporting Documentation, Second Edition* (FEMA-157, 1995,approx. 102 pages). Prepared by the Hart Consultant Group, Inc. Santa Monica, CA.

  Typical Costs for Seismic Rehabilitation of Existing Buildings: Volume I: Summary, Second Edition provides a methodology that enables users to estimate the costs of seismic rehabilitation projects at various locations in the United States. This greatly improved edition is based on a sample of almost 2100 projects. The data were collected by use of a standard protocol, given a stringent quality control verification and a reliability rating, and then entered into a database that is available to practitioners. A sophisticated statistical methodology applied to this database yields costs estimates of increasing quality and reliability as more and more detailed information on the building inventory is used in the estimation process. Guidance is also provided to calculate a range of uncertainty associated with this process. The Supporting Documentation contains an in-depth discussion of the approaches and methodology that were used in developing the second edition.

- *Benefit-Cost Model for the Seismic Rehabilitation of Hazardous Buildings. Volume 1: A User's Manual* (FEMA-227, 1992, approx. 68 pages); *Volume 2: Supporting Documentation* (FEMA-228, 1992, approx. 62 pages); and Computer Software for Benefit-Cost Model for the Seismic Rehabilitation of Hazardous Buildings. Prepared by VSP Associates, Inc., Sacramento, CA.

  The two benefit-cost models presented in this report are designed to help evaluate the economic benefits and costs of seismic rehabilitation of existing hazardous buildings. The single class model analyzes groups of buildings with a single structural type, a single use, and a single set of economic assumptions. The multi-class model analyzes groups of buildings that may have several structural types and uses. The User's Manual presents background information on the development of the benefit-cost model and an introduction to the use of benefit/cost analysis in decision making. It reviews the economic assumptions of benefit-cost models, with and without including the value of life. The User's Manual guides the user through the model by presenting synopses of data entries required, example model results, and supporting information. Seven applications of the models are presented: five of the single-class model; two of the multi-class model.

Supporting Documentation complements the User's Manual by providing four appendices that help the user understand how the benefit-cost models were constructed. The appendices include: 1) a review of relevant literature; 2) a section on estimating costs for seismic rehabilitation; 3) a compilation of tables for the Seattle building inventory; and 4) some insights into the building rehabilitation of the nine cities visited during this project.

Computer Software to run the benefit/cost models is also available. The programs are on 3 ½" diskettes and can be used on IBM compatible personal computers.

- *Seismic Rehabilitation of Federal Buildings: A Benefit/Cost Model. Volume 1: A User's* Manual (FEMA 255, 1994, approx. 158 pages); *Volume 2: Supporting Documentation* (FEMA-256, 1994, approx. 71 pages) and Computer Software for the Seismic Rehabilitation of Federal Buildings. Prepared by VSP Associates, Inc., Sacramento, CA.

  This User's Manual and accompanying software present a second-generation cost-benefit model for the seismic rehabilitation of federal and other government buildings. Intended for facility managers, design professionals, and others involved in decision making, the cost/benefit methodology provides estimates of the benefits (avoided damages, avoided losses, and avoided casualties) of seismic rehabilitation, as well as estimates of the costs necessary to implement the rehabilitation. The methodology also generates detailed scenario estimates of damages, losses, and casualties. The Manual describes the computer hardware and software required to run the program. It also explains how to install the program, how to use Quattro Pro for Windows, and how to enter necessary data. A tutorial provides a fully worked example. Benefit/Cost analyses of eight federal buildings are included. The Supporting Documentation contains background information for the User's Manual including information on valuing public sector services, discount rates and multipliers, the dollar value of human life, and technical issues that affect benefit/cost analysis, such as seismic risk assessment and sensitivity analysis.

  Computer Software to run the benefit/cost model is available on 3 1/2" diskettes and can be used on IBM compatible personal computers with at least 386 CPU. The computer must also have Windows and Quattro Pro.

- *Establishing Programs and Priorities for the Seismic Rehabilitation of Buildings: Handbook* (FEMA-174, 1989, 122 pages) and *Establishing Programs and Priorities for the Seismic Rehabilitation of Buildings: Supporting Report* (FEMA-173, 1989, 190 pages). Prepared by Building Systems Development, Inc. with Integrated Design Services and Claire B. Rubin.

These two volumes provide the information needed to develop a seismic rehabilitation program, with particular reference to establishing priorities. The Handbook is intended to assist local jurisdictions in making informed decisions on rehabilitating seismically hazardous existing buildings by providing nationally applicable guidelines. It discusses the pertinent issues that merit consideration, both technical and societal, and suggests a procedure whereby these issues can be resolved. The Supporting Report includes additional information and commentary directly related to sections in the Handbook: supporting documentation, annotated bibliographies, and reproductions of selected laws and ordinances that are presented in summary form in the Handbook.

- *Financial Incentives for Seismic Rehabilitation of Hazardous Buildings - An Agenda for Action. Volume 1: Findings, Conclusions, and Recommendations* (FEMA-198, 1990, 104 pages); *Volume 2: State and Local Case Studies and Recommendations* (FEMA-199, 1990, 130 pages); and *Volume 3: Applications Workshops Report* (FEMA-216, 1990, about 200 pages). Prepared by Building Technology, Inc., Silver Spring, MD.

  The intent of these documents is to identify and describe the existing and potential regulatory and financial mechanisms and incentives for lessening the risks posed by existing buildings in an earthquake. Volume 1 includes a discussion of the methodology used for these documents, background information on financial incentives, as well as findings, conclusions and recommendations for use by decision makers at local, state and national levels. Volume 2 includes detailed descriptions of the twenty case studies that were examined as part of this project. Volume 3 reports on workshops for the development of local agendas for action in seismic rehabilitation. It includes directions for convening additional workshops and teaching materials, which can be used in such workshops. This information is directed primarily to groups that are interested in planning for local seismic mitigation in existing buildings who wish to convene a workshop to initiate the process.

- *Development of Guidelines for Seismic Rehabilitation of Buildings - Phase 1:* Issues Identification *and Resolution* (FEMA-237, November 1992, 150 pages). Prepared by the Applied Technology Council, Redwood City CA (ATC-28).

  This report is intended to assist in the preparation of Guidelines for the Seismic Rehabilitation of Existing Buildings. The report identifies and analyzes issues that may impact the preparation of the Guidelines and offers alternative as well as recommended solutions to facilitate their development and implementation. Also discussed are issues concerned with the scope, implementation, and format of the Guidelines, as well as coordination efforts, and legal, political, social, and economic aspects. Issues concerning historic buildings, research and new technology, seismicity and mapping, as well as engineering philosophy and goals are discussed. The report concludes with a presentation of issues concerned with the development of specific provisions for major structural and nonstructural elements.

- *Interim* Guidelines*: Evaluation, Repair, Modification and Design of Steel Moment Frames* (FEMA-267, 1995, approx. 248 pages). Prepared by the SAC Joint Venture, Sacramento, CA.

  These Interim Guidelines apply to welded steel moment frame (WSMF) buildings and structures that are subject to large inelastic demands from earthquakes. They are intended to provide practicing engineers and building officials with an understanding of the types of damage such structures may experience in strong earthquakes and the potential implications of such damage. This publication provides recommended methods for evaluating, inspecting, and repairing existing damaged WSMF buildings, as well as recommendations for designing and constructing new WSMF buildings and structures for improved performance in future strong earthquakes.

- *Handbook for the Seismic Evaluation of Buildings – A Prestandard* (FEMA-310, 1998, approx. 248 pages). Prepared by the American Society of Civil Engineers, Reston VA.

How to Order: FEMA publications can be obtained at no charge from:

FEMA Distribution Center
P.O. Box 2012
Jessup, MD 20794
PHONE: 1-800-480-2520;
FAX: (301) 497-6378

B.5 Earthquake Engineering Research Institute

The Earthquake Engineering Research Institute (EERI) publishes a variety of documents related to earthquake safety, preparedness, and loss reduction. A partial list of EERI publications is provided below.

- *Construction Quality, Education, and Seismic Safety. EF96-02*

  This white paper addresses a topic of critical importance to everyone involved in designing, constructing, and inspecting buildings so they perform successfully in an earthquake. Recent earthquakes have shown that the construction and inspection processes are responsible for a significant amount of unnecessary earthquake damage. The report examines the problem, focusing on the relationship between the education of construction trades people, code enforcement personnel, and the earthquake performance of structures. The focus includes strategies to improve education of, and existing training methods for, construction workers and building inspectors.

- *Expected Seismic Performance of Buildings. SP-10*

  Developed by the EERI ad hoc committee in order to help building owners, code administrators, and others involved in building maintenance programs understand how seismic design provisions and quality of construction affect earthquake performance. Focus on buildings in Seismic Zone 4 built to the recent 1991 Uniform Building Code

(UBC), and on older unreinforced masonry buildings rehabilitated under the Uniform Code for Building Conservation (UCBC).

- *Practical Lessons from the Loma Prieta Earthquake. LP-93*

  A report based on the proceedings of the symposium held in San Francisco, March 22-23, 1993. Edited by the National Research Council's Geotechnical Board, the publication consists of keynote papers presented at the major sessions, and an overview chapter that summarizes the principal lessons learned, as well as giving recommendations to improve seismic safety and earthquake awareness in California and other parts of the country vulnerable to earthquakes.

- *Public Policy and Building Safety, EERI Endowment Fund White Paper. EF96-01*

  This white paper has been written primarily for building officials and engineers involved in incorporating social, economic, and political considerations in decisions about building safety. It grew out of a concern that engineering design requirements often do not reflect a realistic understanding of many other issues important in their adoption. The paper is divided into four sections. Section I is a case study of the City of Los Angeles' recent experience in passing an inspection and repair ordinance for damaged steel frame buildings. Section II is a general discussion of the policy-making process. Section III is a checklist that summarizes the recommendations discussed in previous section. Section IV provides suggestions for further reading for those who desire more technical backup.

- *Reducing Earthquake Hazards: Lessons Learned From Earthquakes. 86-02*

  Report prepared by a large, multidisciplinary group of earthquake professionals who reviewed observations from many post-earthquake investigations. Disciplines involved include geosciences, engineering, architecture and urban planning, and social sciences. The objectives of the publications are: to inform about advances; to promote communication; to detail lessons learned; and to target areas for future research.

- *Seismic Retrofit Policies: An Evaluation of Local Practices in Zone 4 and Their Application to Zone 3, PF92-1*

  The report is a result of six months research on California seismic retrofit policies with an attempt to develop recommendations for use in areas of moderate seismic hazard.

How to Order: EERI publications can be obtained from:

Earthquake Engineering Research Institute
499 14th Street, Suite 320
Oakland, CA 94612-1934
PHONE: (510) 451-0905
FAX: (510) 451-5411

Appendix C: Earthquake Hazard

C.1 General

Earthquake risk has two basic components, hazard and vulnerability. The earthquake hazard is a quantification of the various ground effects at a specific site produced by earthquakes, and the likelihood that these effects will exceed certain levels. More simply stated, it is a representation of how hard the ground will shake, and how often it is likely to do so. Earthquake hazards are site specific. That is, they are different at each individual site, depending on the site's location and the properties of the ground beneath the site. Earthquake vulnerability is a quantification of how much damage a constructed facility is likely to experience, given that it is subjected to certain hazards. Again, more simply stated, vulnerability is a representation of how much damage is likely to occur when ground shaking of a certain level occurs. This appendix provides background information on earthquake hazards, and the way in which they are quantified for purposes of risk evaluation. A later appendix provides similar information on earthquake vulnerability.

C.2 Primary Earthquake Hazards

The primary effects produced by earthquakes, that result in damage to constructed facilities are *ground fault rupture* and *ground shaking.* These are described below, other secondary hazards are described in the following section.

C.2.1 Ground Fault Rupture

A fault is a weakened zone within the crust of the earth along which movement can occur. It can be thought of as being much like a crack in the rock that forms the earth's crust, and along which, the material on either side can move in opposite directions. It is this movement, or slipping, of the earth along these faults that produce earthquakes. When a fault slips, it is said to rupture. The amount of motion that occurs along the fault and the length of fault involved in the rupture is dependent on the size of the earthquake. Small earthquakes produce fault ruptures over only a few square meters of fault surface and include only a few millimeters of slip. Great earthquakes, such as the 1906 San Francisco earthquake, can include ruptures of a fault that extend for hundreds of kilometers with slippage between opposite faces of the fault being as large as 10 meters.

In most places, deep soil deposits cover the rock, and therefore, it is usually impossible to directly observe a fault. However, most large earthquakes produce so much movement along the fault that the soil overlying the rock is also forced to move with the rock that supports it. When this occurs, the movement of the fault can be directly observed on the ground surface.

Depending on the orientation of the fault with respect to the ground surface and the type of slippage that occurs, the ground surface features may consist of a crack that runs along the ground surface; a steep cliff, sometimes called a scarp; or a wide depression termed a graben. When any of these features appears on the ground surface, they are termed ground fault ruptures.

Large magnitude earthquakes can produce very severe deformations of the earth's surface along the zone of ground fault rupture. Figure C-1 is a picture of a fence line that crosses the San Andreas fault, north of San Francisco. The large offset seen in this fence occurred during the earthquake of 1906, when the ground in this area moved nearly 4 meters. Figure C-2 shows a scarp that occurred in Nevada in 1954, in an earthquake known as the Dixie Valley earthquake. When ground fault ruptures of the type and size shown in these figures occur, any structures constructed across the zone of rupture will be forced to follow the ground movement. It is almost impossible to design most types of structures to resist these types of ground fault rupture without very severe damage. Therefore, the best way to avoid fault rupture is to avoid building directly over the traces of known active faults, where ground fault ruptures are most likely to occur.

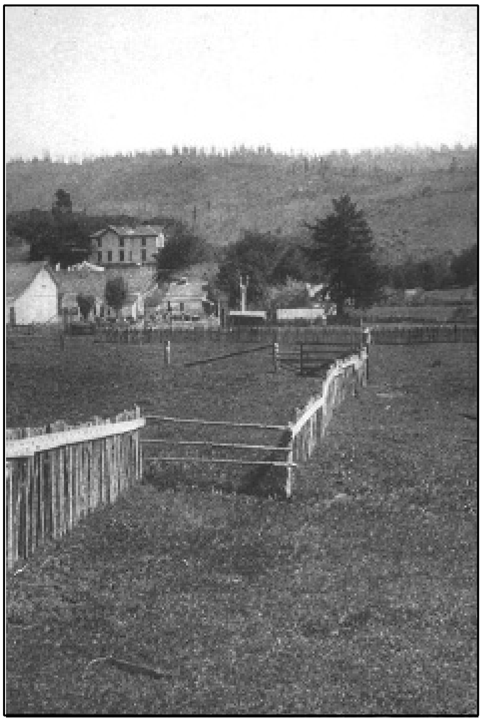


Figure C-1: Fault rupture along the San Andreas Fault, 1906 San Francisco earthquake (courtesy EQUIIS Photographic Database)

Figure C-2: Fault rupture along the Dixie Valley Fault, 1954 Dixie Valley earthquake (courtesy EQUIIS Photographic Database)

Ground fault rupture is most likely to occur along the faults that are most active. These faults are generally well defined and their traces have been mapped by the California Division of Mines and Geology (CDMG) in a series of maps known as Maps of Alquist-Priolo Earthquake Fault Zones ("Special Studies Zones" prior to January 1, 1994).

These maps show the locations of known active traces of faults in sufficiently large scale to allow individual streets and larger buildings to be identified. They are available from the CDMG by calling (916) 445-5716. A sample of such a map is shown in Figure C-3.

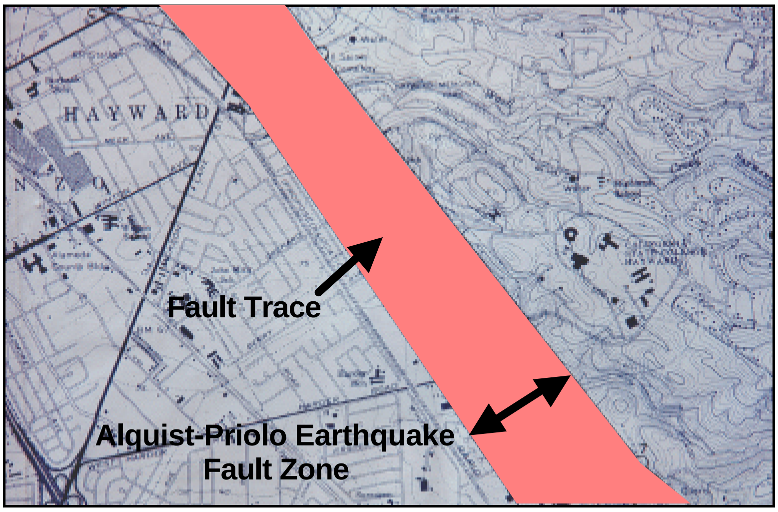


Figure C-3: Typical Alquist-Priolo Earthquake Fault Zone Map (courtesy CDMG)

C.2.2 Ground Shaking

Although fault rupture is the primary effect of an earthquake, ground fault ruptures are typically limited in extent and therefore do not pose a risk to most facilities. However, the movement that accompanies fault rupture produces violent ground shaking that radiates outward from the zone of fault rupture and through the ground for distances of many miles. This ground shaking is the single largest cause of earthquake damage.

The severity of ground shaking that occurs at a site, during an earthquake, is dependent on a number of factors. These include the size of the earthquake, the distance of the fault rupture from the site, the type and direction of movement that occurred along the fault, and the types of soils that underlie the site. In general, the closer a site is located to the zone of fault rupture, the stronger and more intense will be the ground shaking experienced by the site. Ground shaking is a very complex wave form, having components of different frequency and amplitude (much like the sound from an orchestra). The soils at a site tend to act as filters on this wave form, amplifying components at some frequencies while attenuating components with other frequency content. Generally, soft soils tend to amplify those components of ground motion that are most damaging to building structures, while rock tends to de-amplify these components.

As stated above, the farther a site is located from the zone of fault rupture, the less intense the ground shaking experienced at the site is likely to be. Also the larger an earthquake is, the more intense will be the ground shaking produced, the longer it will last, and the larger the distance over which intense ground shaking will be transmitted. Very small earthquakes may not produce noticeable shaking at all. Moderate magnitude earthquakes may produce ground shaking that can be felt over a distance of a few square miles, for a period of a few seconds. Large magnitude earthquakes can produce ground shaking intense enough to cause damage to constructed facilities for distances of more than 100 kilometers from the zone of fault rupture and the shaking can last for up to several minutes.

The severity of ground shaking can be characterized in a number of different ways. The most common way is through the use of an intensity reading. Intensity scales measure the severity of earthquake ground shaking at a site through evaluation of the way people react to it and its effects on typical types of structures such as chimneys and masonry buildings. Since the effects by which intensity is gauged are somewhat dependent on the quality of the effected construction, this is a somewhat subjective measurement. However, intensity is an easy concept to understand, so despite this limitation, it is still commonly used as a measure of ground shaking severity, and is one of the most common measures used in risk analysis. Several different intensity scales are in use around the world. In the United States, the most commonly used intensity scale is the Modified Mercalli scale, shown in Table C-1.

Table C-1

MODIFIED MERCALLI INTENSITY SCALE.

MODIFIED MERCALLI INTENSITY SCALE	
I.	Not felt. Marginal and long-period effects of large earthquakes.
II.	Felt by persons at rest, on upper floors, or favorably placed.
III.	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV.	Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frames creak.
V.	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI.	Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken, knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visible, or heard to rustle).
VII.	Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.
VIII.	Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX.	General panic. Masonry D destroyed; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.
X.	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks to canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI.	Rails bent greatly. Underground pipelines completely out of service.
XII.	Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Source: Richter, C.F. Elementary Seismology. San Francisco CA: W. H. Freeman Co., 1957.

Note: To avoid ambiguity, the quality of masonry, brick, or other material is specified by the following lettering system. (This has no connection with the conventional classes A, B, and C construction.)

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses, like failing to tie in at corners, but neither reinforced nor designed to resist horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

For a given earthquake, a wide range of different intensities of ground shaking occurs, with the most intense motion being experienced near the site of fault rupture, and on deposits of soft soils, as previously described. Following the occurrence of a damaging earthquake, the USGS typically plots a map showing the distribution of different intensities of ground motion over the affected region. Figure C-4 is the intensity map produced following the 1989 Loma Prieta earthquake. Study of these maps allows estimates of probable intensities of ground motion at different sites in future earthquakes, to be estimated.

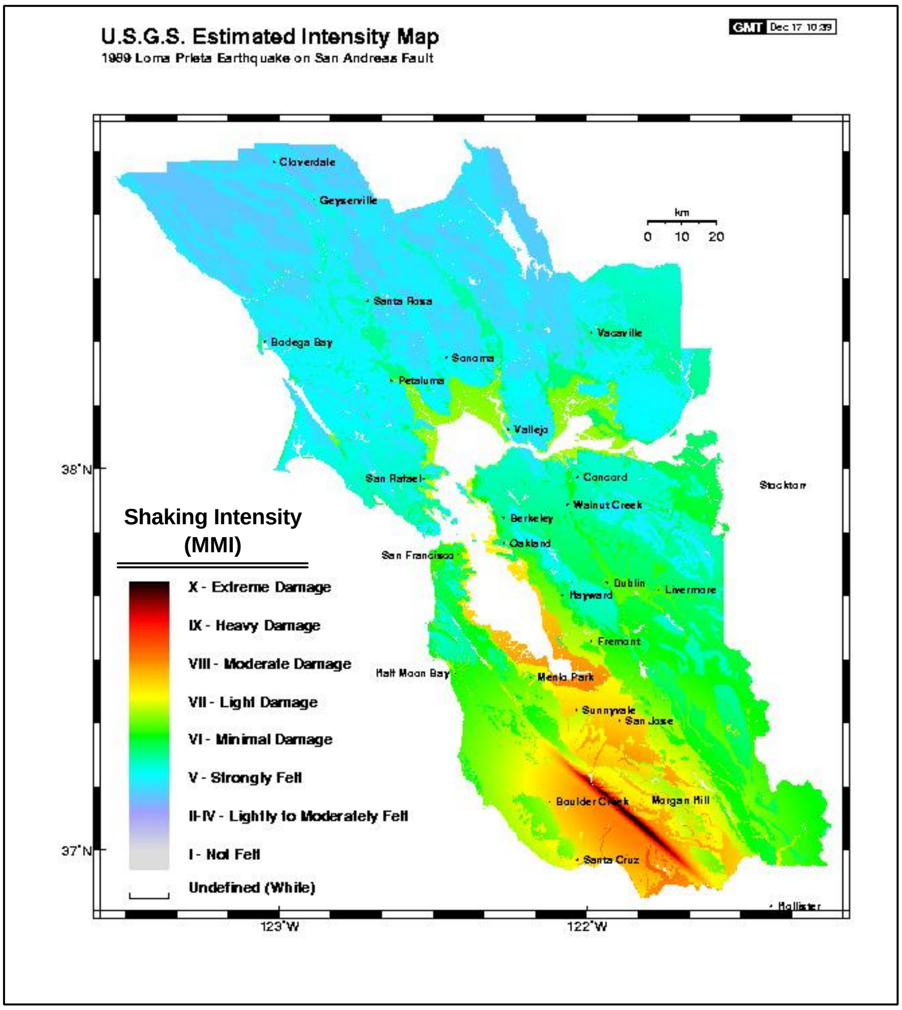


Figure C-4: Isoseismal map for the 1989 Loma Prieta earthquake (courtesy USGS)

Although intensity is a useful measure of ground shaking severity for the purpose of risk analysis, it is not particularly useful for engineering purposes. In order to quantify the effects of earthquake ground shaking for purposes of structural analysis and design, engineers prefer to characterize ground shaking by the strength of ground accelerations, velocities and displacements, and the frequency content of the waves that transmit this motion. Engineers commonly used a tool, known as a response spectrum, to depict these quantities. The response spectrum is a plot that relates how hard structures having specific dynamic characteristics will shake, when subjected to a specific ground motion. Important ground motion parameters that may be obtained from a response spectrum, and which are often used by engineers in characterizing ground motion include: peak ground and spectral response accelerations, peak ground and spectral response velocity, and peak ground and spectral response displacements.

C.3 Secondary Hazards

Ground fault rupture and ground shaking are the primary earthquake-induced site hazards. Secondary hazards include several types of potential ground failure including liquefaction, lateral spreading, land sliding and compaction. These are described in the sections below. In order to accurately assess whether a site is susceptible to these secondary hazards, site specific geotechnical investigation is typically required. This may include obtaining soil samples, by drilling borings, and analyzing the soil in testing laboratories. However, CDMG has recently published a series of maps known as "Maps of Seismic Hazard Zones," that indicate in an approximate manner the general susceptibility of different regions to these ground failures. One such map is shown in Figure C-5. If reference to such maps indicates significant potential for one of the ground failures described below, a geotechnical engineer should be retained to more accurately assess the real significance of this hazard, on a site-specific basis.

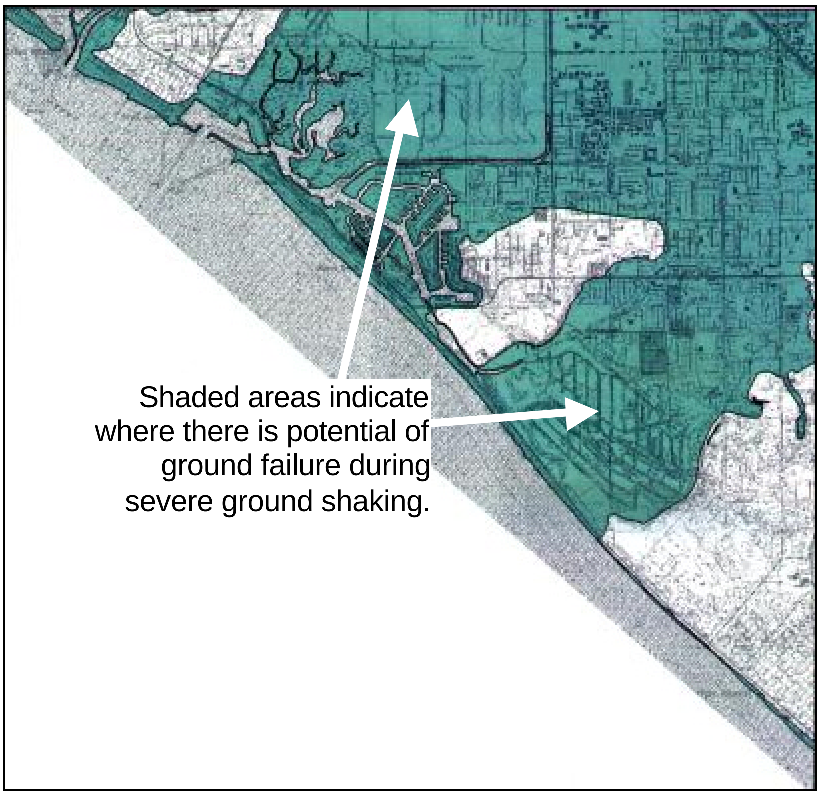


Figure C-5: Typical Seismic Hazard Zone Map (courtesy CDMG)

C.3.1 Liquefaction

Liquefaction is a type of ground failure that can occur on sites underlain by deposits of loose sands or silts, with a high water table present. Under the action of strong ground shaking, loose sand and silt soils become compacted and more dense. Essentially, the motion induced by the ground shaking tends to sift these materials, allowing particles to fill in the voids between adjacent particles. If this densification occurs in saturated soils, as the soil particles fill in the voids between particles this forces out the water which occupied that space. The displaced water generally rises to the ground surface. Under severe ground shaking, this effect can be very severe, creating enough pressure in the rising water to cause large geysers of muddy water to be ejected from the ground.

When liquefaction occurs on a site, it can affect structures in several ways. First, the rejection of water from the soils and the rising of this water to the ground surface can cause a quick sand like condition, in which soil supported foundations can exceed the temporary bearing strength of the soil, and in which buried utilities can be come buoyant and float to the surface. The quick sand condition can result in local settling and tilting of foundations with secondary damage occurring to the supported structures. This effect can be made more sever through the ejection of sand materials, in the geysers that liquefaction creates. As sand and silt material is ejected from the ground surface, this creates voids in the ground beneath the surface, which leads to further settlement of the ground and ground supported structures.

Although liquefaction is a relatively rare phenomena, it can cause spectacular damage to structures. Figure C-6 is a photograph of several large apartment buildings in Japan, that suffered extreme tilting due to liquefaction that occurred in the 1964 Nigaata earthquake. Construction on deep foundations, such as piles and piers, tends to be more resistant to the effects of liquefaction than are structures supported on shallow spread footing foundations. On sites where liquefaction potential represents a significant threat to existing construction, the risk can be reduced through a variety of ground improvement techniques. These include injection of chemical stabilizing materials into the liquefaction susceptible soils, and installation of dewatering systems.

Figure C-6: Apartment buildings damaged by liquefaction, 1964 Nigaata earthquake (courtesy EQUIIS Photographic Database)

C.3.2 Lateral Spreading

Lateral spreading is a secondary effect of soil liquefaction. When liquefaction occurs in soils that are on a sloping surface, or are adjacent to an excavation or embankment, the liquefying soils can flow downhill under the force of gravity. This typically results in the formation of characteristic fissures in the soils running parallel to the open face, or embankment edge.

Lateral spreading can also be extremely destructive of structures, including structures supported on pile foundations. As the ground flows, it tends to drag with it, any structures that are supported on or within it. Since the displacement caused by these flows is typically highly non-uniform, these movements can literally rip structures apart. Figure C-7 is a picture of a bridge that was destroyed by lateral spreading in an earthquake in Costa Rica, in 1991.

Figure C-7: Bridge Destroyed by Lateral Spreading, 1991 Limón, Costa Rica earthquake (courtesy EQE International, Inc.)

C.3.3 Landsliding

Earthquake-induced landslides are often triggered in areas of steep terrain. Most are minor and cause only local damage. However, very large earthquakes can trigger catastrophic landslides. For example, a large earthquake off the coast of Peru in 1971 triggered a landslide high in the Andes Mountains, which buried the town of Ungay, killing 20,000 people. If a landslide occurs underwater or falls into a closed body of water, it can cause a tsunami or seiche, which locally can cause considerable damage. A landslide-induced seiche destroyed the town of Valdez in 1964 during the great (Mw 9.2) Prince William Sound, Alaska earthquake.

C.4 Quantifying Seismic Hazards

Small magnitude earthquakes, that produce low intensity effects occur very frequently, while great earthquakes, that produce very intense and destructive earthquake effects occur very infrequently. In order to realistically assess the seismic risk to a development (community, agency or business) it is necessary to estimate the probability that hazards of given severity will be experienced by the development. The risk of damage or loss can then be computed as the product of the probability that earthquake effects of given severity will occur and the probable loss, given that these earthquake effects are experienced. For example, if it is known that there is a 10% chance in the next year that MMI VIII ground shaking will be experienced, and that if MMI VIII ground shaking is experienced a financial loss of $100 million will occur, then the risk has been defined as being a 10% chance that a loss of $100 million will occur.

The probability that hazards of given severity will be experienced is typically represented graphically in the form of a hazard curve. A typical hazard curve is shown in Figure C-8. These curves can be used to estimate the probability that earthquake ground shaking (or other hazards) will be experienced at a site, within a defined period of years. Thus, in Figure 8, it can be seen that the site for which this curve has been developed would be expected to experience Modified Mercalli Intensity VI ground shaking approximately 1 time every 10 years, Modified Mercalli Intensity VIII ground shaking one time every 100 years, and Modified Mercalli Intensity IX ground shaking every 1,000 years or so. Alternatively, this data can also be read to mean that in any year, there is approximately a 10% chance of experiencing MMI VI ground shaking at the site, a 1% chance of MMI VIII and a 0.1% chance of experiencing MMI IX ground shaking. Such data can then be used to estimate probable losses over a period of time.

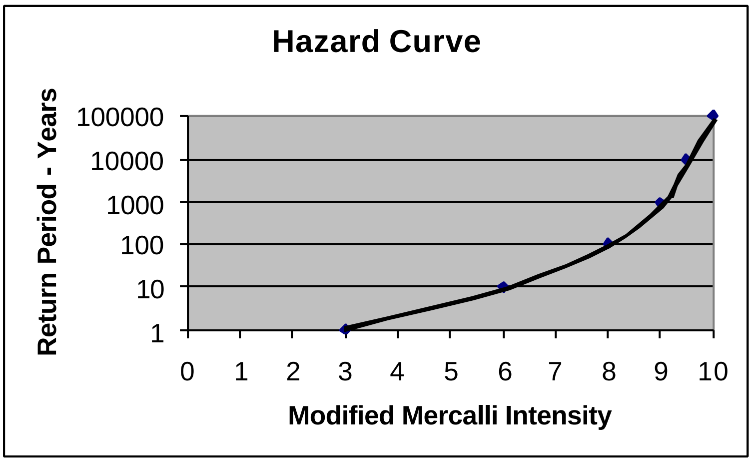


Figure C-8: Typical Seismic Hazard Curve

Hazard curves are typically developed by geotechnical engineers and seismologists, using specialized software that can perform the complex calculations involved. Generally, in order to develop a hazard curve for a site, the seismologist or geotechnical engineer needs to identify all of the potential earthquake sources in a region that could cause ground shaking (or other hazards) at the site, determine the distance of these sources from the site, estimate the return period or probability of different size earthquakes on each of these sources, then calculate the probable intensity of ground shaking at the site, presuming that an earthquake of given magnitude occurs on each of these sources.

The USGS has performed such hazard calculations, on a regional basis, for sites located around the United States. This data, which is available on the world wide web, through the USGS, can be used to perform preliminary loss estimates in lieu of retaining a geotechnical engineer to develop site specific hazard data.

The sections below describe the basic factors and procedures used in hazard calculation.

C.4.1 Earthquake Sources

Most earthquakes occur as a result of strains that build up in the earth's crust under the influence of gravitational forces. Rather than being solid, the earth's crust is actually quite fractured and as shown in Figure C-9, is actually composed of a series of individual tectonic plates. These plates are very large. One of them underlies most of North America while another underlies much of the Pacific Ocean. Under the influence of forces created by the rotation of the earth, the tectonic plates tend to move with respect to each other. Generally, each of the plates tends to spin in a counter-clockwise direction, but in addition, some plates are growing outward, from areas of sub-sea volcanic activity, while others are shrinking as they dive beneath the edges of neighboring plates. The relative motion of each these plates with respect to the adjacent plates is very slow, but constant. For example the edge of the Pacific Plate which lies along the western edge of the State of California tends to move about 2-1/2 inches (60 mm) relative to the North American plate to its east. Locally, where the plates abut each other, they tend to interlock preventing movement from occurring. As a result, over a period of many years, the plates build up very large stresses. Eventually, the stresses within the rock build up to a point where they exceed the strength of the rock. When this happens, a rupture occurs, allowing the edges of the plate that were interlocked to rapidly snap forward to a new displaced position, releasing a portion of the previously accumulated strain and stress, in the form of energy, that radiates through the ground as ground shaking.

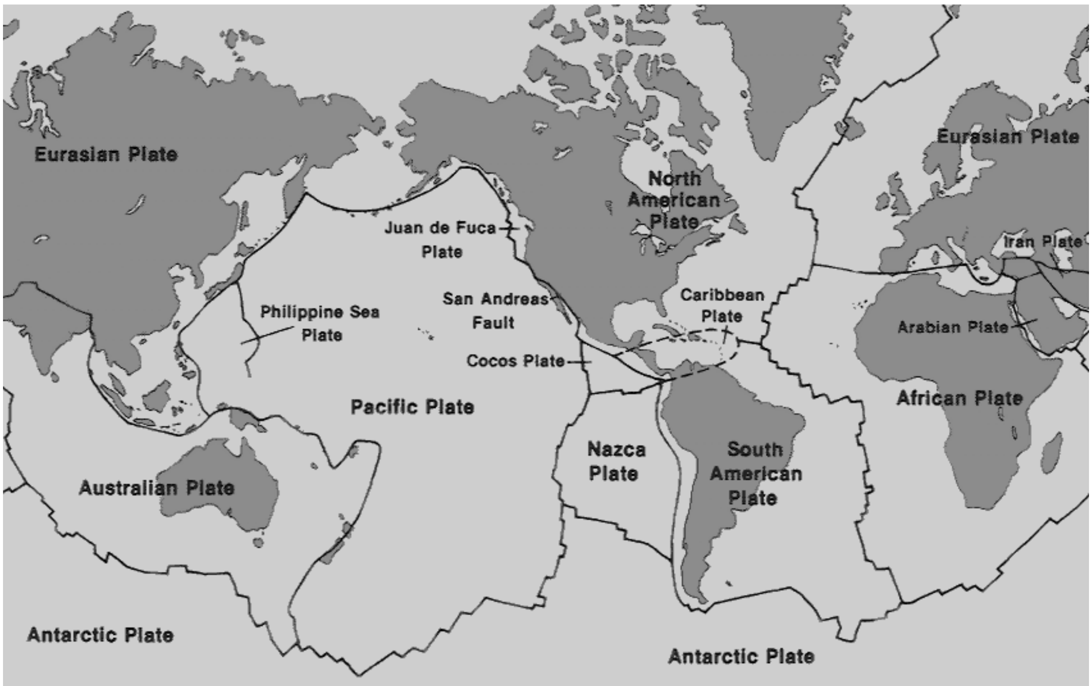
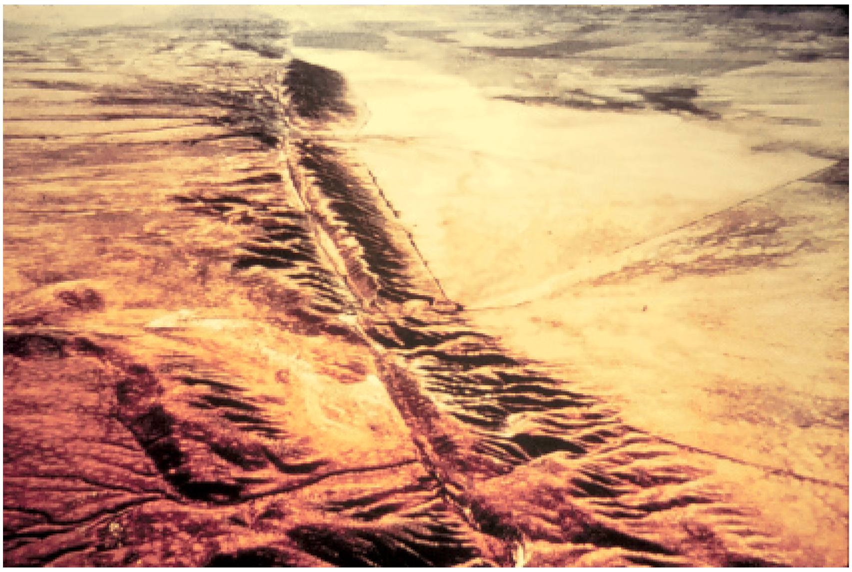


Figure C-9: Map of Tectonic Plates (courtesy USGS)

Earthquakes nearly always occur along faults, as this is where the earth's crust is weakest, and where the rupture process can most readily occur. The largest and most active faults, tend to be located at, or close to the boundaries between the tectonic plates. The San Andreas fault, for example, the source of the great 1906 earthquake in northern California, and a similar sized event centered near Fort Tejon, in southern California, in 1857, runs along the boundary between the Pacific and North American plates. Typically, the earth's crust adjacent to such plate boundaries is highly fractured and broken, due to past earthquake activity and tectonically induced stresses. As a result, a number of large active faults are typically present adjacent to plate boundaries. This is the case in coastal California as well.

The path of a fault, along the ground surface is known as its trace. The traces of highly active faults, are usually quite evident, due to the unique ground features that constant movement along these faults have created. The San Andreas fault, for example, has created a deep rift valley along much of its length, that is clearly visible from the air (See Figure C-10). Other faults are evident because of the sharp faces of hillsides that were created by constant uplift of the ground along the fault. Frequently, it is possible to detect the traces of active faults by observing the courses of rivers and streams, whose courses are often offset along the fault trace, by past earthquake activity.



C-10: Aerial view of the San Andreas Fault, near Coachella Valley (courtesy USGS)

Not all faults are equally active and many faults have no obvious traces on the ground surface. Such faults are sometimes termed hidden or undiscovered faults. Most faults tend to have a set activity rate. That is, they tend to produce earthquakes of a given size, with some regularity over a given interval of years. The San Andreas fault for example, is thought to produce earthquakes like the great 1906 event, approximately one time every 300 years or so. The more active a fault is, the more likely that it has produced surface effects that have allowed it to be mapped. Future earthquakes are most likely to occur along these known highly active faults. However, earthquakes can also occur along other less active faults, that are not presently known. This has happened several times in California in recent years. The 1971 San Fernando, 1987 Whittier Narrows, and 1994 Northridge earthquakes all occurred on previously unknown faults. Figure C-11 is a map showing the major known active fault systems in California.

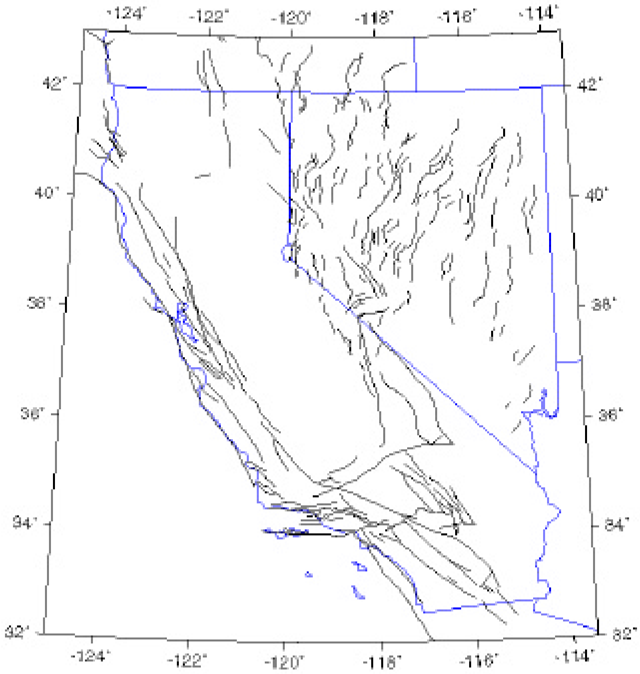


Figure C-11: Map of major active fault zones within California and Nevada (courtesy USGS)

To account for the possible presence of unknown or unmapped faults, a seismic hazard assessment will incorporate background seismicity in addition to known faults as potential sources of earthquake hazard. Background seismicity defines geographically diffuse earthquake sources with magnitudes ranging from the smallest of interest, typically $M_w > 5$, up to about M_w 7. The frequencies of these earthquakes are calculated from the observed rates of historic earthquakes.

Figure C-12 shows the location of major earthquakes that have occurred in California since 1769. Careful inspection of this figure, and comparison with Figure C-11, indicates that the majority of these earthquakes have occurred along known, mapped faults, and in a particular along the San Andreas system, comprised of the San Andreas fault itself and also its splay faults. In northern California the San Andreas fault system includes the San Andreas, Hayward, and Rodgers Creek faults. In southern California, this fault system is made up of the San Andreas, San Jacinto, Imperial, and Whittier-Elsinore faults. Most, but not all of the relevant movement between the Pacific and North American plates is relieved by slip along these faults. However, significant slip also occurs along other faults as indicated in Figure C-12.

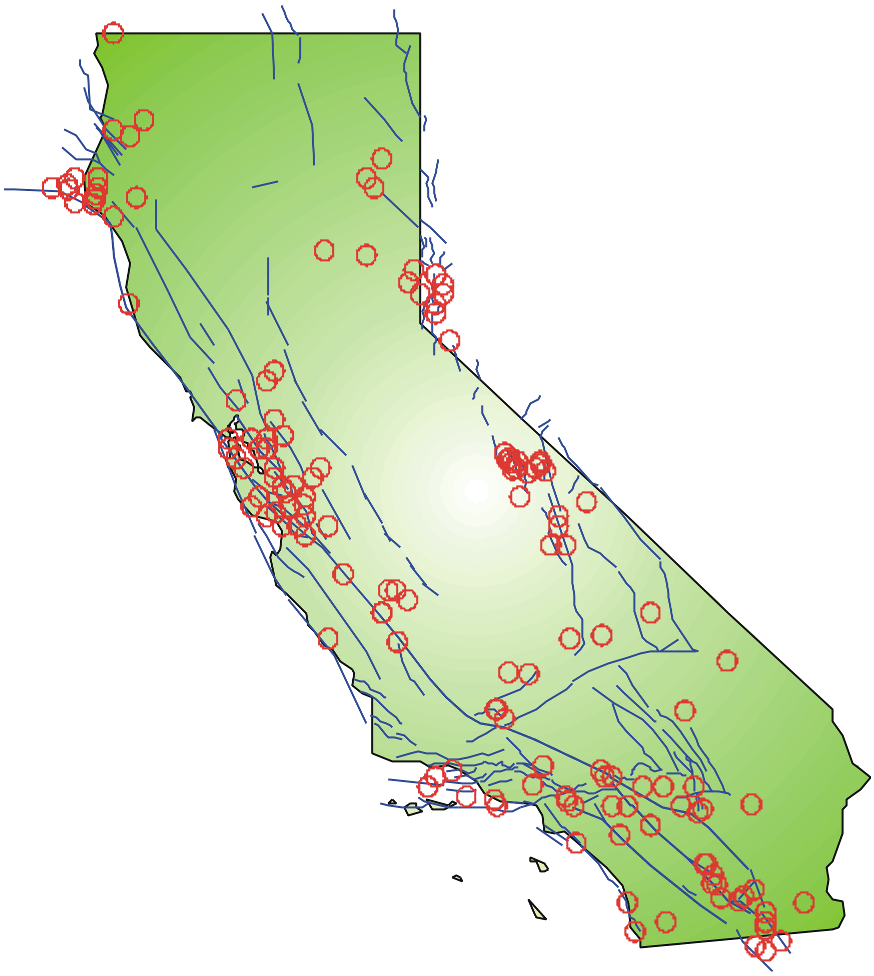


Figure C-12: Map of Major California Earthquakes since 1769

C.4.2 Quantifying Earthquake Size

The size of an earthquake is typically characterized by its magnitude. Magnitude is actually a measurement of the amount of energy released by a fault rupture during an earthquake and is directly related to the length and depth of the fault that ruptured, the amount of displacement along the fault, and the strength properties of the rock that break during the earthquake. The earthquake's magnitude is estimated by measuring the amplitude of seismic waves recorded on seismograms at stations distributed around the earthquake rupture, accounting for the distance between the recording site and the rupture and the geologic conditions beneath the site. It is important to keep in mind that ground motions from any earthquake may range from high to low depending on the location with respect to the earthquake rupture and the specific geologic conditions. Therefore, any one measurement of the ground motion may give an indication of the magnitude, but is generally not enough information to constrain the size of an earthquake rupture. The earthquake's magnitude may only be deduced by recording many seismograms surrounding the earthquake to get an indication of the dimensions of the rupture. This is why the news media often gives different reports of the magnitude of an earthquake. Initial estimates of earthquake magnitude are typically based on the readings obtained from a relatively few instruments. As more instrumental data becomes available, it is possible for earth scientists to improve their estimates, and make them more accurate. Several weeks or months after the earthquake, earth scientists can also map the aftershock patterns and surface displacements that have occurred which give an independent indication of the dimensions of the earthquake rupture and, therefore, the magnitude of the earthquake.

A number of different magnitude scales have been developed to estimate the size of the earthquake. The more common scales are the Richter, local, body-wave, surface-wave, and moment magnitudes. These scales are based on various measurements of the seismic waves. Especially for larger earthquakes, these magnitudes may differ from one another. The moment-magnitude scale (M_W) is the most physically based, because it is directly related to the rupture dimensions and displacement on the fault. Geologic and seismic observations have led to the conclusion that larger earthquakes typically rupture a larger section of a fault, cause the ground to vibrate longer, and radiate more energy than smaller earthquakes.

C.4.3 Recurrence Rates

For many faults of the San Andreas system, there is sufficient paleoseismic information to characterize the repeat time of large earthquakes (called characteristic earthquakes). Knowing the repeat time and the date of the last large earthquake on the fault, scientists can determine where the fault is in its earthquake cycle, the time period between large earthquakes. This allows them to calculate the probability that the next large earthquake on the fault will occur by a specific date in the future. A fault with an elapsed time since the last large earthquake approaching the average repeat time has a relatively high probability of producing another large earthquake in the near future. In contrast, a fault with an elapsed time much smaller than the repeat time of large earthquakes have relatively low probabilities of producing another large earthquake soon.

The southern segment of the Hayward fault is a prime example of a fault that is relatively late in its earthquake cycle. The last large earthquake on this fault was in 1836 (162 years ago) and large earthquakes are expected to occur on this fault every 210 years or so. Several segments of the San Andreas Fault closest to Los Angeles are also late in their earthquake cycle and pose a higher than average hazard compared to their long-term potential. San Bernardino is particularly vulnerable in the near-future, since both the nearby San Andreas and San Jacinto Faults are late in their cycle.

C.4.4 Attenuation Relationships

A mathematical relationship between the magnitude, distance from the fault to a particular site, and the intensity of ground shaking likely to occur at the site is known as an attenuation relationship. Some attenuation equations also take other factors into account, such as site soil characteristics, the type of faulting, and the regional geologic characteristics. Such attenuation equations are used to estimate the expected level of ground shaking from various postulated earthquakes when developing a hazard curve.

Attenuation equations are derived by Seismologists by performing statistical analyses of data bases of recorded ground motions from past earthquakes. Attenuation relationships can not provide “exact” predictions of the ground shaking intensity at a site from a specific earthquake. However, they can be used to provide a “best estimate” of the likely intensity of such ground shaking, together with an indication, based on the statistical scatter present in the data base, as to how much more or less intense the ground shaking might actually be than the indicated amount.

The shaking parameters that are most commonly estimated by such an equation are the Modified Mercalli intensity (MMI), the peak ground acceleration (PGA), and the response spectral acceleration (Sa). In many urbanized areas, such as California, strong ground shaking is recorded on accelerographs. Such recordings represent a quantitative measure of the ground shaking in terms of the acceleration of the ground as a function of time. It is these recordings that are used to develop attenuation relationships.

C.4.5 Site Amplification

The amplitude, duration, and frequency content of the ground shaking at a given point on the Earth’s surface is strongly affected by the geologic materials that underlie the site. Deeper, softer materials will tend to increase the amplitude, duration, and predominant period of the ground motion, except possibly at high frequencies as noted below. High levels of ground shaking on soft soils, such as Bay mud along the margins of San Francisco Bay, will strongly attenuate high-frequency ground shaking through nonlinear soil response, which can actual result in de-amplification. However, this same nonlinear behavior will generally amplify the longer-period components of ground motion in these same deposits.

The best means of identifying areas where ground shaking is likely to be amplified by the underlying soils is to determine the average shear-wave velocity in the upper 30 meters of the deposit ($V_{s,30}$). This velocity can be used directly to determine the amplification potential of the deposit by means of defined amplification factors, or such measurements can be correlated with geologic map units to identify those units with given ground-shaking amplification characteristics. This latter effort is currently being done for all of California by the CDMG under the auspices of the 1990 Seismic Hazards Mapping Program.

Appendix D: Earthquake Vulnerability

D.1 General

Earthquake vulnerability is a measure of the damage a constructed facility is likely to experience given that it is subjected to ground shaking, or other hazards, of specified intensity. The dynamic response of a structure to ground shaking is a very complex behavior that is dependent on a number of inter-related parameters that are often very difficult, if not impossible, to precisely predict. These include: the exact character of the ground shaking that the building will experience; the extent to which the structure will be excited by and respond to the ground shaking; the strength of the materials in the structure; the quality of construction and condition of individual structural elements; the interaction of the structural and non-structural elements of the building; the weight of furnishings and contents present in the building at the time of the earthquake; and other factors. Most of these factors can be estimated, but never precisely known. As a result, it is typically necessary to define vulnerability functions for buildings within levels of confidence. Figure D.1 is a typical vulnerability curve for a hypothetical facility, relating projected damage to ground shaking intensity, with levels of confidence expressed.

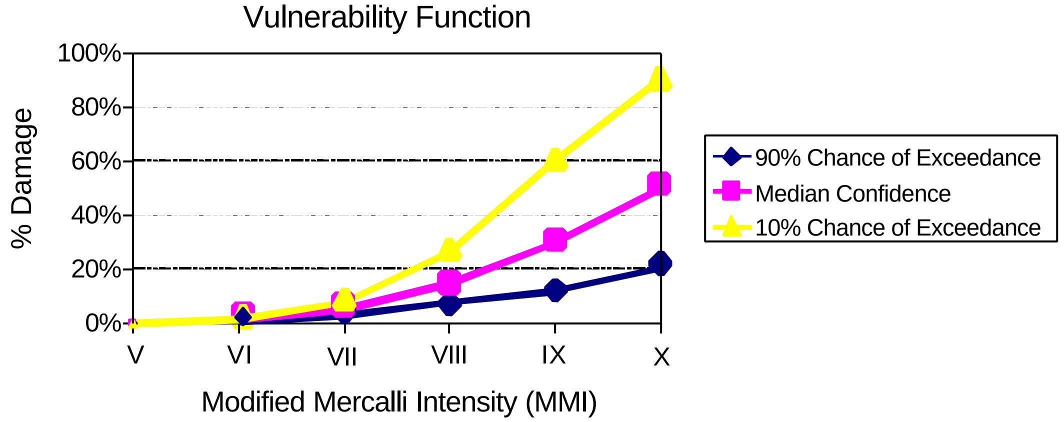


Figure D-1:   Typical Vulnerability Function

In Figure D-1, damage is expressed on a percentage scale, ranging from none (0%) to complete (100%), as a function of a ground motion parameter, in this case, Modified Mercalli Intensity (MMI). Three separate curves are shown in the figure. The middle curve, represents the median confidence level estimate. This represents a best estimate of the probable damage that would be experienced by the facility at a given ground motion intensity, and given the amount of data that was available upon which to form the estimate. The actual damage experienced by the facility could either be less or greater than that indicated by the median curve. In fact, it is equally likely that actual damage would be less than the median estimate as it is that it would be greater than the median estimate.

The upper curve in the figure is labeled as being associated with a 10% chance of exceedance. This means that there is only a 10% chance that the actual damage experienced by the facility would be greater than indicated by the curve and a 90% chance that it would be less. Similarly, the lower curve is indicated to represent a 90% chance of exceedance, indicating that there is a 90% chance that damage would be less than indicated by this lower curve, and only a 10% chance that it would be greater. This difference between the lower, median and upper curves is a measure of the uncertainty inherent in the vulnerability estimate. Almost all vulnerability estimates have significant levels of uncertainty associated with them. In large part, this is because the estimates are made without performing detailed studies of the construction, condition and behavior of the facility. Often, vulnerability estimates are made based on visual observations, and without referencing drawings or performing engineering calculations. To the extent that more detailed study of the construction, condition and behavior of the structure is performed, through review of site specific soils data, the construction documents for the building, and the quantification of structural characteristics with calculation, it is possible to reduce this uncertainty and make the estimates more precise.

Generally, development of vulnerability estimates requires the specialized knowledge of a structural engineer, expert in earthquake engineering. Three basic methods are commonly used by such engineers to develop vulnerability estimates. One of these is termed an experience data approach, the second, an engineering approach, and the third a combined approach. The experience data approach is based on the fact that certain classes of constructed facilities tend to share common characteristics and to experience similar types of damage in earthquakes. A series of standard vulnerability functions have been developed over the years for these classes of buildings. When using the experience data approach, it is only necessary to identify the class of construction that the facility may be characterized as, and then to make reference to one of these standard vulnerability functions. A commonly used reference for such standardized vulnerability matrices is ATC-13[1]. Loss estimates that are made using this approach tend to be highly uncertain and are more valid when used to evaluate the risk of large portfolios of facilities, than for individual facilities. This is because when applied to large portfolios

1 Applied Technology Council. ***Standardized Loss Estimation Methodology for Buildings in California.*** Report No. ATC-13, Redwood City, CA, 1985.

of facilities, the uncertainties associated with estimation of the vulnerabilities of the individual components of the portfolio tend to balance out. A useful reference for performing vulnerability estimates of buildings using the experience data approach is the publication ATC-21[2].

In the engineering approach, engineering calculations are used to quantify the amount of force and deformation induced in the facilities by the earthquake ground shaking, and to compare these with the capacity of the structure to resist these forces and deformations. Engineered estimates of vulnerability also tend to have significant uncertainties associated with them, because it is very difficult to accurately quantify the precise strength and deformation capacity of the structure and also to predict its response.

The combined approach, in which both engineering calculations and experience data are used to estimate vulnerability is the least uncertain in that it allows calibration of the engineering calculations with the observed behavior of actual structures. This is the approach most commonly used when knowledgeable structural engineers perform either vulnerability estimates or upgrade designs for facilities. A number of standardized methodologies have been developed in recent years to guide engineers through this process. The most recently published methodologies may be found in FEMA-273[3], FEMA-310,[4] and ATC-40[5].

The following sections describe the intent of the building codes, with regard to seismic performance, and generalized performance data for typical classes of construction.

D.2 Buildings and Structures

D.2.1 Building Codes

The building code sets minimum criteria for the structural design of buildings. For many years, building codes enforced by local governments in California have been based on the *Uniform Building Code* (UBC)[6], a model building code developed by the International Conference of Building Officials. The first edition of this code was published in 1927 and updated editions of this code have been published on a three-year cycle, since. Since, 1991, California cities and counties have been required to adopt the same edition of this code, as is adopted by the State of California. The

[2] Applied Technology Council (ATC). ***Rapid Visual Screening of Buildings.*** Report. No. ATC-21, Redwood City, CA, 1987.

[3] Federal Emergency Management Agency (FEMA). ***NEHRP Guidelines for Seismic Rehabilitation of Buildings.*** Report No. FEMA-273. Washington, D.C., 1997.

[4] Federal Emergency Management Agency (FEMA). ***Standard Methodology for Seismic Evaluation of Buildings.*** Report No. FEMA-310. Federal Emergency Management Agency. Washington, D.C., 1998.

[5] Applied Technology Council (ATC). ***Methodology for Seismic Evaluation and Upgrade of Reinforced Concrete Buildings.*** Report No. ATC-40. Redwood City, CA, 1987.

[6] International Conference of Building Officials (ICBO). ***Uniform Building Code***. Whittier, CA, 1997.

State has typically adopted the most recent edition of the UBC, within about a year of its first publication. However, prior to 1991, the building code enforced by many cities was often quite out of date. With the publication of the 1997 edition of the UBC, the International Conference of Building Officials (ICBO) ceased publication of model codes. Future codes in California are likely to be based on the International Building Code, a model code published by the International Code Council, a consortium of the International Conference of Building Officials, the Building Officials and Code Administrators International, and the Standard Building Code Congress International.

The earthquake design provisions contained in the UBC have traditionally been based on recommendations developed by the Structural Engineers Association of California (SEAOC). These recommendations have adopted a seismic design philosophy intended to protect life safety, but allow for some structural and potentially significant nonstructural damage for earthquake levels as severe as can be expected at some sites in the most active seismic regions of California. The provisions are based on the observed performance of real structures in past earthquakes. After each major earthquake, engineers investigate the types of damage that occurred and develop improvements to the code to allow it to meet its basic performance criteria, more reliably. The code implicitly sets forth the following three-level earthquake performance criteria:

1. Resist minor levels of earthquake ground motion with no structural damage and with only minor damage to nonstructural features such as glazing, architectural finishes, and suspended ceilings.

2. Resist moderate levels of earthquake ground motion with minor repairable structural damage, and possibly some extensive nonstructural damage.

3. Resist major levels of earthquake ground motion, which has an intensity equal to the strongest either experienced or forecast for the building site, without collapse but possibly with some major structural as well as extensive nonstructural damage.

Buildings designed in accordance with the UBC are anticipated to experience significant damage and loss, when affected by a major earthquake. Further, the design provisions of the UBC primarily address damage caused by ground shaking. They do not address the effects of other site hazards, such as liquefaction, consolidation, landslides, and ground-surface rupture. Any of these types of ground failures can result in excessive damage and potentially, even collapse of buildings meeting the code criteria. Major changes to the building code criteria have been adopted following each major earthquake that has affected California including the 1994 Northridge, 1989 Loma Prieta, and 1971 San Fernando events.

D.2.2 Lateral Force-resisting Systems

Buildings are designed to resist wind and earthquake forces through the provision of a lateral force-resisting system. The lateral force-resisting system for a building typically comprises a combination of vertical and horizontal elements and their connections.

Typical vertical elements are frames (beams and columns), braces, and walls. Typical horizontal elements are roofs, floors, and braces. Horizontal elements are usually termed diaphragms. Details of how these elements are constructed and interconnected are critical to a building's seismic performance.

D.2.3 Typical Configuration Deficiencies

A building's configuration, that is its basic shape, can have a significant impact on the way it performs in an earthquake and there are many geometric features of a building that can result in poor structural performance. Some of the most important of these are soft and weak stories, torsional systems, and discontinuous elements. Soft and weak stories occur in buildings when there are fewer walls or frames, or taller floor to floor heights in the first story, than in stories above. Unfortunately, because architects like to design buildings with high ceilings and airy spaces at the first story, this is a very common condition. A building is said to have a torsional system if in the layout of the vertical elements of the lateral force-resisting system are arranged such that instead of just shaking back and forth, the building tends to twist when affected by ground shaking. This is a very common defect in buildings located on a corner, which will often have solid walls on two sides and open walls on the street side. Discontinuous elements are another serious problem. An example of a discontinuous element, is a solid wall that rises from the second story through the roof level, and is supported on columns at the first story. Such configurations can be problematic because the strong elements above can literally crush the weaker elements below.

D.2.4 Performance of Typical Building Types

D.2.4.1 Wood Frame Buildings

Wood frame structures are typically four stories or less in height. The most common types of wood frame construction consist of repetitively framed wood joists, supporting plywood or straight board flooring, and supported by light framed walls. The walls are typically comprised of 2x4 vertical studs, sheathed with various structural panels, such as plywood, or architectural finishes such as plaster or gypsum board. Most low-rise residential construction in California is of this type, as are many smaller commercial buildings.

Wood-frame construction can be supported on a slab-on-grade, a concrete or masonry stem wall, or on a wood cripple wall foundation. Stem walls are concrete or masonry foundations that project above the ground. Cripple walls are short stud walls (varying from a few inches in height to several feet) between the foundation and the first floor level. Both are used to elevate the first floor above the ground and provide ventilation under the building. Many older wood frame buildings have no foundations, or weak foundations constructed of unreinforced masonry or poorly reinforced concrete.

When properly designed and constructed, wood frame buildings have performed very well in strong earthquakes. This is because these structures tend to be light and typically have many walls providing significant strength, stiffness, and redundancy. Buildings with heavy finishes, such as masonry veneers on perimeter walls, or slate or clay tile roofs tend to be heavier, and more susceptible to damage.

In smaller, single-story structures, the most common seismic deficiency consists of a lack of adequate anchorage of the building to its foundation. This can result in a building sliding off of its foundation, resulting in extensive damage. This vulnerability is most common in structures constructed prior to about 1940. Another common deficiency in these small buildings is a lack of adequate bracing of the cripple walls, located just above the foundation. Poorly braced cripple walls include those with let-in bracing, horizontal wood siding, and stucco (no plywood beneath). If the cripple wall is poorly braced, the structure may roll off the cripple studs below the first floor and fall to the foundation. Such collapses have occurred in many older structures.

Older, large buildings, and buildings with two or more stories, tend to be more of a seismic concern. In such structures, the stucco, plaster and gypsum materials traditionally used as wall sheathing do not have adequate strength to resist the large forces induced by strong ground shaking. Extensive damage to plaster, stucco, and gypsum board finishes is common. After an earthquake, older buildings are often observed to be leaning a significant amount, and doors and windows in these structures may either become jammed or cracked.

In the 1994 Northridge earthquake, a number of multistory apartment buildings, constructed with garages at the first story, collapsed. Similar damage was observed in the 1989 Loma Prieta earthquake in the Marina District in San Francisco. The large garage doors resulted in a weak, soft-story condition.

Deteriorated condition can be a common cause of poor earthquake performance of wood structures. Wood framing can deteriorate as a result of infestation from termites and other pests. Repeated exposure to moisture, followed by drying, can lead to a condition known as dry rot. Similarly, poor construction practice that leaves the structure in a weakened condition can contribute to failures.

Unreinforced masonry chimneys present a common life-safety concern in wood buildings. They are often inadequately tied to the building and therefore fall when strongly shaken. Chimneys with tall projections above the roof can break at the roof line and topple through the roof or onto the ground. Masonry veneers can also represent a significant hazard. In older buildings, the veneer can either be insufficiently attached, or have poor quality mortar, which often results in peeling off of the veneer during moderate or strong ground shaking. Corrosion of veneer ties has also been observed to be a problem.

Often, wood-frame buildings can be easily and economically retrofitted to reduce seismic vulnerability. Common retrofit techniques include providing anchorage to the foundation, providing supplemental plywood sheathing for selected shear walls (and cripple walls) and diaphragms, and providing holddown hardware at the ends of slender shear walls.

D.2.4.2 Unreinforced Masonry Bearing Wall Buildings

Unreinforced masonry bearing wall construction, commonly termed URM, is one of the oldest types of construction found in California. In this type of construction, the perimeter walls, which are typically constructed of multiple layers (wythes) of red clay brick masonry provide the vertical support for the floors and roofs, which are typically constructed of heavy timber framing. Although most buildings of this type employ walls composed of red clay brick, structures constructed of stone masonry, unfired clay (adobe) and unreinforced concrete block also exist. Many brick URM structures have been faced with stone and/or terra cotta obscuring their actual construction. The masonry tends to have relatively low strength, and therefore, the walls can be quite thick, as much as 30 inches or more, for multi-story structures. Typically, these buildings are less than 7 stories in height. URM buildings frequently collapse in earthquakes and following a series of collapses of these buildings in the 1933 Long Beach earthquake, the State of California adopted legislation prohibiting further construction of this building type. Therefore, most URM buildings pre-date the adoption of this legislation, in 1937.

Most URM floor and roof construction consists of wood joists, spanning between the walls and sheathed with straight or diagonal timber boards. Typically, minimal interconnection exists between the walls and the floors and roofs. Some larger buildings have cast-in-place concrete floors. A few buildings have floors consisting of flat unreinforced masonry arches, with a concrete topping.

Following extensive damage to URMs in the 1983 Coalinga earthquake, the State of California again adopted legislation dealing with these buildings. Senate Bill 547 required all cities and counties in California to inventory the URMs in their communities and develop plans for mitigation of the hazards associated with these buildings. Following the enactment of SB547, many California cities began to adopt local ordinances, requiring seismic upgrade of URMs. Most such retrofits have been designed in accordance with criteria that are intended only as a life-safety improvement measure. Therefore, these upgraded buildings can not typically be expected to perform as well as a new building a may still present a significant seismic risk. Retrofitted buildings can usually be identified by the presence of steel braces or moment frames, and the presence of closely spaced steel plates at the outside of the wall, at each floor level and the roof. These plates are part of the hardware, used to retroactively provide anchorage between the diaphragms and walls.

URMs have been proven to represent a significant hazard to life safety during nearly every damaging California earthquake. They present a hazard to occupants, pedestrians, and occupants of adjacent buildings. Perhaps the most susceptible component of URMs are unbraced masonry parapets or cornices extending above the roof level. These architectural elements can topple or separate from the masonry wall and fall onto streets, sidewalks, or adjacent properties. In addition, parapet failure can precipitate failure of the wall below.

One of the major sources of damage and collapse in past earthquakes has been the lack of adequate attachment between floors and walls or roofs and walls. Earthquakes can result in large out-of-plane forces in walls (loads perpendicular to face of the wall), and can cause the diaphragms and walls to separate, leading to partial collapse. Unanchored tops of gable walls are especially susceptible to this type of damage. Excessive horizontal deflection of the flexible and/or weak wood diaphragms has also resulted in wall collapse.

Lack of adequate in-plane load transfer capacity between diaphragms and walls has also been a source of damage. Often no ledger is provided, as framing members are supported directly in pockets in the walls. When diaphragms are adequately connected to walls, failure of the unreinforced masonry walls themselves may occur. This is most common for walls with a large number of openings, or walls with weak mortar.

A common deficiency for URMs is the presence of an open storefront at the first story, to accommodate commercial occupancies. Long rectangular buildings often have virtually no wall at one or both ends to allow for displays, and thus have little strength in the transverse direction. Such buildings have collapsed in past earthquakes. A variation of this configuration is the building located on a corner with two adjacent walls relatively open. Such buildings are essentially unstable.

In many buildings of early construction, the exterior wythe may be joined to interior wythes only by the mortar placed between them in the vertical spaces, referred to as collar joints. In other cases, adjacent wythes may be tied together using header courses (a row of bricks laid with the long dimension across the collar joint). Without the presence of headers, the outer wythe can easily peel off, representing a life safety hazard to occupants and pedestrians.

The most common and cost-effective strengthening for URMs is to strengthen the parapet, by bracing it to the roof with diagonal struts. Similarly provision of anchors between the walls and the floors and roof is a very cost-effective upgrade technique.

Masonry walls with numerous openings may be strengthened either by infilling selected doors and windows, adding new reinforced concrete or gunite walls, or providing new steel bracing. In cases where the outer wythe of bricks is a veneer (no headers present) and could peel away, masonry anchors can be provided through the bricks to tie the wall together.

D.2.4.3 Unreinforced Masonry Infill

Unreinforced masonry infill buildings are buildings with perimeter unreinforced masonry walls that do not provide vertical support for the floors and roof. In these buildings, vertical support is provided either by structural steel or reinforced concrete frames embedded in the walls. Although these buildings can be low-rise, mid-rise or high rise, they are most commonly found in mid- and high-rise commercial occupancies.

Steel-frame masonry infill buildings first came into use in the early 1890s, with the advent of high-rise construction and continued through about 1940. Floor construction typically includes reinforced concrete slabs supported by steel beams. Interior partitions are often constructed out of unreinforced, hollow clay tile. The steel frames may or may not be encased in concrete for fire proofing. Most major California cities have a number of very large buildings of this construction type.

Concrete-frame masonry infill buildings have perimeter and interior walls of unreinforced masonry filled-in between reinforced concrete columns and beams. As with the steel frame buildings of this type, interior walls were typically hollow clay tiles. In some more modern buildings, both interior and exterior walls may consist of concrete block.

There are no records of earthquake-induced collapse of steel frame masonry infill buildings in the United States; however, they can be subject to extensive damage. When these buildings are subject to strong ground shaking, the masonry infill tends to wedge in place between the beams and columns, providing rigidity to the frame and developing significant strength. However, the resulting stresses on the masonry, which can be very stiff with respect to the steel frame, can cause extensive cracking and spalling. Decorative terra-cotta veneers are particularly susceptible to this type of damage, and debris from crushed terra-cotta ornamentation is a common falling hazard in earthquakes.

One of the most common effects of masonry infills in concrete frames is the creation of a short-column effect. When a building with masonry infill is subjected to ground shaking, the masonry tends to prevent the frame from deflecting under the influence of the earthquake-generated forces. When this action occurs, large compressive forces are generated where the masonry bears against the framing elements. When the masonry walls are perforated with partial-height windows, the points of maximum bearing often will occur at the top and bottom of the window opening, creating very high shear forces in the columns at those locations. This has led to partial collapse of a number of buildings, including some modern structures.

Most infilled concrete frames are of nonductile construction, resulting in significant earthquake vulnerability. In addition, the presence of the masonry walls often makes these vulnerabilities more severe. The masonry is a heavy material that adds significant mass to the building, increasing both the amounts of force and displacement the building experiences in an earthquake. If the masonry is not properly confined within the plane of the frame, earthquake shaking can dislodge the masonry, causing it to topple.

Hollow clay tile interior partitions, commonly present in infill frame buildings are also concerns. Infill frame buildings can experience very large lateral deflections in strong ground shaking. When this occurs, the interior partitions will often tend to behave as shear walls. However, these walls tend to be quite weak and brittle, and can shatter when subjected to large shearing deformations. If these partitions are not solidly infilled between the floors above and below, they can also fall out-of-plane into adjacent corridors and rooms. As is the case for the URM building, the parapets and ornamentation such as cornices are subject to damage and are substantial hazards to occupants and pedestrians. Although the SB547 legislation enacted by California in the mid-1980s required inventory of these structures, most cities have not adopted any ordinances requiring their retrofit.

A cost-effective retrofit of infill structures that can improve life safety is to strengthen the unreinforced masonry parapet, and to restrain all ornamentation. Clay tile partition walls should either be removed or provision made to prevent collapse from endangering lives of occupants. Wire meshes or steel stud walls have been installed to prevent toppling into corridors. An especially critical location for such measures are corridors and stair wells that will be used as means of egress after an earthquake. Similarly veneers that could peel away during strong shaking should be removed or tied to the structure.

In order to greatly reduce the risk inherent in these structures, it is necessary to provide supplemental earthquake resisting elements in the buildings, such as shear walls or braced frames. Because these structures are quite heavy, these walls and frames must often be quite massive and require extensive foundation work. Therefore, upgrade of these buildings if often quite costly.

D.2.4.4 Reinforced Concrete Wall Buildings

Concrete shear wall buildings have been commonly constructed for institutional uses, such as government offices, hospital wards, schools, and prisons, since the early 1920s. They have also commonly been constructed for larger multi-family residential occupancies including both apartment buildings and hotels. They can be of any number of stories, thought it is relatively rare to find such structures in California exceeding about 15 stories or so in height. Usually the entire structure, including the foundations, walls, floor slabs, and any interior columns is constructed of monolithic, cast-in-place, concrete, though pre-cast concrete floor systems are sometimes used. The concrete walls almost always provide gravity support for the floors and roofs as well as lateral resistance for earthquake and wind loads. In older buildings, the walls are most often located around the perimeter and are highly perforated by windows, while for newer buildings it is more common to locate the walls around central service cores.

Various concrete floor and roof framing systems used in concrete shear wall structures include flat plate, pan joist or beam and one-way slab, and waffle slab systems. Single-story structures can have diaphragms consisting of wood sheathing. (Roofs of multi-story structures can also include wood sheathing.) Such rigid wall/flexible diaphragm structures will perform in a manner similar to tilt-ups, discussed in a later section.

The primary earthquake resistance in these structures is provided by the concrete walls. In older construction, walls are lightly reinforced, but often extend throughout the building. In newer construction, shear walls occur in isolated locations and are more heavily reinforced. Although these newer buildings, if adequately designed and constructed can perform well, studies of the performance of concrete shear wall buildings in past earthquakes indicates that buildings with a high ratio of wall area to floor area perform much better than buildings with less wall area.

In shear wall buildings it is not uncommon to find some walls are terminated above the foundation, either to create large commercial spaces in the ground story or accommodate parking spaces in the basement. In such cases, the walls are commonly supported by columns a structural discontinuity that has often lead to severe damage in the past.

Collapse of concrete shear wall structures is relatively rare. Where they have occurred, they have been traced to irregular wall layouts, poor quality concrete, inadequate reinforcement, or a grossly inadequate quantity of walls. Because concrete shear wall buildings are relatively stiff, in comparison to other building types, smaller displacements and less subsequent damage to nonstructural elements are anticipated for these buildings. However, they can experience extensive damage to the walls and, particularly at the edges of the walls and around openings for doors and windows.

The layout of wall locations is, to a large part, dictated by functional considerations. In many older buildings it was the only consideration. Floor plans that induce torsion, discontinuous walls or skewed walls often resulted. Buildings with walls distributed primarily around only two or three sides are subject to large torsional displacements (twisting) and have been severely damaged in past earthquakes.

Shear wall buildings with abrupt changes in lateral resistance have performed poorly in earthquakes. Damage concentrates in weak or flexible stories, or at locations where shear walls at upper levels do not continue to the foundation level.

Members not considered part of the lateral force-resisting system (i.e., columns and floor slabs) can experience damage if large deformations occur and they are not detailed to perform in a ductile manner. This is a common problem for many older concrete shear wall structures, with flat slab concrete floors. The joints between the interior columns and floors is often inadequately reinforced to withstand large earthquake induced lateral building movement, and punching type failures of the columns through the floor slabs have sometimes occurred.

Methods for retrofitting reinforced concrete shear wall structures are limited because any new components must have comparable or greater stiffness and strength then the existing walls. The addition of interior shear walls or braced frames (with new foundations) can be used to reduce the demand on weak perimeter walls. In some locations exterior buttresses can also be added, or the length of existing shear walls can be increased. If these retrofits are not possible, then the existing walls can be strengthened by infilling existing door or window openings, or thickening existing walls with shotcrete or cast-in-place concrete. Base isolation can be an effective mitigation for some of these structures, but is often costly.

D.2.4.5 Reinforced Concrete Frame Buildings

Concrete frame structures have been constructed since about 1920. They can include commercial, institutional and residential buildings and have also been commonly used in transportation structures such as viaducts and bridges. Frame buildings can have any number of stories, but are most common in the mid-rise height range (4 to 15 stories). Most early concrete moment frames had perimeter walls of unreinforced masonry infill as discussed in a previous section. Many early frame buildings also had some shear walls. Pure concrete frame construction (in which neither extensive masonry nor concrete wall elements were present) started to be developed in the 1940s.

Concrete moment frames are monolithically cast systems of beams and columns. Floor and roof framing consists of cast-in-place concrete slabs, concrete beams, one-way joists, two-way waffle joists, or flat slabs. Curtain walls can include precast concrete panels, stone panels, metal skin panels, or glass panels. Foundations consist of concrete spread footings or deep pile foundations.

Unreinforced concrete is weak in tension and is brittle. Consequently, reinforcing steel is typically provided along the top and bottom of the beams and distributed around the perimeter of columns to resist tension originating from bending of the members. Lateral reinforcing, or ties, are typically wrapped around this longitudinal steel to help hold the longitudinal steel and the concrete encased within it together, to prevent the bars from buckling, and to help resist loads applied perpendicular to the axis of the member. At ends of columns and beams in moment frames, where earthquake stresses are largest, it is necessary for the tie spacing to be small (approximately 3 to 4 inches) to confine the concrete and provide buckling restraint for the longitudinal bars. For circular columns, continuous circular spirals, rather than individual rectangular ties, are often used.

Earthquake forces are resisted by the concrete roof and floor diaphragms and the moment frames that develop their stiffness through bending of beams and columns. In some older construction, the moment frames may consist of the columns and two-way flat slab systems. Concrete moment frame structures can generally be grouped into three categories, based on the age of their construction: pre-1964 (non-ductile), 1964-1973 (ductility varies), and post-1973 (ductile). These dates are general, based on the prevailing building codes, and may vary depending on specific location and the design engineer. The UBC adopted significant changes to the design requirements for concrete moment-frames in the late 1960s, based on published research. These changes were specifically intended to provide for more ductile frame behavior. Where earlier codes focused on providing strength to resist code-specified lateral forces, with the adoption of the 1967 UBC, the provisions began to focus on aspects of proportioning and detailing to achieve overall ductility as well as strength requirements. Nonductile concrete frames, although often designed to resist lateral forces, did not incorporate the special detailing provisions now required for ductile concrete. Although the UBC first adopted ductile detailing requirements for concrete frames in the late 1960s, adoption of these code requirements was spotty until the 1971 San Fernando earthquake. Extensive damage to the Olive View Hospital, a recently constructed moment frame structure, in that event called attention to the vulnerability of older design provisions and spurred the local adoption of the newer more reliable provisions. Successive improvements and changes to these provisions have been made over the years, since.

Non-ductile concrete frame structures are very vulnerable to severe earthquake damage and collapse. Because these structures tend to have much larger occupancies then URM buildings, tend to fail in a very brittle and sudden manner, and few have been seismically upgraded they currently represent the single most significant earthquake risk in California. Severe damage and collapse of these structures in strong earthquake ground shaking is common. The resulting heavy debris often results in large loss of life and makes victim extraction difficult.

Properly designed and constructed ductile concrete frame buildings have performed well in recent earthquakes. However, the performance of these structures is quite sensitive to how well the code provisions are executed with regard to placement of reinforcing, quality of construction and separation of structural and non-structural elements. At least one major ductile concrete frame building has collapsed due to a failure to faithfully execute the code requirements in the design.

It is sometimes possible to make existing non-ductile elements more ductile by jacketing the existing elements with new steel, reinforced concrete, or composite fabric materials. Such approaches have commonly been used when strengthening columns of existing elevated freeways. However, mitigation of hazards associated with non-ductile concrete frame structures typically involves provision of new lateral force resisting elements rather than strengthening of existing ones. The most common upgrade technique is the installation of new reinforced concrete walls or steel braces. Because existing concrete moment frames are relatively flexible, supplemental energy dissipation systems can also be an effective method of upgrading these structures. The major goal of upgrade programs for concrete frame buildings is to reduce the structure's lateral deformations enough to protect the existing frame elements from failure.

D.2.4.6 Pre-cast Concrete Structures

This type of construction may include structures of all heights although in California, it is typically limited to low and mid-rise applications. Pre-cast structures may be used in commercial, institutional, industrial and residential occupancies. They are most commonly used for parking garages, hotels, mid-rise office buildings. This type of construction was first developed in the 1930s, but was not widely used until the 1960s. Tilt-up construction, a special technique for pre-cast wall construction is discussed in a later section.

These structures consist of a frame assembly of pre-cast concrete girders and columns with or without the presence of shear walls. Lateral forces are resisted by the pre-cast or cast-in-place concrete shear walls when present. If not, forces are resisted by pre-cast concrete moment frames that develop their stiffness through beam-column joints rigidly connected by welded inserts or cast-in-place concrete closures. Diaphragms commonly consist of pre-cast elements interconnected with either welded inserts or cast-in-place closure strips, or reinforced concrete topping slabs.

The pre-cast frame is essentially a post and beam system in concrete where columns, beams and slabs are prefabricated and assembled on the site. Various types of members are used: vertical-load-carrying elements may be T's, cross shapes, or arches and are often more than one story in height. Beams are often T's and double T's or rectangular sections. Pre-stressing of the members, including pre-tensioning and post-tensioning, is often employed, especially when long spans are required.

Pre-cast concrete structures are subject to many of the deficiencies of cast-in-place construction. These deficiencies common to cast-in-place construction will not be discussed here. Rather the deficiencies specifically associated with the pre-cast construction procedure are highlighted. This type of building can perform well if the details used to connect the structural elements have sufficient strength and ductility, and there is a well-defined lateral load path. However, the connections between pre-cast units in most of these structures is not adequate. As a result, the units can pull away from each other, leading to local and global collapse.

A condition specific to precast structures (and especially prestressed structures) is that they are often in a weakened condition prior to being affected by an earthquake. Specifically the connections between adjacent elements are often stressed due to shrinkage, creep and temperature stresses. This can take the form of cracking around metal connectors, or cracking in a topping slab where it is doweled into a concrete wall that resists shrinkage. Corrosion of metal connectors between prefabricated elements can also occur. Spalling of supports for prestressed beams is very common as the beams try to shrink and the resulting forces are resisted by friction at the supports.

The primary weakness associated with pre-cast concrete construction is the connections, thus the most straightforward retrofit is often to strengthen the connections. However, as precast concrete frames are often non-ductile, the lateral force-resisting system of many existing precast frame structures should be modified as well.

Precast frame structures can be strengthened by the addition of concrete shear walls or braced frames and associated collectors and foundations. For large structures subjected to large temperature movement, the shear walls should be located near the center of the structure, or special detailing should be provided to avoid expansion/contraction inducing cracking in the diaphragm around the walls. Connections of new interior lateral force-resisting elements to the existing structure is sometimes complicated by the need to avoid prestressing tendons.

Some structures have pre-cast floor and roof framing members that are connected together with welded steel plates. These members are intended to act as a diaphragm, but the connections are typically too weak. Retrofit options include providing additional connections, provision a topping slab to act as a diaphragm, or strengthening with a composite fiber material if a topping slab is unacceptable from a weight standpoint. Reduction of diaphragm overstresses in pre-cast structures may be most readily achieved through the addition of interior shear walls and braces.

D.2.4.7 Steel Moment Frames

Steel-frame buildings constructed before 1940 are usually clad or infilled with unreinforced masonry. These structures were discussed in a previous section. Modern steel-frame structures without infill include low- to high-rise commercial and residential buildings, mostly constructed after 1950. They are often recognizable by the presence of glass curtain wall exteriors, or in buildings with other types of cladding, by the presence of many large windows.

Moment-resisting steel-frame buildings consist of an assembly of steel beams and columns. Typical moment frame structures have bay widths (spacing between columns) of approximately 20 feet. Floor and roof framing consists of cast-in-place concrete slabs or metal deck with concrete fill supported on steel beams, open web joists or steel trusses. Foundations consist of concrete spread footings or deep pile foundations.

These buildings rely on the rigid or semi-rigid interconnection of their beams and columns to provide lateral resistance. When such frames are subjected to lateral motion, both the beams and columns are subjected to bending stresses, with the largest stress concentrations occurring at the connections. Connections in modern steel frame buildings are typically connected by welded joints, although many older buildings (pre-mid 1960s) have bolted or riveted connections that may be considered semi-rigid in comparison with modern welded joints.

Prior to the 1994 Northridge earthquake, many engineers regarded welded moment-resisting frames as the most reliable type of construction for resisting earthquake damage. No such buildings in the United States had ever collapsed in an earthquake, and there were few reported instances of structural damage in such buildings. However, following the Northridge earthquake, fractured connections were discovered in a number of buildings in the Los Angeles area. A large percentage of these buildings were relatively new (post-1976). The damage was often difficult and costly to detect, requiring removal of finishes from the frame, and careful visual and nondestructive examination of the individual joints. Repairs were also quite costly to implement and is some cases, buildings remained permanently out of plumb. Although none of these buildings collapsed, at least one was so severely damaged that it was deemed more appropriate to demolish the structure, rather than repair it. It has now been determined that similar damage occurred to some buildings in the San Francisco Bay Area during the 1989 Loma Prieta earthquake, and a number of these buildings were damaged in the 1995 Kobe earthquake, with some collapse reported.

In addition to connection problems, steel moment-resisting frames can be subjected to significant architectural damage, due to their inherent flexibility. Elements that are particularly susceptible to such damage include interior partitions, ceilings and windows. Cladding on many older structures was not designed with adequate provision to accommodate the large lateral movement of these buildings. In some cases, such cladding has occasionally fallen from the structure.

The retrofit of steel frame structures to address deficiencies other than the welded steel connections (e.g., configuration problems) can be achieved by methods outlined in previous sections. For instance a soft story can be strengthened by the addition of bracing. Deficient connectors for cladding can be modified, especially over means of egress or where pedestrians are jeopardized. Because of the flexibility of the structures, a higher importance should be assigned to retrofit of nonstructural hazards such as bookcases, cabinets and suspended ceilings that could pose a life-safety hazard.

Acceptable remedial measures have been established for the welded moment steel-frame connections (removing weld material and replacing with tougher material, and strengthening the connection), but they tend to be quite expensive and disruptive and may be comparable with the cost of damage repair, given that an earthquake actually affects the building. Assuming the risk of severe damage is relatively low, an alternative is to evaluate the building to identify high risk connections, and to establish a post-earthquake inspection plan that can be used to either rapidly verify damage, or provide confidence that significant damage has not occurred.

D.2.4.8 Braced Steel Frames

Braced steel frame structures have been built since the late 1800s with similar usage and exterior finish as the steel moment frame buildings. They can be high-, mid- or low-rise, but are typically in the range of 2 to 10 stories in height. They are of similar construction to moment-resisting steel frames, but rather than relying on the rigidity of the beams and columns for lateral resistance, instead rely on the presence of vertical diagonal bracing. Steel braced frame buildings are characterized by the presence of these diagonal steel braces that run between beam column connections at selected locations in the building. Most commonly, these braced frames are located adjacent to the perimeter walls of the buildings. Because the braces tend to disrupt window space when placed on exterior walls, or prevent free use of floor space when placed at building interiors, they are more common in industrial than commercial applications. However, since braced frame buildings are generally more economical to construct that moment-resisting frames, some speculatively constructed office buildings are of this construction type.

Three common systems of braced frames exist: concentrically braced frames, special concentrically braced frames, and eccentrically braced frames. Concentrically braced frames are the oldest form of this system. A number of patterns of concentrically braced frames are common. One pattern is diagonal “X” bracing, in which the braces extend directly between opposite beam-column joints in the frame. This system is often considered architecturally undesirable because the braces prevent access through the braced bay and obscure window space. A more common system is the so-called chevron bracing, in which braces are arranged in a “V” or inverted “V” pattern extending from adjacent beam-column connections to the middle of the beam, above or below. Special concentrically braced frames are similar to ordinary braced frames, except that they employ more rigorous detailing of the braces and their connections and are expected to have superior earthquake performance. These special concentric frames were first introduced in the 1994 UBC.

Eccentrically braced frames were introduced into the building codes in the mid-1980s. They are a hybrid system that employs some of the characteristics of both concentrically braced frames and moment-resisting frames. Rather than meeting in the middle of the beam, the bracing is slightly offset, and the short section of the beam between the ends of the braces is designed to deform significantly under major seismic forces and thereby dissipate a considerable portion of the energy. This system protects the braces from the buckling and yielding, a common damage mode for concentric braced frames. The resulting behavior produces excellent stiffness to protect architectural elements, as well as enhanced energy dissipation capacity.

The primary risk to braced frame structures is that strong ground shaking can cause buckling and/or tension yielding of the diagonal braces or failure of their connections to other framing. In buildings with “V” style braces, following buckling of the braces, large distortion of the floor beams the braces are attached to typically occurs. In some buildings, columns may buckle under the large compressive loads introduced by the braces. Collapse of braced-frame structures is very rare, but has occasionally occurred. A prominent example is the failure of a high-rise braced-frame building, the Piño Suarez complex, in the 1985 Mexico City earthquake.

Although relatively few eccentrically braced frames have experienced strong ground shaking, those that have are reported to have performed very well.

In addition to retrofits that can address deficiencies associated with generic configuration problems, there are a number of retrofit options for braced frames. One is simply to provide additional new braced frames to reduce the loads on the existing frames. Typically new braced frames will also require foundation modifications. Inadequate braced frames can sometimes be strengthened by removing existing braces and replacing them will larger ones or by modifying the existing braces and their connections.

D.2.4.9 Light Metal Buildings

These buildings are typically pre-engineered and prefabricated with moment-resisting frames providing lateral resistance in one direction and light bracing providing lateral resistance in the orthogonal direction. Typically the exterior skin of these buildings consists of metal siding and roofing. They are usually one story in height, may have gabled roofs, and often enclose a large floor area. Possible occupancies include agricultural, industrial, and warehouse occupancies. A majority of these structures were constructed after 1950.

Lightweight steel structures have typically performed very well in earthquakes. More earthquake damage has occurred to these buildings due to impact from toppling contents than due to direct ground shaking. Structures that have sustained shaking damage have typically been in poor condition, or been modified since original construction. Poor condition typically involves members that have been bent or damaged by impacts from forklifts and other traffic. Modifications typically include removal or cutting of rod braces for additions or new openings. The addition of mezzanines without lateral force-resisting systems can also lead to damage.

The most common retrofit technique for these buildings consists of replacement, supplementation or repair of deficient tension rod braces (both vertical and horizontal). Retrofit is usually very straightforward and can be achieved by the addition of more rod bracing, replacing existing rod braces with bigger rod braces, or replacing rod braces that have been removed by the tenants.

D.2.4.10 Tilt-up Buildings

The concrete tilt-up design came into general use in the early 1960s and is one of the least costly types of industrial and low-rise commercial structures to build. These buildings are almost exclusively one and two-stories in height. They were initially used primarily as warehouse structures but are currently used for many other commercial applications including offices and department and grocery stores. The effort spent on design is often minimized. Maximum advantage is taken of standardized design procedures and minimum building code requirements. This approach is only reliable for regular buildings with relatively few openings in wall panels. However, modern tilt-ups can be highly irregular in plan and include many architectural features that will cause their earthquake performance to differ greatly from the box-type structures originally constructed in this manner.

The name "tilt-up" is derived from the method of constructing the perimeter reinforced concrete load-bearing walls. These walls are formed laying flat against the ground floor of the building in panels that are typically 20 to 30 feet wide. Wall thicknesses typically vary from 5-½ to 12 inches. After having cured sufficiently to withstand erection stresses, the panels are tilted into a vertical position. Connections are made between the adjacent panels and between the panels and the roof and floors to provide continuity and vertical stability.

In California, tilt-up buildings commonly have panelized plywood roofs supported by timber framing. The primary components typically include glulam beams, usually spaced on 20- to 24-foot modules, 4-inch wide sawn purlins framing to the glulam beams on an eight-foot module, 2- by 4-inch or 2- by 6-inch sub-purlins (joists) framing to the purlins on a two-foot module, and plywood sheathing. Other roof systems include wood trusses, steel bar joists, or plywood- or oriented-strand board (OSB)-webbed members. Steel framing members are sometimes used in combination with metal decks. Roof and elevated floors, regardless of their construction, are typically supported by the perimeter walls and by interior columns.

The single most common deficiency for tiltup buildings is the lack of adequate anchorage between the walls and the supported floors and roofs. In strong ground shaking, large forces are generated which tend to pull the walls away from the floors and roof. When this occurs, the walls can fall away from the buildings and the supported floors and roofs can collapse. These failures first occurred in the 1964 Prince William Sound earthquake, in Alaska, but were again observed in the 1971 San Fernando earthquake. Prior to the San Fernando earthquake, no formal interconnection of the walls and supported floors and roofs was required. Following that earthquake, the code was modified to required positive direct connections to avoid these failures. However, with each successive California earthquake, it has been demonstrated that the design requirements for these connections have been inadequate, and major revisions to the design requirements have occurred in the 1973, 1976, 1991, and 1997 editions of the building code.

In addition to inadequate anchorage of walls to floors and roofs, other deficiencies can include roof diaphragms that are inadequate to carry the seismic forces and walls that are weakened by the presence of many door and window openings, and essentially behave as non-ductile concrete frames, discussed in a previous section.

Most efforts at retrofitting tilt-up structures are aimed at improving the capacity of the wall anchorage system. This is accomplished by post-installing anchor bolts into the tiltup walls at floor and roof lines, and providing new attachment hardware to connect the walls to the floor and roof framing. This can usually be accomplished economically and without impact on building appearance or occupancy.

Weak diaphragms on these buildings can be retrofitted by the addition of steel braces at interior locations or by providing additional nailing of the plywood to the supporting framing. Walls that have been weakened by excessive door and window openings can be reinforced by infill of selected openings or by addition of braced frames adjacent to the walls.

D.2.4.11 Reinforced Masonry

This type of construction became very popular in the 1940s after unreinforced masonry was prohibited. Reinforced masonry buildings are mostly limited to low-rise perimeter bearing wall structures. The occupancy of this building type varies greatly from small commercial buildings to residential buildings. Generally they are less than five stories in height although many mid-rise reinforced masonry buildings exist.

Reinforced masonry walls in California are typically constructed of hollow concrete blocks, with reinforcing steel inserted within vertical and horizontal cavities in the block, which are then grouted solid (some walls are only partially grouted, grout is provided only in cells with reinforcement, while other walls are fully grouted). Some reinforced brick masonry walls have also been constructed. In these walls, two wythes (layers) of brick are laid up with a cavity space in between. Reinforcing steel is placed in the cavity between the wythes, which is then grouted solid.

The floors and roofs of masonry buildings can comprise a number of different systems. Many one- and two-story structures are provided with floors and roofs of timber construction; however, metal deck and concrete-filled metal deck supported by steel framing are also common in such structures. Many apartment buildings and hotels are constructed with a system of precast, prestressed concrete plank floors, bearing directly on the masonry walls. Some small one-story buildings have reinforced concrete roof slabs.

Reinforced masonry buildings can perform well in moderate earthquakes if they are adequately reinforced and grouted, if the floor and roof diaphragms are competent and if sufficient attachment exists between the walls and roofs and floors. The performance or reinforced masonry walls with flexible diaphragms has been similar to that of tilt-up wall buildings, discussed in the previous section. If the buildings have precast concrete floor elements, their performance depends on the ability of the connections to tie the elements together and allow the structure to act as a unit when subjected to lateral forces. Refer to the previous discussion on pre-cast concrete buildings for deficiencies related to this construction type.

An important factor in the performance of reinforced masonry buildings is the degree of quality control exercised during construction. Some collapses of masonry buildings in past earthquakes have been attributed to failure of reinforced walls where the contractor had neglected to place the reinforcing or grout properly. Continuous inspection during the construction process is an effective method of avoiding such problems; however, such inspection is not required in all cases.

The configuration and detailing of the walls themselves is extremely important to the building's earthquake performance. Walls with extensive openings are often subject to large cracking and spalling of the masonry units around the openings. The pattern in which the masonry is laid up is also important. Most reinforced concrete masonry is laid up in a running bond pattern, in which the joints of the masonry units in each layer are staggered relative to the layers above and below. This is a preferred form of construction. Some buildings incorporate a masonry pattern known as stack bond, in which the joints between units align vertically from the top of the wall to the bottom. Such a configuration is weaker with respect to resisting seismic forces.

As stated previously, many of the deficiencies of reinforced masonry buildings with wood roofs are common to tilt-ups. Refer to the previous section for discussion of upgrade techniques for mitigating these deficiencies. Existing masonry walls can be strengthened for in-plane forces by infilling existing openings in walls. Walls can also be strengthened by the application of shotcrete. In such cases, sufficient anchorage must be supplied at interface of the existing wall and new shotcrete to provide for shear transfer between the existing and new walls. It may also be possible to improve existing masonry walls by bonding composite fibre fabrics to the face of the wall.

Some walls will be too weak for out-of-plane bending due to either minimal reinforcing or relatively tall heights. These walls may be braced with external structural elements to reduce span lengths for out-of-plane bending. Such elements are referred to as strong backs, and are usually steel. These strong backs must be adequately tied to the foundation and the roof to transfer of forces from the masonry wall.

D.2.5 Nonstructural Components

Nonstructural components include portions of the building not having a structural function. Nonstructural components include, but are not limited to, mechanical equipment, partitions, cladding, windows and furniture.

Primary causes of damage to nonstructural elements include sliding or overturning due to inadequate anchorage, excessive distortion due to attachment to a flexible structure and internal damage due to shaking. The type of structure a nonstructural component is located within can have a significant effect on its expected performance. Typically more nonstructural damage is expected for components within flexible steel and concrete frame structures than in wall structures, because of their flexibility.

Prior to the 1964 Alaska earthquake there were no significant seismic requirements in the building codes for protection of architectural components and mechanical and electrical systems. Following that earthquake, the codes started to incorporate provisions intended to protect these components. Although current codes contain adequate provisions, in practice they often are not effectively implemented. This is because the responsibility for designing protection of these systems and components is not clearly delineated between the various members of the design team, and often is overlooked.

There are three types of risk associated with earthquake damage to nonstructural components: life safety, property loss, and loss of function. Typically building codes are concerned with life safety risks only, and not with providing damage control or providing for functionality.

The primary life safety related risk is that people could be injured or killed by damaged or falling nonstructural components. Examples of potentially hazardous nonstructural damage that has occurred during past earthquakes include broken windows, overturned tall and heavy cabinets or bookcases, and falling precast panels. Also, equipment operated using gas such as boilers, furnaces and HVAC equipment can cause fires or explosions when damaged by shaking.

The survival of critical equipment and contents in a facility may be just as important as the survival of the buildings. Often, production and operations equipment represents a large part of the investment in a facility and the greatest financial earthquake risk. For example, the value of computer equipment in a data processing center will often greatly exceed the value of the building housing this equipment. Property damage to nonstructural elements can be substantial. For most commercial buildings, the foundation and superstructure account for approximately 20-25% of the original construction cost, while the mechanical, electrical and architectural elements account for the remaining 75-80%. Contents belonging to the building occupants represent a significant additional expense. Property losses may be the result of direct damage to a nonstructural item due to shaking or of consequential damage such as water damage due to sprinkler failure, or fire due to a ruptured gas pipe. Indirect costs associated with cleanup can be substantial.

Nonstructural damage may make it difficult or impossible to carry out functions normally accomplished in a facility. After serious life threats have been dealt with, the potential for post-earthquake down time or reduced productivity is often the most important risk. Loss of production equipment can lead to obvious impairment of business function, but loss of building equipment can also be critical. Many external factors affect post-earthquake operations, including power and water outages. These effects are outside the control of a typical building owner, although backup systems can be provided.

The most common source of damage to nonstructural components is lack of adequate anchorage. It has been conclusively demonstrated in past earthquakes that properly anchored and braced industrial-grade equipment, with some caveats, has an inherent seismic ruggedness and demonstrated capability to withstand significant seismic motion without structural damage.

The behavior of any given equipment unit depends on several factors. Among these are the level of seismic shaking (dependent on some extent to the structure the nonstructural element is supported on), the unit’s height-to-width ratio and internal distribution of weight, the coefficient of friction between the supports and the floor, and the proximity of other equipment. Consequences of damage may depend on component location. For instance, failure of a water tank on the roof may cause more damage than failure of a water tank in the basement.

Since explicit recommendations for bracing and anchorage of each component are beyond the scope of this document, only general risk-reduction strategies for selected nonstructural components follow.

D.2.5.1 Computer Equipment

Computer installations have the potential to be one of the most damage-prone areas during a major earthquake. Potential losses include both direct damage and business interruption resulting from the irretrievable loss of data and records. Many items found in computer facilities are particularly susceptible to damage, since they are relatively tall and heavy, usually unanchored, and may tip over during ground shaking.

Seismic retrofit of computer equipment usually includes improved attachment of computer and installation racks through the access floor panels to the underlying floor system. However, because computer equipment is often sensitive to strong shaking and attaching equipment rigidly can invalidate its warranty, unique solutions, such as isolating extremely sensitive components, may be considered. Low equipment that is unlikely to topple can be tethered and bumpers installed on the perimeter of openings in the floor to stop equipment from sliding in and toppling.

Computer equipment is often supported on a raised access floor. Computer access floors are panelized, elevated floor systems designed to facilitate access to wiring and other services associated with computers and other electrical components. The system includes structural legs, horizontal panel supports, and panels. Raised floors may collapse during strong ground shaking, due to a lack of lateral bracing. Seismic retrofit should include improving the lateral-load-carrying capacity of the steel stanchion system by installing braces or improving the connection of the stanchion base to the supporting floor, or both.

D.2.5.2 Electrical Equipment Including Control Panels and Transformers

This category includes switchgear, motor control centers, and distributed control system components. Properly braced and anchored electrical equipment has an excellent performance record. However, inadequately anchored equipment is extremely susceptible to damage. Typical observed damage modes include tipping or sliding of transformers; tearing of attached electrical cabling and tipping of electrical cabinets, control panels, and miscellaneous switchgear; and tearing apart of long horizontal runs of electrical conduit. Evaluation of this equipment is sometimes complicated by the fact that verification of anchorage often requires de-energizing equipment. Transformers owned by electrical utilities can only be surveyed with utility cooperation.

In very intense ground shaking, it is not uncommon for slide-in-type components to roll out of their normal operating position or for doors on units to open. Normally, when this occurs, replacement of the component to its normal position and closing of the doors return the unit to normal operation.

Seismic retrofit should include securely bolting components to the floor or adjacent walls using angle brackets and heavy bolts. Detailing needs to be appropriate for the base construction of the equipment. Transformers require well-engineered anchorage because of their weight.

D.2.5.3 Storage Racks and Stacked Material

Storage racks are generally purchased as proprietary systems installed by a tenant and are often not under the direct control of the building owner. Thus they are usually not part of the construction contract, and often have little or no foundation attachment. Storage racks have experienced severe damage and collapsed in past earthquakes. Damage to inadequately designed and/or installed racks may include column deformation as well as tearing of beam-to-column connections. Buckling of diagonal braces, column buckling near the base, and failure of column-to-base plate welds have also been observed. Contents have fallen from upper levels of racks.

Main contributors to observed damage are poor seismic design, poor installation, overloading, and poor maintenance. Proper installation of racks, specifically installation of anchor bolts, is key to their successful response in earthquakes. Storage racks damaged by forklift operations should be replaced to prevent local and possibly total collapse. Retrofitting measures include providing base anchorage, tying adjacent rows of racks together, and providing sliding restraints such that items cannot slide off of shelves. Heavier materials should be stored at lower levels, and items on upper levels should be shrink-wrapped to reduce the likelihood of falling hazards.

D.2.5.4 Suspended Tile Ceilings

Suspended ceilings included suspended metal lath and plaster and suspended acoustical board inserted within T-bars, together with lighting fixtures and mechanical items, to from an integrated system. The exposed-tee-grid systems that constitute about 90% of all installations have sustained the greatest damage in the past. Damage typically occurs due to a lack of positive lateral and vertical bracing. Falling ceiling tiles and metal framing can cause injury or damage to sensitive equipment.

Original construction of such ceiling systems involved no bracing. After damage to ceilings in the 1971 San Fernando earthquake, diagonal wires were required for ceilings, and independent wires were required for lights. Although the diagonal wires provided some improvement, it was later determined that vertical compression struts at selected locations were also required. Thus remedial measures for suspended ceilings include installing vertical compression struts and diagonal wires to provide lateral bracing. Confinement of the ceiling around the perimeter and sufficient bearing around the perimeter also enhance seismic performance.

D.2.5.5 Vibration-Isolated Equipment.

Mechanical equipment (e.g., standby generators, air handlers, and fans) is often supported on springs or isolations mounts to limit transfer of the vibrations it creates to the structure (thereby limiting discomfort to occupants). Older isolators were typically provided with no consideration of seismic loads. Since the 1980s isolators for substantial equipment typically have capacity to resist seismic loads.

During past earthquakes, equipment supported on simple vertical spring vibration isolators have been repeatedly observed to fail, with resulting misalignment of the equipment and damage to attached piping or cabling. Isolators designed to resist seismic loads have also failed, primarily because of poor installation of anchor bolts, inadequate anchor bolt edge distance, or inadequate design. Anchors into equipment pads in penthouses that consist of lightweight (weak) concrete have failed.

Seismic stops that limit lateral displacement but allow vertical displacement required vibration can be used to prevent damage to simple spring isolators. However, because isolated equipment does perform poorly, current codes require that anchorage design forces for them be larger. Prior to retrofit it should be verified that isolation of the equipment is required. In many cases, equipment supported on isolators on grade could be supported directly on grade, permitting more direct and effect anchorage.

D.2.5.6 Rigid Grade-mounted Equipment

Rigid grade-mounted equipment, including pumps, electric drivers, generators, compressors, air handlers, fans, and similar equipment, have historically performed excellently, if they are appropriately anchored to foundations and no ground failure occurs. In case of rotating or dynamic equipment, including pumps, compressors, and drivers, the anchor bolts normally recommended by equipment manufacturers to resist operating loads have proven adequate to prevent damage.

D.2.5.7 Standby Power Systems

As it is generally accepted that power will not be available from utilities immediately after an earthquake, many facilities have decided to have standby power. Standby power typically includes diesel generators and supporting equipment (including batteries, fuel storage and transfer pumps) and in cases with computer or communications facilities, un-interruptable power supply (including batteries, battery chargers and inverters).

Such facilities have typically performed well in when properly anchored. Self-contained diesel generators have about a 90% reliability for startup and prolonged operation following strong ground shaking. Damage in past earthquakes has included failed isolation mounts, unrestrained batteries toppling, and failed fuel lines. Components on generators such as mufflers have also toppled due to lack of restraint.

In addition to verifying adequate anchorage of all equipment, the fuel line should be evaluated for adequate flexibility, and susceptibility to settlement. Fuel lines penetrating building walls are susceptible to shearing if the adjacent soil settles with respect to the building.

D.2.5.8 Tanks

The importance of anchoring smaller tanks has been repeatedly demonstrated during past earthquakes. Tanks have "walked" across the floor or toppled when inadequately legs or anchorage failed. Tank movement has sheared attached piping, resulting in loss of contents. Secondary damage from spilled liquids can cause business interruption problems.

Large, ground-supported atmospheric tanks (e.g., firewater, fuel, and wine) have been relatively poor performers in strong ground motion. These tanks are frequently unanchored, have thin shells, and experience amplified seismic effects from the sloshing motions that can develop within the contained liquids. Common damage includes rupture of rigid piping connections, buckling of the shell, ripping of the floor plate, and flexure of the roof. Tanks which experience damage to floor plates or the welds between the floor plate and the wall can experience rapid loss of contents and implosion due to the resulting vacuum. In strong ground motion, atmospheric tanks have exhibited a failure rate as high as 25%. However, failure does not always imply complete release of materials (buckled walls often do not leak).

Retrofit of steel tanks can include providing flexibility in attached piping, anchorage, and thickening of the wall at the base course. Providing flexibility is typically the most cost-effective. Providing anchorage to an unanchored tank can often involve provision of a new foundation. Thickening of the wall at the base of the tank will only be effective if the base plate is thick enough.

D.2.5.9 Piping

Welded steel and soldered or braced copper lines generally perform well in earthquakes. Threaded pipes, or pipes using mechanical couplings, like those used for sprinklers, are more susceptible to damage. Failure usually initiates at joints.

Damage to piping has resulted from inadequate bracing, failure of bracing hardware, incompatible deflections of structural and nonstructural components. In general, when failure of this piping occurs, it is not as a result of inertial loading, but rather one of the following causes:

1. Rigid length of pipe attached to two structures or pieces of equipment that move differentially. An example of where this can occur is a pipe crossing an expansion joint in a long structure and being rigidly attached to the structure on both sides.

2. Failure of several supports along a run of piping resulting in greatly increased inertial loading. The most common type of support failure consists of trapeze or rod supports suspended from expansion inserts in the undersides of concrete floor slabs. During ground motion, the inserts rock back and forth and work themselves loose, allowing the pipe to fall.

Screwed and compression fitting piping has a poorer performance record. This piping can fail as a result of inertial loads, if it is run in long, improperly supported lengths. However, failures of this piping tend to be in the category of minor leakage rather than massive joint failure.

To minimize damage, equipment attached to piping should be restrained or anchored to ensure that large relative displacements cannot occur. At locations where pipes span between independent structures or at seismic joints, sufficient flexibility should be provided to accommodate anticipated movements. The support and bracing of bends in main risers and laterals is especially important.

Different retrofit approaches should be taken based on the contents of the piping. In general, fluid piping includes two categories: hazardous and flammable materials that would pose an immediate safety danger, materials that might pose property loss but no life safety danger. There are prescriptive design approach to support and bracing. Small diameter piping in the second category are often left unbraced. The increased flexibility of small diameter pipes often allows them to perform better than larger diameter pipes, although they are subject to damage at the joints.

D.2.5.10 Conduit and Raceways

Conduit and cable run in cable trays both have an excellent performance record in earthquakes. Cases have been recorded where rods supporting cable trays have pulled out of the supporting structure, but the cable had adequate strength to support both itself and the tray. Toppled cantilevered raceway supports have loss of function.

Bracing of raceways can be implemented to minimize such occurrences. However, except for the case of cantilevered supports, bracing is usually not justified. Rehabilitation can be accomplished by prescriptive methods contained in SMACNA standards.

D.2.5.11 Firewater Systems

Fire protection systems includes tanks, pumps, pipes, heat and smoke detectors and panels. Firewater systems have been quite vulnerable to seismic damage in recent earthquakes. Piping has been the most significant vulnerability. Fire suppression piping includes main risers, laterals and branches. Bracing is usually limited to main risers and laterals. Unlike process piping, jointing in firewater lines is often compression-type couplings. These couplings have proven to be vulnerable to seismic damage. In addition, firewater piping is usually field routed by the construction crews, often with little regard for bracing requirements. As a result, the piping is frequently vulnerable to damage from swaying and interaction with adjacent structures. Sprinkler heads can be impacted by structural elements or suspended ceiling systems. In wet pipe systems, considerable damage to inventory and electronic can occur as a result of the leaks that frequently develop.

The diesel-driven emergency firewater pumps that pressurize these systems can also be a problem. Frequently, the diesel-driven pumps are mounted on vibration isolation supports. As discussed previously, these can be damaged by even moderate shaking, resulting in loss of functionality. Control cabinets, battery power supplies, day tanks, and other auxiliaries associated with the diesel pumps frequently are not adequately installed to prevent damage as well. Thus, the ability of many firewater systems to function following a major earthquake is questionable.

Fire suppression piping must be evaluated for adequate support, flexibility, protection at seismic movement joints, and freedom from impact from adjoining materials at the sprinkler heads. The support and bracing of bends of the main risers, and laterals, as well as maintenance of adequate flexibility to prevent buckling, are especially important. Rehabilitation is accomplished using the prescriptive requirements of NFPA-13. Other components must be anchored or restrained as discussed previously.

D.2.5.12 Chimneys and Stacks

Chimneys and stacks that are cantilevered above building roofs have often failed in earthquakes. Unreinforced masonry chimneys and stacks typically represent the largest risk. Rehabilitation may take the form of strengthening or bracing and material repair.

D.2.5.13 Light Fixtures

Light fixtures include those recessed in ceilings, surface-mounted to ceilings or walls, supported within a suspended ceiling, or suspended from ceiling or structure with pendant or chain. The most common failure of lights occurs within suspended ceilings and result from the loss of support from the T-bar system. Independent support of lights should be provided, as discussed with suspended ceilings above.

Failure of lights suspended by pendants or chains can occur due to excessive swinging that can cause impact. These lights should be braced to ensure freedom to swing without impacting adjoining materials. Fixtures weighing over 20 pounds should have adequate articulating or ductile connections to the building, and be free to swing without impacting adjoining materials.

Appendix E: Equipment Assessment Methodology

E.1 General

This section presents a summary of the MCEER methodology for assessing and reducing earthquake risk for critical facility equipment systems discussed in Chapter 3 of this document. This overall assessment process was developed to provide a means of quickly assessing the reliability of a facility or system within a facility. *MCEER 99-0008: Seismic Reliability Assessment of Critical Facilities: A Handbook, Supporting Documentation, and Model Code Provisions* (MCEER 99-0008) was developed to present a scoring system with which the reviewer can quickly evaluate critical mechanical and electrical systems to determine which systems might warrant more detailed evaluation or modifications. This handbook can be obtained available directly from MCEER.

E.2 Overall Assessment Process

The assessment process summarized herein is intended to be used by people without expertise in engineering or seismicity. No engineering calculations or rigorous training are required to perform the reliability assessment. The guidelines presented in the MCEER handbook are intended to give a complete overview of the process and detailed descriptions of the steps involved in performing the review. The scoring system has been developed to limit the need for interpretation, but still retain enough flexibility to be applicable to a broad range of installations and facilities nationwide.

In order to develop a screening process that can be performed rapidly by facility personnel on such a broad basis, a degree of conservatism is inevitable. Since this methodology is intended to provide broad estimates of a facility's vulnerability, a conservative approach is acceptable, and even desirable.

The following are the major steps involved in implementing the reliability assessment methodology using the handbook.

STEP 1: SYSTEM AND COMPONENT IDENTIFICATION

A facility may have specific functionality requirements during or following an earthquake, as specified by federal law or federal, state, or local regulators. For example, hospital performance requirements for critical care may be specified in a state-issued license; data processing requirements for banks may be specified in Federal law. In addition, a facility owner may determine that a function is essential if it is deemed financially important for continued operation or business recovery.

A critical system is one that is required to provide either (i) the essential facility function, as defined above, or (ii) life-safety protection as required by other laws or regulations. A component of a critical system could be either a particular equipment item; a portion of a system such as piping, ducting, etc.; or a human action that is required to provide function of the critical system.

The handbook describes how critical systems and critical components can be identified for a facility. A method is provided for systematically reviewing important systems and the impact of their failure on other important systems. A means is provided to incorporate special considerations, such as emergency plans, personnel actions, and known maintenance problems.

STEP 2: ASSESSMENT OF INDIVIDUAL COMPONENTS

The handbook presents a method for rapidly evaluating individual equipment components and incorporating those evaluations into a system evaluation. That method uses assessment techniques based on historical earthquake performance of similar equipment items. Assessments are made of specific items that have been known to be causes of damage in past earthquakes, or known to be seismically vulnerable for other reasons.

Scoresheets are provided for individual components, and a method for assigning scores is presented, based on the design and installation of the component, the location within a building and geographically, and other factors. Higher scores indicate higher seismic reliability.

STEP 3: ASSESSMENT OF SYSTEM RELIABILITY

The handbook provides a method for rapidly, but systematically evaluating the reliability of critical systems in an earthquake. A system scoring system is provided to quantify the relative reliability of systems and components. This method can be used by an individual to identify and prioritize vulnerabilities on a system and facility basis.

For each of the major systems identified, a system evaluation should be performed. The methodology described in the handbook makes use of the system and component information developed for each system and the scores for individual components.

STEP 4: RISK MANAGEMENT

The results of the screening methodology provide a basis for making risk management decisions. The review of critical electrical and mechanical systems and their components provides the information necessary to create a specific plan for improving a facility's post-earthquake functionality.

The component and system evaluations described in this process are part of a screening assessment. It highlights important system components, their interactions, and their impact on system function. It is not the only indicator of where upgrades or repairs should be made, but it provides a consistent method for identifying obvious vulnerabilities and prioritizing risk management implementation.

Mitigation is not limited to physical repairs to equipment or systems. Mitigation can be achieved through means such as upgrades, analyses and emergency response procedures. All mitigation efforts as defined in this process are intended to improve overall system reliability.

E.3 Identifying Facility Performance Requirements

The owner of a facility should identify what the functional requirements of the facility are during and following an earthquake. Essential functions are those which must be provided by a facility during an earthquake, immediately following an earthquake, or within a specified time period following an earthquake. Examples may include requirements to provide emergency or critical care for hospitals or money transfers for banks. Federal law or federal, state, or local regulators may specify other specific functionality requirements.

Essential functions may be identified by any of the following means:

- Specific facility performance requirements that are unique to a given facility, industry, or type of installation, may be specified by law or other regulatory or licensing requirements, under federal, state, or local jurisdiction.
- Minimum standards of life-safety protection must be maintained irrespective of the event that has occurred and the level of escalation. This would include fire detection and alarm, fire response, building evacuation and egress, and similar systems or functions, as required by federal, state, or local laws and regulations.
- A facility owner or manager may identify any additional function as critical and evaluate systems using this Recommended Practice because of financial considerations or any other reasons. Examples of such considerations would be concerns for capital costs, business interruption, and damage and recovery costs.

E.4 Identification of Critical Systems

As discussed above, critical systems are likely to include both life-safety systems and business operation systems. Life-safety systems are usually defined as those functions whose failure results in conditions where lives are in imminent danger or are not sufficiently protected from potential dangers. Typical examples of life-safety functions are:

- Fire response (including detection, suppression, and smoke barriers/purge)
- Shutoff of hazardous material releases (primarily natural gas)
- Elevator safety
- Evacuation/Egress

Business operation systems are defined as those systems that must function in order to continue operation of the facility at full or reduced capacity. This definition of capacity is the starting point for the identification of the critical business operation functions. For example, operation of elevators may be considered to be essential for full building operation in one situation but non-essential for another similar building if the desired state is limited operation. This designation depends on the essential function of the facility, and is determined as the first step of the evaluation. Typical examples of business operation functions are:

- Lighting/Power (including lighting, normal building power, emergency power)
- Water Supply/Waste Removal (including water supply, sewage removal)
- Storm Drainage
- Normal Personnel Transport (including elevators)
- Building HVAC (including heating, ventilation, air conditioning, HVAC control)
- Communications (including telephone/communications, data telecommunications)
- Data Processing (including data processing equipment, computer equipment)
- Refrigeration
- Gas Supply
- Structural Concerns (including raised access floors)

Within MCEER 99-0008, there area series of checklists were developed to assist in identifying critical systems and components. These checklists can be used to identify subsystems and utilities that are also required for functionality of the system. While functionality of the critical systems is generally provided by operation of combinations of equipment and/or human actions, in some cases, a single operator action may be all that is required in order to provide for functionality. In other cases, the combined operation of several systems may be required. In some cases there may be redundant means for providing full or partial operation.

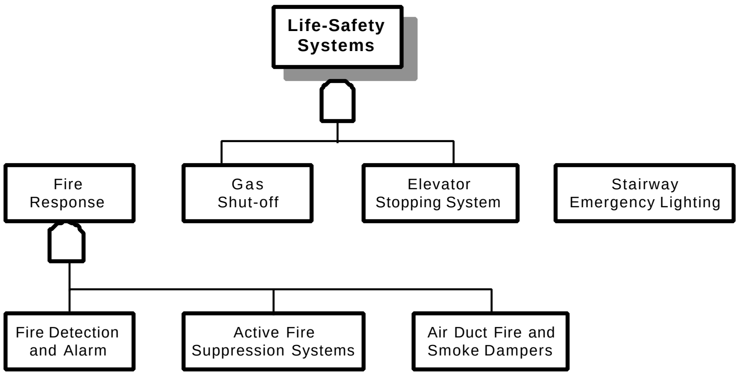
The goal of the entire process of identification of components is to narrow the scope of components examined from an all-encompassing list of building equipment to a list which reflects only those components necessary to provide functionality of critical systems while also accounting for any enhanced safety provided by installed redundancy.

E.5 Critical Systems Diagrams

One method of providing a pictorial view of the system interrelationships is by developing diagrams of critical systems. These diagrams provide a framework for quantifying the relative reliability of the systems following an earthquake and are also a useful tool for the process of making practical risk management decisions. The critical system diagrams are a type of logic tree, similar to a fault tree, which uses “AND” and “OR” logic to express the system interrelationships to the overall successful functioning of the building being examined. Similar diagrams can be constructed

Diagrams can be used to define overall system requirements for life-safety or business operations, as shown in Figure E-1, as well as detailed descriptions of components required for specific systems, as shown in Figure E-2.

KEY		
SYMBOL	NAME	MEANING
	AND GATE	Component above gate functions if all components below function
	OR GATE	Component above gate functions if any component below functions



See Figure E-2

Figure E-1: Life-safety Systems/Fire Response Level Logic

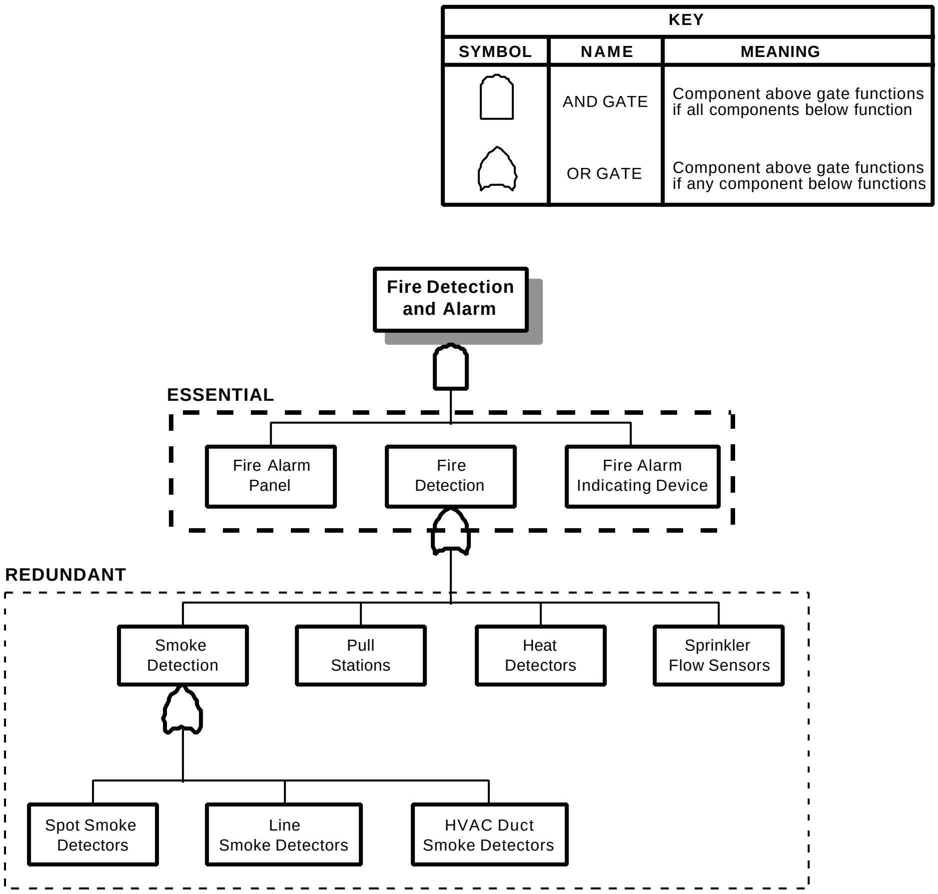


Figure E-2 Fire Detection and Alarm Logic Example

E.6 Components Evaluation

The scoring methodology for an individual component uses the following logic:

1. Each component is assigned a basic score that is a function of the performance history of that type of equipment, and the seismicity of the site. Those scores have been developed for broad categories of major equipment components

2. The basic scores are modified by Performance Modification Factors (PMFs) which indicate the decrease in reliability due to specific configurations or details that may be present in an equipment installation. Each detail that might affect the

seismic vulnerability is assigned a PMF consistent with its relative effect on functionality.

3. The evaluation and checklist are completed such that the basic score and all applicable PMFs are identified.

4. The equipment item is assigned a score equal to its basic score minus the largest (worst case) applicable PMF. If further evaluations or system modifications lead to the determination that a particular PMF is no longer relevant, the second most critical PMF is then used.

An example data sheet is shown in Figure E-3. Similar sheets have been developed for major electrical and mechanical equipment categories found in critical facilities.

E.7 Component Scores

Scores for individual components were generated based on standard lognormal fragility formulations defining the conditional probability of failure, f_O, for a given acceleration level, a, as:

$$f_O = \Phi\left[\frac{\ln(a/A_m)}{b_R}\right] \quad \text{(E-1)}$$

where Φ is the standard Gaussian cumulative distribution function, β_R is a measure of the random variability, and A_m is the median acceleration capacity.

Of course, perfect knowledge of a system is unattainable and some amount of uncertainty exists. Including this uncertainty, β_U, makes the fragility a random variable. A mean fragility curve can also be calculated, which is the weighted average of all possible curves. An important short cut is available to calculate the mean curve without averaging all individual curves. The mean curve is also a lognormal function of the median capacity and a combined uncertainty β_c, where

$$b_c = \sqrt{b_R^2 + b_U^2} \quad \text{(E-2)}$$

Fragility data were generated using various methods, including earthquake experience data, limited testing data, statistics on capacities and uncertainties used in risk calculations for similar components at older nuclear power plants, and judgment of engineers intimately familiar with equipment vulnerabilities.

Basic Scores were calculated as the negative of the logarithm (base 10) of the annual probability of failure.

$$\text{Basic Score} = S = -\log_{10}(P_{fa}) \quad \text{(E-3)}$$

The annual probability of failure is calculated by convolving the fragility curve of a component with a “generic” seismic hazard curve. The convolution is described by the following equation:

$$P_{fa} = \int_0^\infty \frac{-dH(a)}{da} P_{fc}(a)\,da \quad \text{(E-4)}$$

where P_{fa} is the annual probability of failure and P_{fc} is the conditional probability of failure. H(a) is the hazard curve.

Batteries and Racks

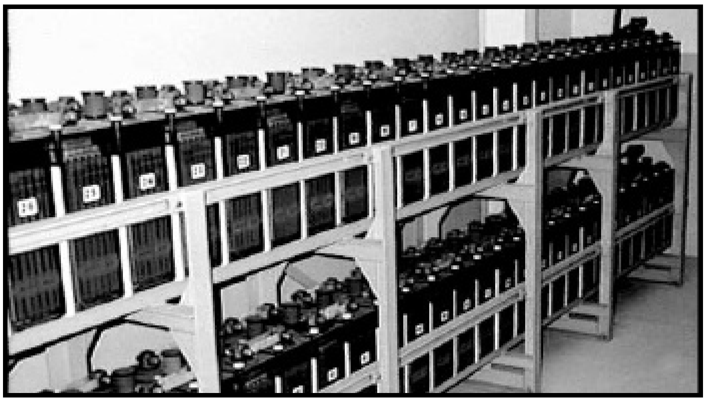
Component ID:

____

Location:

____

____



Comments:

Earthquake Load Level (circle one letter)

ZONE	NEHRP	UBC	Location in Building: Bottom Third	Middle Third	Top Third
Z	1-3	1	A	A	A
O	4-5	2	A	B	C
N	6	3	B	C	D
E	7	4	C	D	E

Scores and Modifiers - Batteries and Racks

(circle a Basic Score and **all** PMFs that apply - use the column indicated by the Earthquake Load Level above)

	Description	A	B	C	D	E
	Basic Score →	5.3	4.4	3.9	3.5	3.2
PMF	1. No anchorage	1.5	1.5	1.5	1.5	1.5
PMF	2. "Poor" anchorage	1.3	1.3	1.3	1.3	1.3
PMF	3. No battery spacers	0.7	0.7	0.7	0.7	0.7
PMF	4. No cross-bracing	0.9	0.9	0.9	0.9	0.9
PMF	5. No battery restraints	2.0	2.0	2.0	2.0	2.0
PMF	6. Interaction concerns	0.5	0.5	0.5	0.5	0.5
PMF	7. Other:____________________					
	Final Score = Basic Score – **highest applicable** PMF					

Note that this is a screening process and is inherently conservative. If there is any question about an item, note it and select the appropriate PMF. See the following page for PMF guidelines.

Figure E-3: Sample MCEER 99-0008 Component Scoresheet: Batteries and Racks

Explanation of Performance Modification Factors (PMFs)

1, 2 If there are no anchor bolts at the base of the frame, select PMF 1. If the anchors appear to be undersized, if there are not anchors for every frame of the rack, or if the anchorage appears to be damaged, select PMF 2.

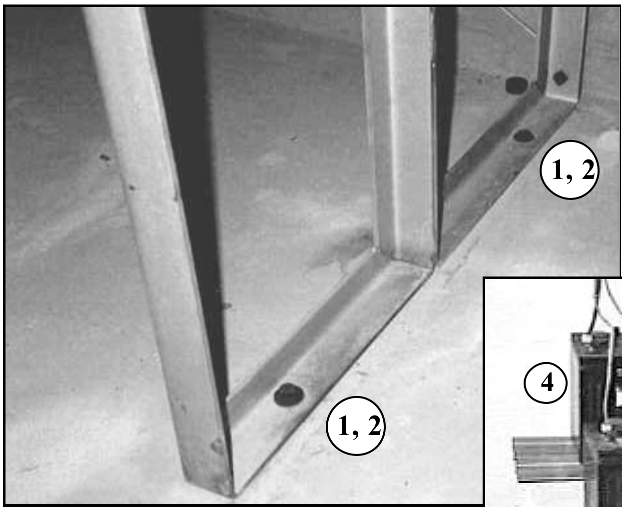
3 Look for stiff spacers, such as Styrofoam, between the batteries that fit snugly to prevent battery pounding. If there are none, select PMF 3.

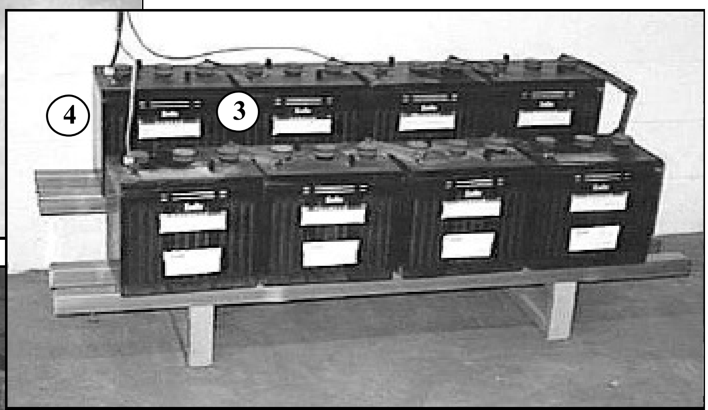
4 The rack should provide restraints to assure that the batteries will not fall off. The photo above shows a rack with no restraints, while the photo to the left shows a rack with restraints. Select PMF 4 if adequate restraint is not provided.

5 Racks with long rows of batteries need to be braced longitudinally as shown in the photo to the left. Select PMF 5 if no cross-bracing is present.

6 If large items such as non-structural walls could fall and impact the battery racks, select PMF 6.

7 For other conditions that the reviewer believes could inhibit battery function following an earthquake (e.g., a history of problems with this piece of equipment), assign a PMF value relative to the existing PMFs in the table. Add a descriptive statement for the concern.





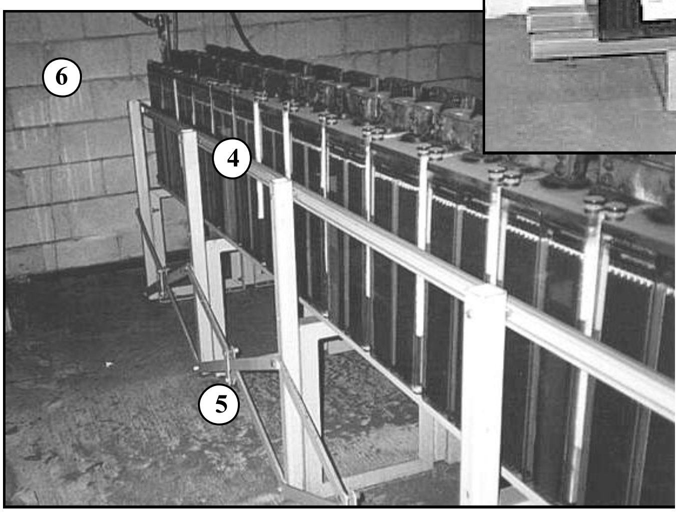


Figure E-3 (continued): Sample MCEER 99-0008 Component Scoresheet: Batteries and Racks

SYSTEM SCORING

An emphasis of this project was to develop a methodology that allows the user to make risk management decisions based on reliability of systems rather than individual components. In order to achieve that goal, a scoring system was developed, such that scores are assigned to individual components and to entire systems. Eventually a score can be assigned to every system required to maintain the operations capability of a given facility. Those scores are based on the scores of the individual components and the importance of those components in maintaining system function.

However, it was also recognized that rigorous risk analyses using Boolean algebra on complicated logic diagrams would not be practical. As such, several simplified methods were assessed for determining system scores, such as taking the highest score or adding scores for redundant systems and taking the lowest score for dependent systems (where failure of any component causes the system to fail).

Each method was tested by performing rigorous systems analyses of multiple cases with varying numbers of components using the proprietary program EQESRA™. EQESRA™ was developed to evaluate the probability distribution of system failure frequency from information about component fragilities (seismic or non-seismic failures), Boolean expressions for accident or event sequences, and seismic hazard. The program performs component combinations in accordance with the Boolean expression to yield an overall system or plant level fragility. It then convolves the system fragility with the seismic hazard to yield a probability distribution on failure frequency, which was translated into basic scores for comparison to results from the simplified methods. The EQESRA™ program uses the methodology described in Kaplan (1981) and Kaplan and Lin (1987).

Based on these analyses, the following simple rules were developed for scoring:

1. When a group of components is linked by an "**and**" gate (indicating dependency), the overall score for that group is the lowest of the component scores, S_{min}.

2. When a group of components is linked by an "**or**" gate (indicating redundancy), the overall score for that group is the highest of the component scores (S_{max}) plus a factor (f). This factor depends on the number of components (N) linked in parallel and takes the form: f = 0.5(N-1). So the score for a redundant group of components is: S_{max} + 0.5(N-1).

An example is shown in Figure E-4.

KEY		
SYMBOL	NAME	MEANING
	AND GATE	Component above gate function if all components below function
	OR GATE	Component above gate function if any component below function

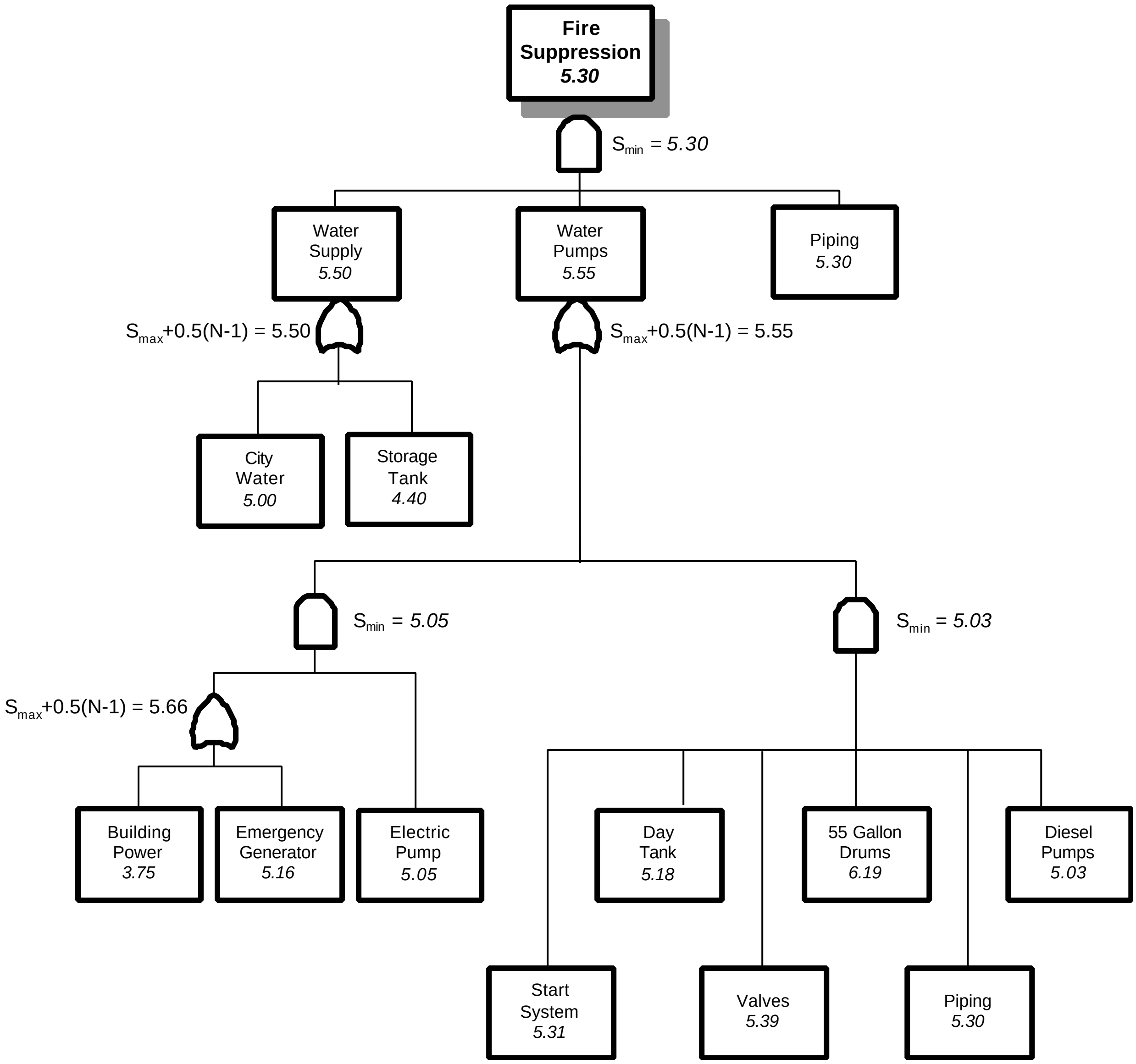


Figure E-4: Illustration of MCEER 99-0008 System Scoring
(Numbers shown were selected for illustrative purposes only)

Appendix F: Typical Consultant Work Statement

F.1 Retaining Seismic Retrofit Design Professionals

Retaining engineers experienced in seismic retrofit is an important aspect of the retrofit process. One of the most important attributes to look for is experience and satisfactory performance on previous projects. As discussed previously, the seismic retrofit professional will typically go about the assessment and mitigation in a three phased approach, consisting of:

1. Initial investigation;

2. Detailed investigation, conceptual retrofit design, and costing of alternatives; and

3. Final design, production of design documents, and a 'bid package'.

Step two is perhaps the most crucial from the decision-making viewpoint, since this is where the alternatives are evaluated for cost and effectiveness.

In retaining an engineer, a clear and detailed scope of services should form the basis for the relationship. The scope of services must of course be specific to the particular situation, but might consist of the following tasks:

Example Scope of Services for Seismic Retrofit Design Professional

Phase I – Initial Investigation

1. Review all available construction documents for the building including structural and architectural drawings and specifications for the original construction as well as similar documents for any significant modifications or upgrades. The purpose of this review shall be to determine the basic structural load carrying systems, and to identify seismic performance issues related to configuration and structural detailing.

2. Review available geotechnical reports for the site to determine a site class for use in developing seismic hazards and to identify conditions that could lead to ground failure or other site instabilities. Where site specific soils data is not available, reference should be made to available generalized geotechnical data such as found on regional maps produced by the United States Geologic Survey (USGS) and the California Division of Mines and Geology (CDMG). Reference should also be made to the seismic safety element of local general plans.

3. Perform a seismic hazard for analysis for the site to identify the location of the site relative to significant faults, and to estimate the probable intensity of ground acceleration as a function of return period (or probability of exceedance).

4. Conduct a visual survey of the building to document the structure's condition and to confirm that available construction documents are representative of existing conditions. To the extent that construction documents are unavailable, perform field investigation to develop sufficient information to identify the vertical and lateral structural load carrying systems, and to quantify their strengths.

5. Perform a preliminary structural evaluation to quantify the probable performance of the building structure to resist the effects of ground shaking having a 10% probability of exceedance in 50 years. {*Note that either more or less probable levels of ground shaking may be specified, based on the importance of individual facilities. For facilities located within a few miles of major active faults, it may be more appropriate to specify that the evaluation be performed for a median estimate of the ground shaking resulting from a characteristic earthquake on that fault.*} The evaluation should, as a minimum, conform to the requirements of FEMA-310 for a Tier 1 evaluation. Alternative evaluations that quantify the adequacy of the seismic force resisting system considering, strength, ductility, and configuration issues may be used.

6. Develop an inventory of critical non-structural components including building utility equipment (power supply, HVAC systems), operating equipment, ceilings, building fascia panels, elevators and fire protection systems. Identify the adequacy of installation of these non-structural components to resist damage.

7. Develop a preliminary opinion as to the probable performance of the facilities, in the event of the designated earthquake ground motion (see item 5 above) using the performance levels contained in FEMA-273 and FEMA-310.

8. Prepare a written report documenting the scope of study, the findings and recommendations, with written documentation of the evaluation process (FEMA-310 checklists, calculations, etc.) included as appendices. If preliminary study indicates significant potential for earthquake induced ground failure and sufficient site specific soils data was not available to conclusively assess this, the report should include a recommendation for site specific geotechnical investigation. If the existing construction of the structure is not sufficiently well defined to permit quantification of its structural characteristics, include recommendations for detailed field investigations to confirm the construction.

Phase II – Detailed Investigation and Conceptual Retrofit Design

9. Review the phase I evaluation report and available construction documents for the facility to develop an overall understanding of the building's construction and its probable seismic performance.

10. Conduct a visual survey of the building to observe the building condition and note obvious deviations from the available documentation. Observe potential opportunities for introduction of seismic upgrade elements. Note sensitive areas of the building, such as historic spaces, traffic corridors, etc. that may not be impacted by seismic upgrade measures.

11. Meet with the facility manager to discuss alternative performance criteria and to select an appropriate criteria, or set of criteria. Also discuss restrictions on placement of retrofit elements, relative to building appearance and functionality concerns.

12. If recommended in the phase I evaluation, perform field investigation of the building to confirm the details of its construction and material strengths.

13. If recommended in the phase I evaluation, obtain site-specific geotechnical data to evaluate potential ground failure and associated mitigation measures.

14. Perform structural engineering calculations to quantify seismic deficiencies in the building relative to the selected performance levels. As a minimum, the criteria of FEMA-310 for a Tier 2 evaluation should be performed. Alternatively, the performance analysis procedures contained in the California Building Code, Division IIIR, or in FEMA-273, or in the California Seismic Safety Commission's SSC-96-01 may be used.

15. Review alternative potential methods for seismic upgrade for each specified performance criteria, to a level sufficient to confirm feasibility and to select a recommended approach. Meet with the facility manager to review the alternatives and to agree on the appropriateness of the recommended approach.

16. Develop conceptual level upgrade designs for each specified performance criteria. Supporting calculations shall be performed to a sufficient level of detail to confirm that the overall size and scope of the recommendations are appropriate. The level of detail should be sufficient to permit a rough order of magnitude cost estimate to be performed. Consideration should be given to collateral upgrades triggered by the seismic work, including disabled access, fire/life safety and other code upgrades.

17. Prepare conceptual level sketches showing recommended upgrades for non-structural components.

18. Prepare preliminary cost estimates for the recommended seismic upgrade work, for each performance

criteria, together with required collateral upgrades.

19. Prepare a report indicating the scope of the study, the findings with regard to building deficiency and performance and the recommendations for alternative levels of upgrade, as well as any recommendations for additional investigation to be performed as part of final design. Include schematic drawings documenting the upgrade recommendations and cost estimating work sheets in an appendix.

Phase III – Construction Documents and Construction Support

1. Assemble a complete design team including project management, structural engineering, architecture, mechanical and electrical engineering, and cost estimating, as required to support the development of construction documents.

2. Review all available documentation for the building as well as previous evaluation reports and supporting calculations in order to develop an understanding of the building deficiencies and recommended upgrade approach.

3. Meet with the building official, as necessary to confirm the design criteria and proposed approach, as well as to confirm the extent of required collateral upgrades.

4. Develop construction documents including drawings and specifications, together with supporting calculations, to implement the recommended structural upgrades, together with all required collateral upgrades. Submit copies of construction documents to client for review, at the 40%, and 90% stages of completion. Final construction documents shall be suitable for obtaining building permits, competitive construction bids, and for executing the work.

5. Prepare an estimate of probable construction cost at each stage of document submittal and for the final construction documents.

6. Provide support to client in development of bid packages for construction contracts.

7. Respond to comments from plan checkers and revise construction documents as necessary to obtain approval.

8. Respond to bidder requests for clarification.

9. Provide support to client in evaluation of construction contract bids for completeness and consistency with the requirements of the construction documents.

10. Attend periodic meetings at the construction site, during the construction period to coordinate with construction progress.

11. Conduct periodic site visits to confirm that the work is generally being conducted in accordance with the design requirements.

12. Review contractor submittals and shop drawings.

13. Respond to contractor Requests for Information and assist client in negotiation of contractor change order requests.

14. Review special inspection and test reports.

15. Perform a walkthrough of the project site at 95% completion to develop a punchlist of items not completed by contractor.

Worksheet 1-A: Decision Hierarchy

POLICY DECISIONS – MADE BEFORE RISK ASSESSMENT

Decision-Maker: For each facility-type and earthquake event, choose and circle the appropriate performance objective: Operational (O), Immediate Occupancy (IO), Life Safe (LS), Collapse Prevention (CP) or Not Considered (N). Also choose and circle a corresponding enforcement alternative: required (R) or encouraged (E). For precise definitions of facility-types, see Worksheet 1-B for examples. For precise definitions of performance objectives, see Table 3-4.

Facility type	**MPE (500 year)**	**LE (100 year)**	**Mandate**
Essential public facilities	O IO LS CP N	O IO LS CP N	R E
Public facilities with vulnerable occupants	O IO LS CP N	O IO LS CP N	R E
Other public facilities	O IO LS CP N	O IO LS CP N	R E
Private commercial - emergency response	O IO LS CP N	O IO LS CP N	R E
Private commercial with hazardous materials	O IO LS CP N	O IO LS CP N	R E
Private commercial – essential operations	O IO LS CP N	O IO LS CP N	R E
Private commercial - ordinary operations	O IO LS CP N	O IO LS CP N	R E
Other private commercial	O IO LS CP N	O IO LS CP N	R E
Multi-family residential	O IO LS CP N	O IO LS CP N	R E
Single-family residential	O IO LS CP N	O IO LS CP N	R E
Historic	O IO LS CP N	O IO LS CP N	R E

STRATEGIC DECISIONS – MADE AFTER RISK ASSESSMENT

The Risk Manager will collect information on all facilities with a performance objective other than "N" in the table above. With the aid of the Asset Manager and engineering consultants, the Risk Manager will evaluate each facility to determine if it is capable of meeting the selected performance objective. For those facilities that do not meet these objectives, the Risk Manager, assisted by the Asset Manager and engineering consultants, will recommend mitigation alternatives and select the alternative that best meets the stated objective. The Risk Manager will provide the Decision-Maker with cost and benefit information necessary to evaluate the recommendation and make the final decision.

Worksheet 1-B – Facility-type Definition

Risk Manager: Unambiguously define each facility-type you will use (e.g., by zoning or use code, by exact address, etc.) to prevent misunderstanding on the category of any particular facility. Decision-Maker: Adjust or endorse this classification system.

(A) Facility-type	(B) Examples; notes	(C) Zoning or use codes, addresses
Essential public facilities	Fire & police stations, hospitals, emergency operation & communication facilities, water supply facilities	
Public facilities with vulnerable occupants	Schools, non-emergency medical facilities, correctional facilities, nursing homes	
Other public facilities	Libraries, office buildings, public works equipment yards, local vehicular bridges, wastewater treatment facilities	
Private commercial - emergency response	Telephone switching facilities, private ambulance services, private medical facilities	
Private commercial - hazardous materials	Chemical and gas manufacturers and distributors, industrial facilities	
Private commercial - essential operations	Bank data processing centers, customer service centers, manufacturing facilities in certain high-tech industries	
Private commercial - ordinary operations	Research & development facilities, warehouses, retail, wholesale, service, transportation, construction facilities	
Other private commercial facilities	Other facilities	
Multi-family residential	Apartment buildings, condominium associations	
Single-family residential[1]	Detached or attached single-family dwellings.	
Historic	Local, state, or national historic registry	

[1] Public agencies rarely examine seismic risk for single-family residences, except in the case of unreinforced masonry (URM) buildings.

Worksheet 2 – Facility Task List

Risk Manager: For each facility, assign a unique identifier into Column A. Fill this in together with the facility address or location into Column B. From Worksheet 1-B, enter the facility-type into Column C. In Columns D and E, circle the performance objectives for the MPE and LE events, respectively. For Columns F and G, enter the name and contact information for the persons performing the building and equipment screenings, respectively. Columns H and I are only needed if the screening exercise results in recommendation for more detailed evaluation.

(A) ID	(B) Facility Address or Location	(C) Facility-Type	(D) MPE Objective	(E) LE Objective	(F) Building Screening	(G) Equipment Screening	(H) Building Assessment	(I) Equipment Assessment
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*
			O IO LS CP N	O IO LS CP N	*Contact:*	*Contact:*	*Contact:*	*Contact:*

(Use additional sheets as necessary)

Worksheet 3 – Rapid Building Screening[1]

FEMA 154 **(NEHRP Map Areas 5,6,7 High)**

Sketch of Building

Scale:

Facility
Address ______________________
No. Of Stories ______________________
Year Built
Total Floor Area ______________________ (sq.ft.)
Building Use ______________________

Inspector ______________________
Date ______________________

INSTANT PHOTO or DIGITAL IMAGE

OCCUPANCY	
Residential	No. Persons
Commercial	
Office	0-10
Industrial	11-100
Pub. Assem.	100+
School	
Govt. Bldg.	
Emer. Serv.	
Historic Bldg	
Non Structural Falling Hazard	
DATA CONFIDENCE	
* = Estimated, Subjective or Unreliable Data	
DNK = Do Not Know	

STRUCTURAL SCORES AND MODIFIERS

Building Type	W	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	C1 (MRF)	C2 (SW)	C3/S5 (URM INF)	PC1 (TU)	PC2	RM	URM
Basic Score	4.5	4.5	3.0	5.5	3.5	2.0	3.0	1.5	2.0	1.5	3.0	1.0
High Rise	N/A	-2.0	-1.0	N/A	-1.0	-1.0	-1.0	-0.5	N/A	-0.5	-1.0	-0.5
Poor Condition	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Vert. Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-0.5	-0.5	-1.0	-1.0	-0.5	-0.5
Soft Story	-1.0	-2.5	-2.0	-1.0	-2.0	-2.0	-2.0	-1.0	-1.0	-2.0	-2.0	-1.0
Torsion	-1.0	-2.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0	-1.0
Pounding	N/A	-0.5	-0.5	N/A	-0.5	-0.5	N/A	N/A	N/A	-0.5	N/A	N/A
Large Heavy Cladding	N/A	-2.0	N/A	N/A	N/A	-1.0	N/A	N/A	N/A	-1.0	N/A	N/A
Short Columns	N/A	N/A	N/A	N/A	N/A	-1.0	-1.0	-1.0	N/A	-1.0	N/A	N/A
Post Benchmark Year	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	N/A	+2.0	-2.0	+2.0	N/A
SL2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
SL3	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
SL3 & 8 to 20 Stories	N/A	-0.8	-0.8	N/A	-0.9	-0.9	-0.9	-0.9	N/A	-0.8	-0.8	-0.9

COMMENTS

Detailed Evaluation Required?
Yes No

[1] Adapted from FEMA-154 Rapid Visual Screening and Data Collection Form

Worksheet 4 – Building Assessment

Facility: ____ Date: __________

Engineer: _______________________________ Interest Rate Employed:__________

PRESENT VALUE OF RETROFIT COSTS

Retrofit Option	Best Estimate ($)	Contingency[1] ($)	Duration[2] (months)
Do Nothing (As-is Conditions)	-	-	
Option 1 (describe): ___________________________			
Option 2 (describe): ___________________________			
Option 3 (describe): ___________________________			

1 Contingency is an amount held in reserve to account for unforeseen conditions.

2 Duration is an indication of the amount of time required to implement the retrofit.

LOSS ESTIMATES

Retrofit Option	Loss Item	MPE (500-Year)		LE (100-Year)	
		Best[3]	High[3]	Best	High
As-is Conditions	Repair Cost				
	Loss-of-Use[4]				
Option 1	Repair Cost				
	Loss-of-Use[3]				
Option 2	Repair Cost				
	Loss-of-Use[3]				
Option 3	Repair Cost				
	Loss-of-Use[3]				

3 The “best” estimate is the engineer’s estimate of the most probable outcome. There should be roughly a 50% chance that the actual outcome would be either higher or lower than this estimate. The “high” estimate represents the engineer’s estimate associated with a high confidence of non-exceedance. Engineers familiar with the performance of Probable Maximum Loss estimates will associate this “high” estimate with a PML.

4 Loss-of-Use is the duration (measured in days or months) of the time that the facility will not fulfill its normal function.

Worksheet 5 – Equipment Assessment

Equipment System: ________________________ Type (circle one): Damage / Life-safety / BI

Inspector: __________________________________ Date: _________________________

Mitigation Option	Risk Score *S*	Best Estimate	High Estimate	
As-is (do nothing):		-	-	*By EI*
Option 1:				*By EI*
Option 2:				*By EI*

Loss-of-use Costs for Failure (from Worksheet 6)

UGF (1 hr)________ *UGF* (1 week)_________ *UGF* (1 day)_________ *UGF* (1 month)_________

Case	Loss Items	MPE (500-year)	LE (100-year)	
As-is	Repair Cost, *R* (Best $ Estimate):			*By EI*
	Duration Units (circle one):	hour day week month	hour day week month	*By EI*
	Loss-of-Use Duration, *LUD:*			*By EI*
	Loss-of-Use Cost (Given Failure), *UGF:*			
	Loss-of-Use Cost, $U = 10^{-S} \times UGF$:			
Opt. 1	Repair Cost, *R* (Best $ Estimate):			*By EI*
	Duration Units (circle one):	hour day week month	hour day week month	*By EI*
	Loss-of-Use Duration, *LUD:*			*By EI*
	Loss-of-Use Cost (Given Failure), *UGF:*			
	Loss-of-Use Cost, $U = 10^{-S} \times UGF$:			
Opt. 2	Repair Cost, *R* (Best $ Estimate):			*By EI*
	Duration Units (circle one):	hour day week month	hour day week month	*By EI*
	Loss-of-Use Duration, *LUD:*			*By EI*
	Loss-of-Use Cost (Given Failure), *UGF:*			
	Loss-of-Use Cost, $U = 10^{-S} \times UGF$:			

Maximum repair cost R_{max} (from *Risk Manager* or *Asset Manager*): $____________________

Worksheet 6 – Loss-of-Use by Facility

Expert(s): ____ Date: ___________

Facility: ____

Financial Manager: Provide best estimates of dollar costs resulting from this facility being out of operation for various durations. Assume the building is safe to enter to remove documents and equipment, but elevators, electric power, water, etc., are unavailable. Total UGF = sum of column

$ Units (circle one) = dollars / hundreds / thousands / millions

	Loss-of-Use Duration			
Cost Item	**1 hour**	**1 day**	**1 week**	**1 month**
Extra Rent:	0	0		
Movers:	0	0		
Production Losses:				
Outsourcing Costs:	0			
Loss of Market Share:	0	0		
Extra Marketing:	0	0		
Overtime:	0	0		
Other:____________________				
Total *UGF*				

Worksheet 7 - Benefit-Cost Analysis

Column A **Facility**	B **Retrofit Option**	C **Perf. Obj.**	D **Occup. Class**	E **Retrofit Cost, C**	F C_{pa} *Eqn. 4-2*	G D_{IF}	H D_{MPE}	I **E[D pa]** *Eqn. 4-3*	J U_{LL}	K U_{MPE}	L **E[U pa]** *Eqn. 4-4*	M **E[D pa] + E[U pa]**	N **Benefit, B**	O B/C_{pa}
1	A - *As-is*													
	B													
	C													
	D													
2	A - *As-is*													
	B													
	C													
	D													
3	A - *As-is*													
	B													
...	...													

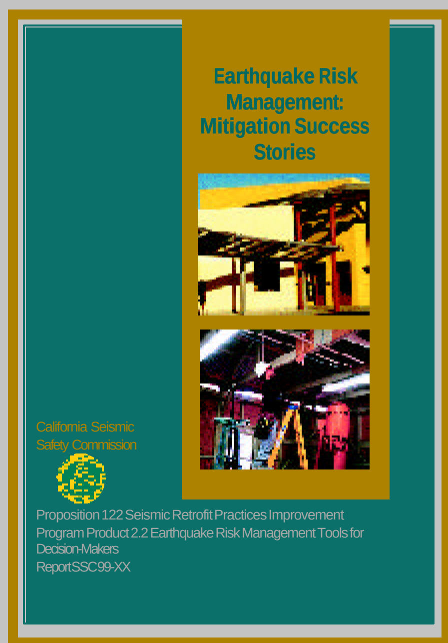
Worksheet 7 - Benefit-Cost Analysis

Column A **Facility**	B **Retrofit Option**	C **Perf. Obj.**	D **Occup. Class**	E **Retrofit Cost, C**	F C_{pa} *Eqn. 4-2*	G D_{LF}	H D_{MPE}	I **E[D pa]** *Eqn. 4-3*	J U_{LL}	K U_{MPE}	L **E[U pa]** *Eqn. 4-4*	M **E[D pa] + E[U pa]**	N **Benefit, B**	O B/C_{pa}
1	A - *As-is*													
	B													
	C													
	D													
2	**A** - *As-is*													
	B													
	C													
	D													
3	A - *As-is*													
	B													
...	...													

Where Can I Get More Information?

Five case studies of successful earthquake hazard mitigation projects within California have been brought together in the California Seismic Safety Commission publication:

Earthquake Risk Management: Mitigation Success Stories (SSC Report 99-05)



This companion resource illustrates the practical aspects of the risk management decision-making process, offering valuable lessons and insight. These studies also show that earthquake risk management can be a financially viable endeavor, especially when all of the costs of potential losses, direct or otherwise, are fully considered.

Seismic Safety Commission

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