PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Organizational and Societal Considerations for Performance-Based Earthquake Engineering

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A report on research conducted by PEER as part of
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ABSTRACT

Decisions about seismic performance are the underpinnings of a rigorous approach to performance-based earthquake engineering and should specifically consider the decision variables within the PEER framing equation. This report considers the decision-making process for seismic safety from the perspective of organizations — building owners, investors, and others concerned with single facilities or a collection of facilities — and from the perspective of society.

The dominant mode of seismic performance decision making, "risk and safety as by-products of design," falls short in not allowing trade-offs or choices in decisions concerning seismic risks. The opposite mode, "performance-optimized decisions," focuses on desired performance levels but masks relevant choices and trade-offs. Only an "investment based" approach provides a framework consistent with the variables of the PEER framing equation for making explicit trade-offs in seismic performance and their costs. Decisions about desired levels of seismic performance should allow for explicit consideration of trade-offs associated with investment in seismic safety and in other forms of risk management. Particular attention should be given to public safety, to reparability of a structure, and to usability of a structure; each as separate dimensions of performance objectives.

Seismic safety is a matter of public welfare for which governmental regulation is necessary for establishing minimum standards for seismic performance. Such standards at least implicitly involve the controversial notion of "acceptable risks" to society. Determining acceptable levels of risk is a value judgment that requires collective choices about minimum standards. Knowledge of relevant risk considerations, technical details, and costs and benefits is crucial to establishing these standards. Finding the appropriate compromise between public processes and technical expertise in determining safety goals is a serious challenge. Recasting acceptable risk into a discussion of desired *safety goals*, the costs involved in achieving these, and the trade-offs imposed could address some of the limitations of the concept of acceptable risk

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PREFACE

The Pacific Earthquake Engineering Research Center (PEER) is an Earthquake Engineering Research Center administered under the National Science Foundation Engineering Research Center program. The mission of PEER is to develop and disseminate technology for design and construction of buildings and infrastructure to meet the diverse seismic performance needs of owners and society. Current approaches to seismic design are indirect in their use of information on earthquakes, system response to earthquakes, and owner and societal needs. These current approaches produce buildings and infrastructure whose performance is highly variable, and may not meet the needs of owners and society. The PEER program aims to develop a performance-based earthquake engineering approach that can be used to produce systems of predictable and appropriate seismic performance.

To accomplish its mission, PEER has organized a program built around research, education, and technology transfer. The research program merges engineering seismology, structural and geotechnical engineering, and socio-economic considerations in coordinated studies to develop fundamental information and enabling technologies that are evaluated and refined using test beds. Primary emphases of the research program at this time are on older existing concrete buildings, bridges, and highways. The education program promotes engineering awareness in the general public and trains undergraduate and graduate students to conduct research and to implement research findings developed in the PEER program. The technology transfer program involves practicing earthquake professionals, government agencies, and specific industry sectors in PEER programs to promote implementation of appropriate new technologies. Technology transfer is enhanced through a formal outreach program.

PEER has commissioned a series of synthesis reports with a goal being to summarize information relevant to PEER's research program. These reports are intended to reflect progress in many, but not all, of the research areas in which PEER is active. Furthermore, the synthesis reports are geared toward informed earthquake engineering professionals who are well versed in the fundamentals of earthquake engineering, but are not necessarily experts in the various fields covered by the reports. Indeed, one of the primary goals of the reports is to foster cross-discipline collaboration by summarizing the relevant knowledge in the various fields. A related purpose of the reports is to identify where knowledge is well developed and, conversely, where significant gaps exist. This information will help form the basis to establish future research initiatives within PEER.

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1 Introduction

The decision-making process in performance-based earthquake engineering (PBEE) for engineered facilities has two appealing aspects: (1) it allows choices about desired performance to be more transparent and (2) it allows choices about seismic performance of individual facilities, subject to minimum standards, to be matched to differing situations. A key issue is the basis for making these choices — the "decision variables" of the PEER framing equation for performance-based earthquake engineering. This report addresses relevant decision variables from the perspectives of organizational decision makers and from a societal perspective.

From the perspective of organizational decision makers, performance-based earthquake engineering confronts two basic issues. One is the extent to which organizational needs and desires can be translated into meaningful objectives — both from a decision perspective and from an engineering perspective. The second is the diversity of organizations and the fact that their needs vary greatly. The first two sections of this synthesis report consider the relevance of findings concerning organizational choices and decision making for these challenges.

From a societal perspective, the stakes of seismic safety entail more than the sum of the investment decisions by homeowners, businesses, and others about seismic upgrades or choices about risk management. Seismic safety is a matter of public welfare involving potential loss of life or injury, disruption of communities, and costs to governments for addressing earthquake losses and recovery. These concerns about public welfare establish the need for governmental setting of minimum seismic safety standards and for other actions to promote seismic safety. These issues are typically framed as establishing "acceptable risks" from the perspective of society. The third section of this synthesis report considers societal perspectives and the problematic concept of acceptable risk. Also considered are decision processes for assessing societal objectives for earthquake safety.

The final section of the report considers what this review suggests about performance objectives and further research needs. Candidate design principles are provided for performance objectives and issues to consider when developing information for governmental decision making about performance objectives. A new direction is suggested in this report for thinking about seismic performance of structures and systems (e.g., lifelines, campus collection of buildings). This entails explicit consideration of trade-offs associated with investment in seismic safety while allowing for differences in time horizons, tolerance for risk, and weights attached to different aspects of safety. The suggested new direction also entails a reformulation of societal considerations from discussion of acceptable risk to discussion of desired levels of safety and the trade-offs entailed.

2 Organizational Choices about Seismic Safety

One starting point for thinking about seismic performance objectives is to consider the choices that organizations have made about seismic safety. This section considers commonalties and differences in organizational choices about seismic safety. The first part addresses decision situations and stakes in highlighting the diversity of needs. The second part provides case vignettes about organizational choices for seismic safety. These cases show that despite the diversity of situations, the framing of choices about seismic safety is often greatly simplified. The third part discusses social science research findings concerning different stakeholders — owners, insurers, and lenders — who are involved in shaping organizational choices. These findings indicate that choices about seismic safety also include decisions about purchase of insurance, other financial risk management options, and other means for managing risk.

2.1 DECISION SITUATIONS AND STAKES

The diversity of organizations that must at least implicitly make decisions about seismic safety include private and public entities, large and small firms, firms with single facilities and those with distributed facilities, those with essential and nonessential facilities, and those entities that deliver electric, gas, water and other lifeline support. Not only do organizations differ in size and in revenue base, but they also differ in their time horizons, tolerance for risk and uncertainty, and involvement with the public. Put differently, the stakes in making decisions about seismic safety differ greatly from those of a small business concerned about tomorrow's sales, to those of a school district concerned with protecting the lives of children, to those of an energy utility concerned about reliable delivery of service and exposure of the energy network to seismic hazards.

2.1.1 Delineating Different Situations

One approach to thinking about differences among organizations is to consider their different situations. In principle, different needs could be used to identify different classes of situations for desired performance. This is the explicit logic of the distinctions contained in current seismic code provisions and guidelines with respect to the "importance" of facilities as defined by different occupancy classes or uses. These facilities vary from "ordinary" and "essential" facilities to more gradated distinctions in facility types (see discussion in Applied Technology Council 1995; California Seismic Safety Commission 1991, 1995). One of the more extensive classification systems was established in California for hospitals following the Northridge earthquake under the 1994 amendments to the Alquist Hospital Safety Act. Seismic requirements for new construction and retrofit of existing facilities to ensure continued service in the aftermath of an earthquake are evaluated using a rating system that distinguishes among five structural and five nonstructural performance categories. Such distinctions in facilities are not limited to buildings. For example, the California Department of Transportation, "Caltrans," makes a distinction between "important" and "ordinary" bridges as a foundation for expected performance levels (see Yashinsky and Ostrom 2000).

It turns out to be much more difficult to sort out situations that might appear at first to be the case. It is obvious that essential public facilities, like a firehouse or police station, pose a different situation than a single-family home. The differences in situations posed by nonessential public facilities and private commercial operations, for example, are far from obvious. Moreover, the variation within classes of situations can be great. Public essential facilities differ in terms of types of facilities (e.g., firestations versus hospitals) as well as for the importance of any particular facility in delivery of services (e.g., the importance of an individual firehouse). The importance of any particular facility must be analyzed in the context of the network of service delivery just as the importance of a bridge must be considered with respect to its role in a highway network (see, e.g., Chang et al. 2000).

2.1.2 Delineating Different Stakes

The major conceptual contribution of performance-based engineering has been to shift attention from types of facilities to the costs of achieving different levels of seismic resistance and what might be at stake when making decisions about seismic safety. Understanding the stakes, in terms of potential loss of life, damage to contents, or interruption of service, logically leads to consideration of desired performance objectives. This has led, with the publication of key guidelines (FEMA 1997; SEAOC 1996), to consideration of different discrete performance objectives for buildings such as collapse prevention, life safety, limited operation, and immediate occupancy.

Researchers at the University of California, San Diego (UCSD) have devised a similar delineation of performance objectives for bridges in linking socio-economic outcomes to various damage states (Hose et al. 2000). The UCSD categorization distinguishes five levels — fully operational, operational, life safety, near collapse, and collapse. This can be contrasted with the Caltrans distinction between "immediate" (i.e., full access to service almost immediately after an event) and "limited" service levels (i.e., limited access possible within days; full access within months) under the presumption, which is a fundamental goal of Caltrans, of a "no-collapse" performance requirement (Yashinsky and Ostrom 2000).

A key point about the development of performance-based earthquake engineering is that it allows for explicit consideration of the relationship between costs of achieving different levels of seismic resistance and desired levels of performance. This allows, as has been the case for discussion of seismic retrofit of existing buildings, for making trade-offs among reduced levels of performance (relative to new buildings) in return for lowered costs of achieving that performance. This has been an important factor for addressing the often prohibitive costs of bringing existing buildings up to the seismic standards of new buildings.

The daunting technical issues have been identified in earlier reviews (e.g., Applied Technology Council 1995) and are subject of discussion in other PEER reports in this series. From the perspective of organizational needs a key issue is whether such qualitative distinctions adequately capture relevant decision considerations (or can be made to do so). Those addressing seismic safety of bridges, led by the UCSD group, argue that the multilevel performance approach is consistent with existing decision making and is technically feasible, while recognizing that the distinctions drawn in practice narrow once one establishes a baseline level of no-collapse (Hose et al. 2000).

The answer provided in this review with respect to the appropriateness of discrete performance objectives for buildings is mixed, as should become evident from the remainder of this report. On the one hand, relevant decision makers typically opt for simple decision rules that simplify choices consistent with discrete labeling of stakes or objectives. On the other hand, the dimensions that appear to be important for decisions about seismic safety vary greatly among organizations and situations. As such, it is difficult, if not impossible, to devise categorization that adequately covers all situations while also allowing for sufficient differentiation in situations. These issues are addressed later in this report.

2.2 CASE ILLUSTRATIONS OF SEISMIC PERFORMANCE CHOICES

An understanding of the choices that are involved can be garnered from case studies of decision making about seismic improvements. Unfortunately, these decisions are rarely documented other than with respect to engineering designs that were eventually employed. Short of that, we can turn to secondary sources that illustrate relevant performance considerations.

2.2.1 Campus Seismic Safety

One of the few detailed studies of decisions about seismic safety is a PEER-funded project studying seismic-related decisions by university administrators at four California universities — the University of California at Berkeley and Los Angeles, Stanford University, and California State University at Northridge — in the aftermath of the 1989 Loma Prieta and 1994 Northridge earthquakes (DeVries et al. 2000). Each campus engaged in a systematic process for setting priorities for retrofit, repair, or replacement of buildings that consisted of structural assessments of buildings, consideration of campus seismic safety policies, and selection and prioritization of buildings for attention.

Of relevance to this discussion are the differing seismic safety policies on the campuses and priorities established for seismic upgrading. It is interesting to note that the campuses actually had written policies, albeit some quite old, for "acceptable risk." The UC campuses were bound by a 1975 policy of the UC Regents that established an objective of preventing "substantial loss of life" with buildings ranked by their structural safety in four categories (good, fair, poor, and very poor). The Cal State Northridge campus was bound by a policy established in 1993 that established for new construction a standard of "life safety" and for existing construction a standard of "reasonable life safety" consistent with state building code requirements. In establishing this policy, the Trustees "took the position that even a total economic loss in an earthquake is acceptable if there is little risk of serious injury or death to the building's occupants." Stanford University established a very different policy in 1989 aimed at avoiding closure in the aftermath of future events while listing three institutional goals: protect lives, preserve ability to provide life-safety aid, and preserve the university's teaching program.

The setting of priorities for seismic upgrading varied in the particulars but was similar in the overall approach on the four campuses. Although the importance of considering of performance objectives other than life safety received attention on the UC Berkeley and Stanford campuses, only at Stanford was it an important consideration in priorities for upgrading facilities. Berkeley administrators were constrained by the UC Regents' policy and dictates from state-funding organizations about going beyond life-safety. For all four campuses, the issues of life-safety, occupancy (number of people in a building), availability of funding, and feasibility of conducting repairs/retrofits were important. Buildings that were deemed to have special historic value were treated separately.

2.2.2 Hewlett Packard, Worldwide

Beginning in 1988, Hewlett Packard (HP) initiated an extensive seismic program, modeled after the approach taken at Stanford University, addressing construction of new facilities and the upgrading of existing facilities. An extensive program for seismic upgrading of facilities in the United States entailed an evaluation of facilities worldwide for which facilities were ranked with respect to life safety and potential for business interruption. Those facilities selected for upgrading included an industrial concrete-frame building constructed in the 1960s in Santa Clara, California, and manufacturing facilities in Corvallis, Oregon.

An important consideration for the seismic upgrade of each of these was the ability to maintain production during the upgrades. HP designates three levels of seismic performance for new construction: Level A — critical facilities to be designed so that damages are repairable in less than two weeks after a major earthquake and for which most operations can resume immediately; Level B — repairable within 60 to 90 days and for which essential operations are protected but nonessential operations are disrupted; and Level C — requiring more than 90 days to repair (typically office, sales, and warehouse facilities) for which anticipated damage is moderate. The levels of seismic performance for existing construction are similarly designated with the addition of a category C-minus for buildings that may not be repairable and for which loss of operation is expected to exceed 90 days. HP has also developed guidelines for bracing and anchoring of nonstructural elements focusing on different types of equipment as supplementing the three-level ranking system for structures (abstract, FEMA 331, August 1998, pp. 1518; Bonneville and Lanning 2000).

2.2.3 Questar Corporation, Salt Lake City

This major energy resources and service company headquartered in Salt Lake City, Utah, confronted major issues concerning performance of their business continuity center in the event of a major earthquake. The Center houses a backup gas center for controlling their distribution system and a data center. Questar management decided to build a new facility according to UBC Zone 4 "essential services" standards in order to provide minimal or no interruption in operations in the event of a major earthquake. The design includes base isolation (nine isolators), bracing of heating, ventilating, and air conditioning (HVAC) and other equipment, "smart" electronic fire suppression, the highest level of redundancy available for computer systems hard drives and power systems, off site back-up computing facilities located outside of the area, redundant data communication systems, and multiple back-up sources of power (abstract, FEMA 331, August 1998: 2225; also see Taylor et al. 1998: 193–224).

2.2.4 Seafirst — Bank of America, Seattle

This division of Bank of America (now fully incorporated as Bank of America) confronted issues in dealing with seismic hazards in the state of Washington. As noted in the FEMA description of the bank's seismic program, bank officials have established goals of "life safety" for all bank areas and "operational continuity" in areas critical for bank operations. An important emphasis of the life-safety components of the mitigation program was the identification of ways to address potential nonstructural risks, resulting in attention to lighting, ceiling tiles, office equipment, raised floors, and HVAC systems (abstract, FEMA 331, August 1998: 29–33).

2.2.5 Anheuser-Busch Van Nuys Brewery

The seismic risk to this Anheuser-Busch facility was substantial given its location, age, and construction of the plant facilities. Production at the facility was disrupted because of the 1971 San Fernando earthquake resulting in loss of market share. A seismic upgrade program undertaken in the early 1980s was undertaken with a goal that "production following future severe earthquakes would be minimally interrupted." Analyses of upgrading options entailed evaluation of the benefits associated with "preventing a prolonged loss of production capacity and minimizing any potential loss of market share" (abstract, California Seismic Safety Commission 1999a: 21–24).

2.2.6 State of California, State Buildings

Through California's *Earthquake Safety and Public Buildings Rehabilitation Bond Act,* resulting from enactment of Proposition 122 in 1990, the state has engaged in an extensive program of evaluation and retrofit, reconstruction, and repair of state facilities for improved seismic performance. As stated in an overview report about the program, "life safety is the overriding priority." To establish desired improvements, buildings were initially rated with respect to seven levels of relative risk — ranging from Level I (potentially no structural damage, negligible nonstructural damage, probably remain operational, immediate occupancy with some disruption for cleanup) to Level VII (unstable under existing vertical loads, imminent threat to occupants and/or adjacent property, total disruption of systems).

Establishment of performance objectives entailed consideration of minimal acceptable performance according to the seven-level scale for eight types of occupancies (hospitals, essential facilities, hazardous materials, public schools, nursing/prisons, universities/research, offices/courts, other occupancies). For the first three categories of occupancies, Level II (negligible structural damage, repairable; minor nonstructural damage, repairable; negligible risk to life, minor disruptions for hours to days in systems; occupancy with only minor disruptions during cleanup) was deemed the minimum acceptable performance. For the other categories of occupancy, Level III (minor structural damage, repairable; moderate nonstructural damage; extensive repair; disruption of systems for days to months; occupancy within weeks with minor disruptions) was deemed the minimum acceptable performance. (abstract, California, Department of General Services, Division of the State Architect, *State Building Seismic Program, Report and Recommendations*, revised October 1994).

Given the emphasis of the program on protecting lives, the eventual priorities for retrofitting were based on ranking buildings with combined levels of high vulnerability and high occupancy. This information and analyses of the costs for upgrading or replacement were used to make seismic protection decisions for 50 high-risk state facilities.

2.3 SOCIAL SCIENCE RESEARCH CONCERNING STAKEHOLDERS' CHOICES

The cases discussed in the preceding section address decisions about investments in seismic upgrading of facilities from the perspective of facility owners or managers. These, of course, are not the only stakeholders in decisions about seismic safety. Lenders and insurers play potentially important roles, although as discussed in what follows those roles at present are more limited than one might think. This section reviews social science research concerning various stakeholders' choices about seismic safety improvements.

2.3.1 Small Businesses

Researchers from the Disaster Research Center of the University of Delaware have undertaken several studies of businesses in the United States concerning consequences of major floods and earthquakes in selected areas of the country (see Dahlhamer and D'Sousa 1998; Dahlhamer and Tierney 1998; Tierney and Nigg 1995; Tierney 1997). These studies provide an understanding of owner/manager awareness of hazards, of their choices concerning disaster preparedness, and of the impacts and recovery from earthquakes by businesses.

In studying the preparation before and impact of the 1994 Northridge earthquake on businesses — typically small retail and services firms in leased property, Tierney (1997) found that the majority of businesses were forced to close because of disruption of utilities. Relatively few businesses had taken steps to prepare for a major earthquake (although 24 percent had purchased business interruption insurance). In studying recovery by businesses from the Northridge earthquake, Dahlhamer and Tierney (1998) reported that recovery was smoother for businesses having a number of employees and that suffered lesser business disruption. Dahlhamer and D'Sousa's study (1998) of earthquake preparedness by businesses in Tennessee confirms findings of limited efforts by businesses to physically prepare for earthquakes, although 41 percent reported purchase of earthquake insurance and 29 percent reported purchase of business interruption insurance. Not surprisingly, larger firms and those that owned property, rather than leased facilities, were more likely to take greater preparedness efforts.

Recent survey research by Japanese researchers (Fujitani et al. 2000; Takahashi et al. 2000) reaffirms the multi-dimensional aspects of safety that occupants and building owners seek for earthquake performance of buildings. In the survey of occupants and owners undertaken in 1998, earthquakes rated third in importance as a "serious problem in daily life," ranking disease and traffic accidents. (This is a striking contrast to much lesser concern about earthquake risks when rated by citizens in seismic-prone areas of the United States.) The Japanese researchers found that building occupants and owners rated life-safety highest in importance but close behind the importance of continuity of services and maintaining value of property.

2.3.2 Insurers

A comprehensive research program undertaken at the Wharton School of the University of Pennsylvania concerning insurance and disasters and a recent assessment of research on this topic involving those researchers (see Kunreuther and Roth 1998; Kunreuther 1999) provide critical insights about insurance and natural disasters. This work documents the reluctance of homeowners to purchase earthquake insurance (because they feel the disaster will not happen to them) and of private insurers to aggressively market it (because they fear the financial consequences of a major earthquake for their firms). This research documents that insurers apply a "safety first" decision rule — keeping the likelihood of insolvency below a minimum threshold value — in making decisions about premiums, availability of lines of insurance, and reinsurance.

This type of decision making draws their attention to financial risks associated with the mix of their portfolios, rather than to evaluating individual structures, and to assessments of "probable maximum loss (PML)" and/or catastrophic risks. (State regulators also assess the solvency of insurance markets with use of PML estimates provided by insurers.) An important research issue for PEER is understanding how PBEE approaches can lead to better understanding of the performance of a portfolio of buildings as a basis for revising existing, largely ad hoc PML procedures (cf. ASTM 1999).

At present it is not cost effective for insurers to inspect or rate structures, except for large commercial structures, with respect to earthquake performance. As a consequence of these financial disincentives, insurance firms are not usually important players in specifying performance objectives or building design. Businesses have increasingly relied on earthquake insurance for protecting property values and on business interruption insurance for protecting costs of downtime.

2.3.3 Lenders

Lenders' perspectives of earthquakes have been less studied than those of the insurance industry. In a now dated study of mortgage lenders for large banks in the western Washington, and the Los Angeles and San Francisco areas, Risa Palm (1983) found highly variable treatment of earthquake risks with most lenders not considering the risks at all as part of lending decisions. Large lenders evaluating commercial loans were more likely to consider earthquake risks than were smaller lenders or those providing home loans. When such risks were addressed, remedial action typically included requiring purchase of insurance, special engineering of structures, or larger equity investments by purchasers.

Other anecdotal evidence suggests that lenders, much like insurers, view earthquakes as a component of their overall "investment risk." They are able to distribute risk through geographically broad portfolios of loans, selling loans to secondary markets, and use of financial instruments to protect against catastrophic risks. As a consequence, lenders tend to be more concerned with the overall portfolio of risk than with the performance of individual buildings within that portfolio. One issue is the extent to which more rigorous methods of PBEE will make it easier to address risk for individual structures.

2.4 IMPLICATIONS OF ORGANIZATIONAL CHOICES ABOUT SEISMIC SAFETY

Several observations are relevant from the preceding discussion of organizational choices about seismic safety. First, as reflected in the brief case illustrations of organizational choices, decisions about anticipated performance of facilities in earthquakes are often framed with respect to differing qualitative objectives. Second, as reflected in the discussion of different stakeholders' perspectives, the menu of instruments for addressing earthquake risks entails not only investment in improvements in seismic performance, but also purchase of various forms of insurance — principally commercial earthquake and business interruption insurance — and use of alternative forms of risk management. Third, and complicating these generalizations, is the fact that owners/investors differ considerably in their time horizons — how long they expect to own the building — and with respect to their tolerances for risk or preferences for safety.

2.4.1 Common Attributes of Choices

Although the case illustrations presented here entail different situations, they contain several common attributes concerning seismic safety choices:

1. Protection of life safety, albeit an undefined goal, constitutes a common minimum standard of performance and is presumed to be present in existing seismic code provisions.
2. Categories of performance objectives reflect multiple, somewhat inconsistent, sets of considerations. These include reference to
    a. Danger posed by condition of building in event of an earthquake for life safety;
    b. Performance of structures with respect to potential for collapse or significant damage, along with consideration of repair time for the structure;
    c. Damage to contents of buildings and heating, water, power and other systems (nonstructural damage), along with consideration of repair time for these systems;

d. Operational use of a facility and repair time before the facility is reusable.

3. Occupancy/use of structure is an important consideration in deciding which of the above types of objectives are most relevant.

4. An additional important consideration is that of secondary effects of earthquakes for facility operations, including the potential for fire, and disruption to power and other systems.

2.4.2 Alternative Forms of Risk Management

As noted above, the menu of instruments for addressing earthquake risks considered by firms not only entails investment in improvements in seismic performance, but also purchase of various forms of insurance and use of alternative forms of risk management. This is not surprising given that owners/investors differ considerably in their time horizons and with respect to their tolerances for risk and preferences for safety levels.

A central issue for future development of performance-based earthquake engineering is development of an understanding of how PBEE frameworks and methods contribute to broader choices about the financial management of earthquake risks. Such choices are aptly summarized in a report by the Earthquake Engineering Research Institute (2000). These include two sets of mechanisms. One set addresses means for reducing potential harm from earthquakes:

- Loss reduction measures aimed at preventing losses through seismic strengthening of structures and nonstructural improvements
- Relocation of facilities or operations away from major seismic areas

The second set includes means for sharing or transferring risk:

- Purchase of insurance for facilities and/or for business interruption
- Transfer of risk through capital markets via catastrophe bonds or other forms of "securitization" of risk

3 Organizational Decision Making: Decision Processes and Styles

The first section of this report addressed choices that organizations make about seismic safety. This is useful in helping to understand the goals organizations have pursued but tells little about the framing of meaningful choices and how to present information about those choices. These, of course, are important components to the development of PBEE, since it entails development and presentation of technical analyses for informing decisions about seismic improvements.

This section considers organization decision processes and a set of stylized approaches to decision making about seismic risks. The first part addresses literature about individual decision making. This literature underscores the ways in which complex information is simplified. The second part addresses decision making by organizations focusing on the use of technical information in decision making. This underscores the role of organizational considerations in shaping the interpretation of information. The third part presents a set of stylized approaches to decision making about seismic risks. These serve to sharpen distinctions among different ways of presenting information.

3.1 INDIVIDUAL DECISION MAKING ABOUT SEISMIC RISKS

An extensive literature exists addressing individual decision making concerning risks of natural hazards with respect to such decisions as the purchase of hazards insurance, the adoption by homeowners of various mitigation measures, and decisions to evacuate in the face of warnings. This literature draws from theories from social psychology and decision making in highlighting the ways in which people seek out and process information about risks and decide about investments in risk reduction. The following summarizes several key notions as summarized in a recent review by Lindell et al. (1997; also see Stern and Fineberg 1996: 111–14) of the relevance of this literature for hazards adjustments.

3.1.1 *Biases and Heuristics in Decision Making*

Perhaps the most influential line of research concerning individual decision making is the study of different biases that individuals bring to decisions and the heuristics that they employ to simplify decisions. Research by Tversky and Kahneman (1974, 1981) and others that followed identified biases that shape decisions and heuristics that serve as shortcuts in making decisions (for a review, see Slovic 1995). One bias is an *availability bias* by which individuals imperfectly recall specific events or images of events in attempting to gage the likelihood of future events. This suggests, for example, in the case of earthquake risks that images of earthquakes are more important in shaping sense of risk than are statistics about them. A second bias is an *overconfidence bias* with which people have trouble addressing uncertainties associated with small samples. This has obvious implications for such things as interpretation of recurrence intervals for earthquakes. A third bias is a *representation bias* with which people tend to attribute characteristics of a process to the events they generate. With this, individuals might be expected to think of long recurrence intervals of earthquakes (a characteristic) as deterministic statements that events will not occur for a long time, rather than as probabilistic statements about the events.

Decision heuristics refer to shortcuts that individuals make in processing complex and uncertain information. Most important for present purposes are *anchoring and adjustment heuristics* which show that individuals evaluate information relative to a given base (anchor) and adjust their decisions relative to updating to that base. This means that decisions depend on the way the stakes of decisions are framed. As stated by the PEER researchers studying campus seismic safety:

> University officials described the value of seismic-retrofitting in terms of relative gains and losses instead of changes in the university's absolute wealth. This may explain why [the] universities, with the exception of Stanford, do not routinely consider upgrading a building's performance beyond the level of life safety, the minimum standard of safety in all university policies… If the decision is framed positively — "By spending $1 billion dollars now, we will save 80% of our buildings" — university officials are more likely to be risk-averse and pay the money for prevention. Under the current system, most universities focus on the

> losses … [By] framing the decision in terms of loss, universities [are] risk seeking — more willing to take a gamble on bigger losses than accepting a pre-determined smaller loss. (DeVries et al., 2000: 63–64)

3.1.2 Difficulties Evaluating Probabilities and Myopic Decision Making

A common finding of behavioral economists and psychologists who have studied individual perception of risks and evaluation of low-probability, high-consequence events is the difficulties that individuals have in evaluating such probabilities (see Fischhoff 1989; for hazard-related studies see Camerer and Kunreuther 1989). The basic findings from this research are that individuals (1) tend to think of these risks in binary terms — either they perceive a risk or not; (2) are myopic in their decision making about mitigation measures—placing little value on the future benefits of such measures; and more generally (3) overemphasize the up-front costs of investing in earthquake risk-reduction measures. This does not mean that people living in areas subject to seismic risks are necessarily unaware of the risks or unable to recognize that events can occur at any time. What it means, and what the evidence about insurance and investments in protective behaviors shows, is that individuals tend to be very myopic in evaluating these investment decisions. Unless the benefits of investments in seismic safety can be seen as immediate, they are effectively discounted to zero. As a consequence of the perception of costs overwhelming the benefits, there is little likelihood of investment. These dynamics were also evident in a PEER-funded study of homeowners' decision making about retrofitting homes in hillside areas of Los Angeles affected by the Northridge earthquake (see Von Winterfeldt et al. 2000).

3.1.3 Desire to Preserve Options

Until recently decisions about investments involving uncertainty that do not adhere to decision-analysis maxims of maximizing expected payoffs have been viewed as irrational and presumed to be subject to the above distortions. Yet, there is an emerging literature on uncertain investments that makes a case that decisions to opt for no action or for less than optimal (in terms of expected payoff) outcomes are indeed sensible in some circumstances (see Metcalf and Rosenthal 1995 for an overview and examples). This reasoning is that many investment decisions involve irreversible decisions (i.e., a given investment in purchase of a product or technology precludes other decisions at later points), uncertain payoffs, and flexibility in the timing of investments. By making what may appear to be less than optimal decisions about investment, individuals may simply be attempting to preserve options for later, more certain investments to address a given problem. Thus, for example, it may make sense to invest in seismic safety to achieve life safety while holding off on other objectives until greater confidence is gained in technologies or alternatives. This is especially the case if the additional risk can be shifted through purchase of insurance or other risk spreading.

3.2 ORGANIZATIONAL DECISION MAKING ABOUT SEISMIC RISKS

Key tenets of those who study organizations are that organizational choices are shaped by the individual biases of key decision makers as constrained by the procedural and cultural considerations that a given organization embodies. The relevance of different factors varies greatly among organizations, but the common results are simplification of the framing of issues, of the interpretation of information, and of choices. This makes sense to organizational theorists because one of the functions of organizations is to reduce complexity (e.g., through standard operating procedures) whether in the processing of information about seismic risk, producing widgets, or getting out checks. Although the literature is not as extensive as that concerning individual decision making, several points are relevant to a discussion of organizational decision making about seismic risks:

3.2.1 Survivability and Affordability as Guiding Heuristics

As summarized by Meszaros (1999), several patterns have been documented by research concerning organizational decision making about low-probability, high-consequence events. In particular, Meszaros found for chemical firms that "survivability was used to assess how urgent it was to deal with a particular risk; affordability was used to assess the feasibility of mitigating it" (p. 990). In other words, firms are motivated to take action when there is a perceived risk/threat that will likely make them insolvent. At the same time, firms appear to be unwilling to invest risk-reduction measures that are costly and uncertain if such investments are likely to lead to insolvency. Meszaros found that firms would choose to shut down plants for which necessary investments were perceived as unaffordable or having the potential for failing. An important aspect of survivability is the liability that a firm may incur for failure to protect employees or customers from seismic harm. This is a central issue for many firms and is especially important for public facilities such as schools for which individuals are mandated to be present. (For related discussion of liability and design profession see May and Stark 1992.)

Consistent with the difficulties that individuals have in dealing with low probabilities of an event occurring, evaluation of the likelihood of different events tends to be driven by simple decision rules about such probabilities rather than sophisticated evaluations (i.e., "threshold heuristics" rather than probabilistic evaluations). In particular, firms tend to follow a "mini-max regret" strategy in choosing objectives — in minimizing the maximum regret if they did not take action. How the maximum regret is framed undoubtedly differs among organizations, but generally can be thought of as "ruin" — in loss of substantial revenue base or production capacity to force out of business — having contributed to the loss of life, or incurred substantial liability for earthquake harm.

3.2.2 Organizational Hierarchy Matters

Meszaros (1999) found in her study of chemical facilities, as did researchers for the PEER-funded study of campus seismic safety, that those involved in framing decisions about addressing risks engaged in feasibility testing of those decisions. The details of the evaluation of different options were often left to internal technical teams and consultants. However, the advisability of different options — in broad outlines rather than technical details — are often tested through informal consultation against what top-level decision makers seem to prefer. This is one means for reducing uncertainty in the decision processes and an important aspect of organizational choice. One consequence of this is sometimes a premature narrowing of options.

All organizations, of course, are not the same. Some are more capable of creating new organizational arrangements to improve information flows and the evaluation of technical information. Stanford University, for example, appears to have been successful in this regard in its decision making for campus seismic improvements by involving faculty from engineering (i.e., in raising credibility of claims and access) as well as by including Deans and other top-level decision makers in the process at an early stage. Other case studies of decision making about seismic risks highlight the importance of individual champions who are often key engineers or technical personnel who have experienced damaging earthquakes as part of previous employment. Taylor et al. (1998: 96), for example, highlight the role of the chief engineer for the Seattle Water Department in pressing the need for seismic improvements in Seattle based on his experience while working for the East Bay Municipal Utility District in California.

3.2.3 Dealing with Uncertainties of Engineering Expertise

Research concerning the use of experts in decision making calls attention to the credibility of the experts, the match between prior assumptions and information presented by experts, and the degree to which experts agree as factors that enhance the value (or more precisely, the perceived value) of experts. A key assumption of decision makers, suggested by the findings of the campus seismic safety study, is that engineers are conservative in their judgments about recommendations for seismic improvements. This follows from a presumed conservatism of engineers in following the logic that it is better to err on the side of "too safe" than "not safe enough."

Expertise — particularly earthquake engineering expertise — contains two parts. One is the scientific part relating to the probabilities and uncertainties associated with different outcomes. The second is the judgment part relating to the interpretation of "the findings," akin to the process with which a medical doctor interprets test results for a patient relative to statistics about particular maladies. Investments in more refined studies can help reduce the uncertainties, but judgments still remain.

One interesting question is how engineering expertise evolves with more rigorous approaches to PBEE. One contribution of more rigorous methods is to be more explicit about probabilities and associated uncertainty in addressing the likely performance of structures. This explicit evaluation, in principle, reduces potential variability in the interpretation of findings and makes for more consistent interpretations. But, whether in practice this is the case remains to be seen.

3.3 IMPLICATIONS: THREE STYLES OF DECISION MAKING

The preceding discussion of individual and organizational decision making is useful in suggesting various biases and constraints that lead decision makers to choose less than optimal alternatives from a strictly rational-choice perspective. While useful in explaining the complexities of decisions about seismic safety, such understanding falls short of providing a guide to different ways of thinking about performance objectives. To address this problem, this section presents different styles of decision making that take into account the biases and heuristics noted in the preceding section. A stylized depiction follows of each three different decision styles that owners/investors can potentially employ with respect to performance objectives for earthquake engineering.

3.3.1 Risk and Safety as By-products of Design Decisions

With this style of decision making, risk and safety are by-products of decisions about the design and construction of a building. Aesthetic and functional design properties are first specified. Buildings are designed to meet those properties while also fulfilling mandatory code requirements. Designs are adjusted if a given design is shown to fail to meet seismic or other requirements. Stated differently, the objective is to minimize the costs of construction for a given design subject to adherence to seismic and other requirements.

An example of this style of decision making is the construction of the First Hawaii Bank building as described in an Earthquake Engineering Research Institute monograph (Chock et al. 1997). Completed in 1996, the building comprises 27 stories and 420,000 square feet, and houses the bank headquarters and a municipal art museum. The philosophical design task "was to view [the building] not as a banking hall that contained exhibition space but as a museum that could function as a banking facility." Due to restrictive site and land-use considerations, a number of different variations of structural systems were designed and considered with respect to cost, timing, and seismic and wind requirements. Once the basic design was established, the special requirements of wind resistance led to seismic performance obtained at least partly as a by-product of meeting these objectives. No mention is made in the monograph of efforts to assess performance in other than engineering terms.

The chief limitations of this style of decision making are

- Relatively short time horizons. The emphasis is on the costs of construction with little attention to long-run operating or maintenance costs.
- Seismic safety objectives are narrowly defined with respect to code and engineering considerations. A structure is designed to perform to required code or other specified engineering criteria, rather than with respect to objectives concerning potential damage levels, functionality, or other aspects of performance. Implicit in this is a binary view, characterized by the decision literature, of a threshold of safety being achieved with a given design.
- Limited ability to address trade-offs in seismic safety expenditures. At best, one obtains information about up-front costs associated with adherence to different engineering-related levels of performance. This makes it difficult to establish what is being purchased with respect to seismic safety (i.e., with respect to impacts of increased seismic resistance) and leads to suboptimal treatment of costs (i.e., in failing to address benefits of seismic investments).

The above example arguably constitutes the most common form of design practice and decision making. Seismic performance is relevant to the extent that analytic tools are used to evaluate the consequences for engineering criteria of different designs.

3.3.2 Performance-optimized Decisions

This approach is the direct opposite of treating risk and safety as by-products of design decisions. With performance-optimized decision making, one starts with a desired level of performance and optimizes the design to reach or exceed that performance level (perhaps framed in probabilistic terms). As such, the premium is on the level of safety that is achieved subject to uncertainties of site characteristics, design, and construction.

This approach is applied today with respect to essential facilities like computer or operations centers or to critical facilities like nuclear power plants, major dams, and some public facilities. One example is that described at the outset of this report for the Questar Corporation's design and construction of their "business continuity center." In that case, they chose to optimize the design for continued operation of the data center. Other examples are design of nuclear power facilities according to the Department of Energy Guidelines G420.1 (DOE 2000). Much like engineering-based performance objectives discussed earlier, these guidelines specify a "graded approach" to selecting appropriate performance objectives for facilities among four categories of objectives. The highest category are those facilities for which "failure to perform their safety function could pose a potential hazard to public health, safety, and environment because radioactive or toxic materials are present in large quantities and could be released as part of that failure." Associated with each category are DOE-specified standards (DOE-1020-94) for seismic design.

The performance-optimized approach follows from the use of qualitative categories of performance objectives that are common to efforts to define seismic performance. This is appealing in making explicit the seismic safety objectives for a given structure. This allows for choice among different objectives to match particular uses of facilities. The chief limitations of this approach to decision making are

- Lumpy choices for seismic performance. The choices among qualitative categories of performance entail a "fixed menu" approach to seismic performance. Each choice mixes different considerations (continuity of service, injuries, condition of structure) in ways that owners/investors may not think appropriate. Because the choices are among discrete categories, they present discontinuities in performance — entailing big jumps between categories — that do not reflect the realities of seismic design.
- Limited ability to address trade-offs in seismic safety expenditures. At best, one obtains information about costs associated with designs optimized to fulfill a given choice from the fixed menu. This makes it difficult to compare trade-offs among different seismic objectives.

3.3.3 Investment-based Decisions

This style of decision making is consistent with the PEER "framing equation" for performance-based earthquake engineering. This style calls attention to the stream of costs and associated benefits over time of investment in a given structure. Applied to buildings, these include the costs of design, construction, operating, maintaining, repairing, and replacing the building. Benefits include the revenue stream from the use of the building (e.g., rental income, added value of production) and the value of the asset at the time of disposal. Seismic considerations enter at many points within each stream and include such things as costs of seismic resistant upgrades/features, loss of use of the facility after an earthquake, injuries and/or deaths, and benefits associated with reduced damage and increased value (capitalization) of seismic improvements. Important elements of such calculations are discounting of future costs and benefits to take into account the time-value of money and addressing uncertainties associated with given costs or benefit categories with respect to incidence, timing, and magnitude.

The central purpose of such valuation is to allow comparisons among alternative decisions about investments — seismic upgrade to a particular level or not, rebuild versus build new, invest in seismic resistance versus purchase insurance, and so on. A variety of decision frameworks exists for which the most commonly considered are benefit-cost analysis and life-cycle cost analysis. These entail essentially the same considerations but employ different ways of presenting findings and different decision rules for choosing among alternative courses of action. Life-cycle costs implicitly treats benefits as costs forgone and provides a single discounted cost measure; while benefit-costs provides separate calculations of discounted benefits and costs. The decision rule for life-cycle costs is least cost, while that for benefit-cost analysis is highest benefit-cost ratio or largest net benefits.

These techniques and their role in evaluating PBEE are discussed more fully in a separate report in this series. General treatment of these issues can be found in the American Society for Testing and Materials standard for life-cycle cost analysis for buildings (ASTM 1994) and in FEMA's guidance concerning benefit-cost calculations for seismic rehabilitation of buildings (FEMA 227/228, 1992).

The use of life-cycle cost analysis has received much attention in recent years within the earthquake engineering community and as a potential framework for use by PEER in evaluating increased performance of earthquake engineering measures. Illustrations of the potential applicability of this decision framework for seismic risk reduction include discussion of applicability to port facilities (e.g., Taylor and Werner 1995, Werner et al. 1997), bridges (e.g., Chang and Shinozuka 1996), water systems (e.g., Chang et al. 1998), and buildings (e.g., Ang et al. 1998, Ang and Lee, 1999, Beck et al. 1999, Wen and Kang 1998). More generally, the U.S.

Department of Transportation has encouraged states to employ life-cycle cost analysis for evaluating major transportation projects in keeping with federal highway legislation and executive orders (see U.S. Federal Highway Administration 1996). Life-cycle cost analysis has also been heavily promoted by the federal government as a tool for use in evaluating investments in energy efficiency devices.

The life-cycle and benefit-cost decision frameworks are appealing for a number of reasons. First, they draw attention to long-run costs and benefits. This makes it possible to consider trade-offs in higher up-front costs and reduced downstream repair costs or costs of business disruption. Second, they provide a single metric — dollars, as appropriately discounted — for evaluating choice outcomes. This overcomes the difficulties of comparing outcomes with respect to discrete, incommensurate objectives (e.g., lives lost, business interruption, injuries). This also provides a continuous scale for making relative comparisons of value of different choices. Third, the frameworks are flexible enough to allow for incorporation of different time horizons, discounting factors, and components for benefit or cost streams.

There are a number of technical challenges in extending the life-cycle cost or benefit-cost frameworks to evaluating seismic improvements — particularly for application to buildings. These include incorporation of different levels of tolerance for risk among decision makers, modeling uncertainties associated with the incidence, timing, and magnitude of earthquake damages and their impacts, valuing impacts (especially injuries and deaths), and projecting timing and costs of repairs or other responses.

The chief limitations of this approach to decision making are

- The life-cycle framework collapses benefit and cost streams. Life-cycle analysis provides a single measure of cost that combines benefits (including costs averted) and costs over time when properly discounted (and perhaps annualized). This does not make transparent the benefits associated with a given investment in seismic safety. This is not an issue with benefit-cost analysis.

- A single metric for seismic safety benefits. The benefits included as part of life-cycle or benefit-cost analyses are in turn collapsed in a single, dollar metric. This has an advantage of providing a single metric for comparison. But, it also has two disadvantages — the need for tenuous assumptions about the dollar value of life and injuries, and inability to expose the different dimensions of seismic safety or risk reduction.

- Potentially false sense of precision of results. Depending on how results are presented, decision makers may gain a false sense of the precision of the results given the underlying uncertainties. This raises a research need for addressing methods for presenting such results.
- Cost of undertaking necessary analyses. The "900-lb gorilla" of performance-based earthquake engineering is the cost of undertaking necessary analyses, including relevant investment-based analyses versus the value added of the information that is provided. A central issue is the level of refinement of engineering and economic analysis that is required for making informed decisions about seismic performance.

3.3.4 Summary of Decision Modes

The preceding discussion of different modes of decision making about seismic performance helps to identify current deficiencies and desired attributes of performance-based earthquake engineering. The dominant mode of decision making, which stresses "risk and safety as by products of design," falls short in not making trade-offs or choices in making decisions about seismic risks. The opposite approach, which focuses on "performance-optimized decisions," draws attention to desired performance levels but masks trade-offs and choices. Only the "investment-based" approach provides a framework, consistent with the PEER framing equation for making explicit trade-offs in different aspects of seismic performance and the costs of achieving them. That approach, however, entails a number of issues concerning characterization of the costs and benefits of seismic performance and the presentation of findings.

4 Societal Considerations

This section considers societal perspectives for performance-based earthquake engineering. The first part addresses how societal perspectives differ from those of individuals -— whether they are homeowners, investors, or building owners. This emphasizes differences in scale and the interdependencies of decisions about seismic safety. The second part considers evaluation of societal risks and benefits. This discusses the limits of public preferences about seismic safety and the role regional economic assessments. The third part addresses the "fallacy of acceptable risk" in considering the difficulties of establishing societal preferences about levels of risk. This leads to discussion in the fourth part of processes for establishing goals for seismic safety.

4.1 THINKING ABOUT SOCIETAL PERSPECTIVES

What constitutes a "societal perspective" is easy to answer in the abstract, but hard to pin down in the specifics. In concept, societal perspectives reflect seismic safety concerns above and beyond those of individuals who are concerned about specific buildings or facilities. Owners and investors are presumably concerned about the structures they own or for which they hold investments. In the case of insurers and large firms, the concern might be with the mix of a portfolio of structures. As we move beyond these considerations to those of society, the scale shifts to consideration of earthquake impacts upon a community, region, state, or the nation. The risk of harm from earthquakes at the systems, community, or larger grouping is usually thought of as "societal risk" (see Mujumdar 2000). As elaborated upon in what follows, such risks entail a variety of considerations that do not necessarily enter into earthquake risks for individual building or facilities.

4.1.1 Public versus Private Risks

The concept of public risks is useful in thinking about the challenges earthquake risks pose for societal decision making. In particular, earthquake risks pose a form of "public risk" that can be contrasted with the more "private risks" posed by such things as crime and automobile accidents (see May 1991). Public risks can be thought of as those risks that are centrally produced, broadly distributed, temporally remote, and largely outside the individual risk-bearer's direct understanding and control. For private risks the risk is more immediate, focused upon the individual, and generally is understandable. These clearly fall along a continuum for which it is hard to draw sharp distinctions between public and private risks.

Public risks present classic collection action problems for which there are limited incentives for private or group action in addressing the risks. For low-probability, high-consequence events like earthquakes, individuals often have economic incentives to avert losses, but as noted above the calculus of decision making is such that a host of perceptual factors alter this economic rationality. This in turn presents a number of issues for public policy. There is the normative question of how paternalistic government should be in protecting citizens who do not seem to be all that concerned about the risks. The relative obscurity of such risks in the absence of a major event and the dominance of technical experts in defining the extent of the risk raise issues about the role of experts in shaping policy. In addition, there are questions about the design of feasible strategies for bringing about appropriate levels of risk reduction.

4.1.2 Externalities

Earthquake damage to individual facilities can also have consequences that accrue beyond the individual structure, entailing externalities. Externalities refer to consequences of failure of a structure beyond the damage or losses to that structure. These are consequences that would not normally be considered by owners/investors in an individual structure unless they could be found negligent and therefore liable in not addressing particular externalities.

One prime example of such externalities is the potential for fires following earthquakes. For example, Scawthorn and his colleagues (1998) cite some 110 fires following the Northridge earthquake. Another example is pounding of buildings, wherein the movement of one building affects an otherwise undamaged adjacent building — a phenomenon that was commonly observed with highrises in the Mexico City earthquake of 1985. The release of toxic or hazardous materials in the aftermath of an earthquake is another externality. The potential for such harm provides a rationale for public intervention in establishing regulations that limit externalities.

4.1.3 Interdependencies

A different form of external consequences concerns the relationship among different elements of a community. Disruption to one element of a community often entails disruption of others. The prime example is that businesses are often dependent on reliable sources of power, water, fuel, and transportation; thereby making the business sector dependent on the viability of various lifeline systems. Studies noted above by Nigg, Tierney and their colleagues reinforce the importance of this basic equation. Citizens, in turn, rely both on a healthy business sector (for jobs and trade) and on a functioning governmental sector (for services and benefits). For example, damage to Oakland's city hall in the 1989 Loma Prieta earthquake disrupted city services until they could be relocated to temporary facilities (see Olson et al. 1999). Such interdependencies involve more than the external effects of earthquakes of one structure upon another since they go to the heart of what sociologist James Short has labeled the "social fabric" that is at risk (see Clarke and Short 1993, Gupta 2000).

4.2 EVALUATING SOCIETAL RISKS AND BENEFITS

Taken together, the public nature of earthquake risks, presence of externalities, and interdependencies among earthquake effects provide a public-safety rationale for governmental action in addressing earthquake risks. However, the extent and nature of such intervention is not obvious. In principle, the extent of intervention should take into account both the societal risks posed by earthquakes and the benefits of the interventions. Until recently, the societal risks associated with earthquakes in different regions of the country have not been systematically examined. With more sophisticated loss estimation procedures, such as HAZUS, there is greater potential for such estimation. A clear issue is the extent to which more rigorous performance-based approaches will further advance this potential. Regardless of current advances, evaluating risks and benefits pose analytic challenges discussed in what follows.

4.2.1 Public Concern Is a Poor Guide to Societal Risk

The issue of societal risk might be thought of as a matter of asking about the concerns of the public — what citizens value or fear — when considering potential earthquakes. The general finding of efforts to tap citizens' attitudes about earthquake risks is that in areas of moderate to high degrees of seismic risk, citizens are generally aware of the risks but have varying degrees of indifference (see May 1991).

In more recent research, Risa Palm (1995) studied perceptions of earthquake risks among a sample of homeowners residing within four California counties including two that were impacted by the 1989 Loma Prieta earthquake. Seventy-six percent of the residents estimated there is at least a 1 in 10 probability of a damaging earthquake affecting their community in the next ten years, but relatively few homeowners had taken important precautionary steps to prevent damage. Fewer than 25 percent had their houses bolted to the foundation and less than 10 percent had strengthened exterior walls. Many of the homeowners preferred to take a more convenient route of purchasing earthquake insurance, which Palm estimated 50 percent of homeowners in the study areas had purchased by 1993 (prior to the crisis in availability of earthquake insurance in California).

In studying the attitudes of Portland residents, Flynn and his colleagues (1999) found that more than two thirds of the residents considered themselves to be well informed about earthquake risks, but nearly half agreed with the statement "what will be, will be." Reflecting these fatalistic attitudes and the infrequency of damaging events, organized public demand for governmental action in reducing earthquake risks appears to be rare and short lived.

4.2.2 Loss Estimation Is an Imperfect Guide to Societal Risk

A different way of characterizing societal risk is to evaluate the economic consequences of earthquakes at a community, regional, or national level. One example of such an evaluation is a recently completed FEMA analysis (FEMA 2001) of estimated annualized earthquake losses for the United States, derived from use of the HAZUS-99 modeling of earthquake losses. Consideration of the technical issues for loss estimation is itself an extensive topic not addressed in detail here, since it is to be subject of a separate PEER synthesis report (also see National

Research Council, 1989b). But it is useful for present purposes to consider some of the analytic issues posed by such efforts to characterize risk.

As with any risk characterization, perhaps the central analytic issue is choice of the metric for characterizing risks. As noted in a National Research Council review of societal considerations of risk, "the choice of a measure can make a big difference in a risk analysis, especially when one risk is compared with another. It can also make a big difference in whether interested and affected parties see the analysis as legitimate and informative" (Stern and Fineberg 1996: 50). The choice of measure is both a matter of communication — what people and decision makers understand, and a matter of comprehensiveness — what adequately conveys the extent of risks.

Even when the metric chosen is dollars, issues remain. Consider, for example, the metrics employed in the FEMA analysis of potential earthquake losses throughout the nation (FEMA 2001). Risks are defined with respect to the value (annualized) of losses to general building stock and with respect to the share of total value of the building inventory (replacement value) that such losses represent. Depending on which measure is employed, the rankings of risks for states and localities change somewhat. As the report authors note, this is a consequence of variation in both the extent of hazard and in the value of the building stock in different parts of the country.

A second analytic issue is what types of losses to consider. The FEMA study considers the only direct consequences of potential earthquakes for building inventory, defined as capital losses (repair and replacement costs for structural and nonstructural components, building content loss, business inventory loss) and income losses (business interruption, wage, and rental income losses). As the authors note, other potential losses include damages to lifelines and other critical facilities and indirect economic losses. As discussed in a future PEER synthesis report addressing economic modeling of regional impacts of earthquakes, these considerations are more fully captured in some of the regional loss-estimation models than others.

A third analytic issue is deciding what impacts constitute a threshold for public action. Knowing what potential losses are, even if fully calculated, does not establish a threshold for action. Should all losses be eliminated? Adopting the stance that all losses must be eliminated ignores the fundamental reality that it costs money to reduce losses. Should losses be reduced to the extent that they exceed costs of risk reduction? Adopting this stance ignores the fact that many risks impose costs that society cannot adequately address. Ultimately, as discussed below, deciding the threshold for public action is a matter requiring public choice.

4.2.3 Considerations Other Than Economics Are Important

Perhaps the thorniest issue for economic loss estimation, and for evaluation of PBEE, is consideration of human life and injuries. Placing an economic value on life and injury is itself a complex issue that has been subject of much discussion in the risk-analysis literature. One key issue is the comparability of lives of individuals with different life expectancies and with different self-selected exposure to risk (see Stern and Fineberg, 1996: 523).

Even if economic loss estimation properly reflects direct and indirect consequences of earthquakes, it leaves out important considerations for societal considerations of earthquake risk. Chief among these missing from the traditional economic framework are considerations of equity in the distribution of losses and public expenditures to reduce losses. Regional economic models are helpful for modeling the impacts of earthquakes with respect to the economic system. However as Tierney (1999) points out, there are also social systems that come into play in affecting the distribution of risks and consequences of relief programs. Understanding the distributional consequences (across geographic areas, income groups, and age groups) is important for coming to grips with the broader social consequences of seismic hazard mitigation and loss prevention efforts.

4.3 THE FALLACY OF "ACCEPTABLE RISK"

A key issue is how societal concerns can be articulated in specifying minimum performance objectives. This issue is considered here with respect to the concept "acceptable risk" as a basis for establishing baseline standards of performance.

4.3.1 The Appeal of Establishing an Acceptable Level of Risk

The search for acceptability of risks is aptly explained by the risk scholar Baruch Fischoff, who writes

> Perhaps the most widely sought quantity in the management of hazardous technologies is the acceptable level of risk. Technologies whose risks fall below

> that level could go about their business, without worrying further about the risks that they impose on others. Riskier technologies would face closure if they could not be brought into compliance. For designers and operators, having a well-defined acceptable level of risk would provide a clear target for managing their technology. For regulators, identifying an acceptable level of risk would mean resolving value issues at the time that standards are set, allowing an agency's technical staff to monitor compliance mechanically, without having to make case-specific political and ethical decisions. For the public, a clearly enunciated acceptable level of risk would provide a concise focus for evaluating how well its welfare is being protected—saving it from having to understand the details of the technical processes creating those risks. (Fischoff, 1994: 1).

Given this appeal, it is not surprising to find that the holy grail of seismic engineering is the definition of what consitutes an acceptable level of risk. This becomes either the objective to be pursued or a fixed constraint in seeking optimal seismic designs.

The notion of acceptable risk, while common in engineering, is one of the more disputed notions within the risk literature itself. As Fischhoff notes elsewhere: "Many debates turn on whether the risk associated with a particular configuration of a technology is acceptable. Although these disagreements may be interpreted as reflecting conflicting social values or confused individual values, closer examination suggests that the acceptable-risk question itself may be poorly formulated" (1989: 273; also see Otway and Von Winterfeldt 1982).

4.3.2 Is Acceptable Risk a Meaningful Concept?

As noted above, determining a given level of risk can be thought of as establishing a bar above which risk is too high and activities are prohibited, and below which risks are tolerable and activities can proceed. We can envision different bars for circumstances that take into account different degrees of seismic hazard and/or different uses of structures or facilities. From this perspective, the decision variable for performance-based earthquake engineering consists of deciding what is the acceptable level of risk. Yet, fundamental issues remain about framing these choices as acceptance of risk in absolute terms.

The framing issue is whether acceptable risk means acceptance of risks or whether it means achieving desired levels of safety. While it may seem like a matter of semantics as to whether one discusses risk or safety — since they are mirror images —the framing does make a difference in how to think about the problem. Consideration of risk leads to the following questions: How much risk is too much? What does it cost to bring the risk to an acceptable level? Consideration of safety leads to the following questions: What level of safety can we afford to choose? What are the constraints that such levels of safety impose on the ability to build a structure or carryout activities within that structure? Is this safe enough?

Research about decision heuristics, reviewed earlier in this report, tells us that the framing of this discussion as one of "risk" or as one of "safety" is more than semantics. Indeed, a key finding of prospect theory is that the framing of an outcome as a loss (e.g., potential loss of life) or a gain (e.g., potential lives saved) predetermines the starting reference point for making judgments about what is desired (more generally see Stern and Fineberg 1996: 56–61). (Think, for example, about evaluating of losses in stock value from a reference point of the high of the year versus evaluation of gains relative to the low of the year.) How this plays out in the case of seismic risk or safety is not as obvious as it depends on the specific framing of issues and an understanding of risk perceptions.

Risk scholars agree that acceptability of a particular risk is not absolute (see Fischoff 1981; Otway and Von Winterfeldt 1982), but depends on the benefits associated with that risk. As such, benefits drive the choice of alternatives. The associated risks are one cost associated with a given level of benefits. By focusing on risk, some scholars argue that society may be precluding benefits of new technology or other advances (see Wildavsky 1988). Risky choices might be made if there are enough compensating benefits or if the alternatives are less beneficial. From this perspective, risk is a consequence to be considered. In the context of earthquake safety, the least risky choice would be not to build a given structure in a seismic-prone area. That, of course, precludes any benefits from activities within the structure. Thus, the decision to build a structure itself entails some risk that can be tolerated because of the benefits of having the building or facility.

The costs of achieving a given level of safety cannot be ignored. Just as trade-offs are made among benefits and risks, trade-offs are also made among costs of risk reduction and resultant risks. At some point, the costs of reducing risks become too great to pursue further attempts to reduce those risks. The costs that are tolerable, in turn, depend on the risks involved. Clearly, society is much more willing to tolerate large costs for reducing risks of nuclear power plant accidents than for reducing costs of an additional highway accident. From this perspective, "acceptable risks" are the residue of tolerable costs.

4.3.3 Can Acceptable Levels of Risk Be Established?

Even if we accept that the term "acceptable risk" is meaningful in some sense — perhaps redefined as tolerable risks or desired safety, and expressed in some relative terms — an important issue is whether acceptable levels of risk can be established. In an insightful discussion of technological risks, Hal Lewis remarks that the "almost universal obstacle to rational regulation is the failure of laws to specify an acceptable level of risk, and what we are willing to pay to get there" (1990: 77).

Consider the language used for acceptable risk in laws and executive orders relating to seismic performance:

> California Seismic Hazards Mapping Act (1999 regulations section 3721): "Acceptable level" means that level that provides reasonable protection of the public safety, though it does not necessarily ensure continued structural integrity and functionality of the project."
>
> California Safety Element planning requirements: A safety element for the protection of the community from any unreasonable risks associated with the effects of seismically induced surface rupture ….
>
> California Seismic Safety Commission "Policy on Acceptable Levels of Earthquake Risk for State Buildings" (The Commission 1991): Acceptable earthquake risk in state buildings is the risk that remains when the minimum earthquake performance objectives in Tables 1 and 2 [specifying functional levels] have been met or exceeded…. The goal of this policy is that all state government buildings shall withstand earthquakes to the extent that collapse is precluded, occupants can exit safely, and functions can be resumed or relocated in a timely manner consistent with the need for services after earthquakes.
>
> Executive Order 12941, "Seismic Safety of Existing Federally Owned or Leased Buildings" (December 1, 1994): "The Standards of Seismic Safety for Existing Federally Owned or Leased Buildings developed, issued, and maintained by the Interagency Committee of Seismic Safety in Construction are hereby adopted as the minimum level acceptable for use by Federal departments and agencies in assessing the seismic safety of their owned and leased buildings and in mitigating unacceptable risks in those buildings."

These excerpts call attention to differences in terminology ("acceptable risks" versus "unacceptable risks") in what constitutes the relevant standard, and the degree to which these are framed as goals versus as proximate standards.

The need for specification presents the fundamental catch-22 of determining levels of acceptable risk. On the one hand, determining levels of acceptable risk (tolerable risk or desired safety) is fundamentally a value judgment that presumably requires some form of collective decision making. On the other hand, the knowledge of relevant risk considerations, technical details, and costs and benefits are important for establishing meaningful standards. The first consideration argues for public processes for establishing safety goals. The second argues for deference to technical experts. Finding the appropriate middle ground is a serious challenge. A recent study by the National Research Council review panel of risk experts found such deliberation lacking in most instances of risk decision making (see Stern and Fineberg 1996).

The issue of the role of expertise is not new in debates over acceptable risk. Consider the conclusions of Ortway and Von Winterfeldt, in an article that is now viewed as a classic in the field of risk perception:

> The acceptable risk formulation has provided increasingly elaborate and precise answers to the wrong question; future research on the acceptability of technologies must be linked to the critical questions of institutions, participation and policy implementation, for until sources of conflict have been addressed, the decisions taken — no matter how technically rational — may ultimately be only empty prescriptions lacking arrangements for their realization. (1982: 255)

This issue is considered below in discussing decision making about societal objectives.

Some argue that an avenue for considering desired levels of safety is to think about willingness to tolerate different risks. However, comparison of risks, as a means of gaging acceptability, is fraught with problems. It can be useful to make comparisons of the probability of different events — an earthquake, getting struck by lightning, being involved in an automobile accident — in order to communicate what those probabilities entail. But, comparing the acceptance of different risks is comparing apples and oranges because of differences in the consequences of the events, the benefits associated with activities related to the risks, and the costs of addressing the risks. Simply put, individuals and society are much more willing to tolerate some risks than others both because of fundamental differences in perception of risks (and benefits) and because of differing benefit-risk and cost-risk reduction trade-offs.

4.3.4 Are Public Officials Willing to Talk about Expected Losses?

Elected officials are not comfortable in talking about expectations based on uncertain outcomes. Why talk about it if it is not certain to happen? Why confuse people with probabilistic statements? In addition, the term itself implies a politically unacceptable choice. Few elected officials are willing to stand up and say that injuries or deaths in the event of an earthquake are acceptable. Even military officials see deaths not as "acceptable," but as inevitable consequence of military intervention. When forced to talk about risks, politicians tend to gravitate toward an untenable standard of "zero risk."

The political reality is that acceptable risks are often not explicitly defined. Politicians — who must deal with budget trade-offs in deciding where to expend limited public resources — tend to begin by thinking about the costs of achieving safety. They consider, for example, how much it will cost to improve the seismic safety of a school to levels recommended by experts. Choices are framed largely with respect to the costs involved. Elected officials are more likely to start with a sense of "unacceptable costs" for expenditures on seismic safety than desired levels of safety or acceptable risks.

The amount that politicians are willing to spend on seismic safety is not fixed**.** In his provocative book, *Searching for Safety,* Aaron Wildavsky (1988) notes that the quest for safety in this country has been an iterative one between implicitly accepting risk and seeking safety. A given set of standards are put in place — response time for police or ambulance services, goals of protecting life-safety for earthquakes — partly as a compromise among competing interests but largely in reaction to unacceptable costs of additional improvements in safety. These standards hold until the consequences of a particular event show that they are intolerable, creating new demands and increased willingness to make additional investments in safety. Several consequences can follow new events (see May 1992). One consequence is improved technical understanding of the risk involved and of the means for reducing that risk. Another potential consequence is societal learning about what is desired (or feared) for seismic safety, prompting changes in safety objectives for particular situations or classes of buildings.

From this perspective, the de facto level of acceptable risk for earthquake safety is defined by current codes as one of life safety. Increased attention to the economic consequences of earthquakes — particularly urban events like Loma Prieta and Northridge — has invoked the dynamic that Wildavsky discusses. At issue from a societal perspective is whether there is a collective desire to do more. Writing shortly after the Loma Prieta event, Bruce Bolt summarized this quest as follows: "Because of indecision between minimizing loss of life and maximizing broader benefits, general agreement on acceptable earthquake risk remains confused" (1991: 169).

4.4 DECISION MAKING ABOUT SOCIETAL OBJECTIVES

A recasting of acceptable risk into a discussion of desired *safety goals,* the costs involved of achieving these, and the trade-offs imposed could address some of the limitations from a societal perspective of the concept of acceptable risk. The emphasis here is on goals, not technical standards. An example of such an approach is the establishment by the Nuclear Regulatory Commission of a "safety goal policy statement" (see Nuclear Regulatory Commission 1997, and Okrent 1987; for a critique see Fischoff 1983). The statement addresses risks to the public from nuclear power plant operation with two qualitative objectives and associated quantitative objectives.

The point is not the particulars of the objectives, but the fact that a deliberative, public process was used to establish safety objectives. Those objectives were subsequently translated into technical standards and a process for evaluating adherence to those standards using probabilistic risk analysis. The use of probabilistic risk analysis for informed choices about safety goals has become common in risk management for industrial facilities such as nuclear power and offshore oil and gas facilities. However, as Pate-Cornell (1994) notes in a review of quantitative safety goals, the establishment of such goals requires collective processes for deliberation about the goals.

At present, "public" debate about safety objectives consists of deliberations of code-writing entities, deliberations of seismic safety commissions in a handful of states, and the deliberations of more specialized entities dealing with earthquake risks for nuclear power plants, major dams, or federal facilities. The ways that performance-based earthquake engineering considerations enter into existing decision making about code development, standard setting, and adoption of codes by public authorities are topics for additional research. Central issues for performance-based earthquake engineering are the adequacy of existing ways of devising codes and standards and of existing mechanisms for enforcement and compliance.

Three general observations can be made about collective decisions for seismic safety. One is that the nature of involvement by experts and by citizens makes a difference in the definition of levels of desired safety. A variety of research has shown that experts and lay people differ in their assessment of risks and the ranking of priorities for addressing those risks (see review by Fischhoff 1989). A second observation is that the legitimacy of the process for determining levels of desired safety is extremely important for public acceptance of the outcomes of that process. Such legitimacy, in turn, is derived from the trust that citizens place in the agencies that are involved and the perceived fairness of the process (see discussions in Clarke and Short 1992, Dunlap et al. 1993; Slovic 1993). A third observation is that the challenge is not only one of assembling collective views about safety but also of effectively communicating the trade-offs in attempting to achieve different levels of safety. This latter point highlights the importance of having meaningful ways of expressing the stakes when choosing different levels of performance for performance-based earthquake engineering.

5 Conclusions

This report has identified the multiple considerations of stakeholders when thinking about desired levels of performance of buildings and other structures in earthquakes. How can those choices be adequately framed to guide individual and collective decisions about desired levels of seismic safety? Existing engineering frameworks are problematic because they lack scientific rigor and because they present decision makers with a fixed menu of performance choices. The goal of PEER is to develop a more rigorous approach to performance-based earthquake engineering. This report addresses one aspect of this in addressing the bases for making decisions about the performance of structures.

5.1 FRAMING DECISIONS ABOUT PERFORMANCE OF INDIVIDUAL STRUCTURES

Improvements in framing decisions about desired levels of seismic performance should allow for explicit consideration of trade-offs associated with investment in seismic safety and other forms of risk management. Any framework should also recognize differences among individuals in time horizons, tolerance for risk, and weights attached to different aspects of safety. In keeping with the discussion of this report, such a framework should

- *Treat seismic safety and risk as explicit considerations* — not as by-products of other choices. This comes closest to the earlier description of "investor based" decision making about seismic performance that explicitly addresses the costs and benefits of different levels of seismic safety (or its residual, risk).

- *Expand the choices to be considered.* The choices that performance-based earthquake engineering inform should not be (simply) one of deciding what level of seismic resistance to incorporate into a structure. The decision framework should inform broader risk-management decisions concerning trade-offs between investing in seismic resistance or alternative forms of risk management (e.g., insurance purchase, secuitization of risk, alternative uses of facilities).

- *Allow for consideration of different dimensions of safety or risk.* One of the more challenging aspects of thinking about performance is identification of relevant dimensions of performance. The case studies discussed in this report and the qualitative categories of performance contained in the current frameworks discuss a variety of considerations. These are best thought of as different dimensions of risk/safety choices for which improvements can be made along any of the dimensions.

  Candidate dimensions for working purposes, inspired in part by discussion of a similar framework by Japanese researchers (Akiyama et al. 2000), are

  - Public safety: saving lives and avoiding injuries — The potential for loss of life and injuries. This entails a rethinking of current notions of "life safety" with attention to specific means for evaluating consequences of different levels of engineering performance for potential loss of life and injuries.
  - Reparability of a structure — The consideration of the cost of repair of a structure and of the replacement of contents. Such costs include repair of structural and nonstructural damage.
  - Usability of a structure. — The ability to continue the functions normally carried out in a given building or structure, typically considered as the "downtime" associated with earthquake damage. This can be measured in terms of forgone revenues for the period of disruption (or cost or replacement of services for nonrevenue based activities).

- *Expose consequences and trade-offs among different levels of safety (or risk).* The consequences with respect to costs, safety achieved, and other benefits should be evident so that decision makers are clear about the trade-offs involved. This means that use of decision-theoretical approaches like benefit-cost and life-cycle cost analyses should be presented in ways that expose these trade-offs.

- *Express safety and risk consequences for different alternatives in terms of relative safety improvements or risk reduction.* Given the uncertainties associated with absolute measures of safety/risk, it is more appropriate to consider relative risk reduction or safety enhancement than absolute measures. This is analogous to the way in which the benefits of a medical procedure are expressed, usually in terms of relative risk reduction (e.g., relative to not having the procedure, the odds of living a particular number of years are increased Y percent).
- *Consider externalities.* A key normative issue in policymaking is the extent to which owners of buildings or facilities should be held accountable for the external effects of their actions. These issues are covered by our legal system (liability and torts) and arise in policy discussions. Ideally, a decision framework would incorporate externalities of earthquakes for individual structures such as release of hazardous materials, fires that affect more than the structure in question, or effects on adjacent structures. This calls attention to the role of such considerations in the establishment of minimum standards and/or risk-analysis requirements for approval of new facilities.

5.2 FRAMING SOCIETAL DECISIONS

Societal considerations for seismic safety are not well served by a quest to define acceptable levels of seismic risk. Shifting the discussion to desired levels of safety is important for framing relevant decisions, but it is not sufficient in itself for making relevant decisions. As with any client, the engineering profession should seek to inform, rather than make, collective decisions about minimum standards of performance for different situations or classes of facilities. That quest will be advanced with attention to framing collective deliberations to

- *Make clear the regulatory or other choices of governmental entities.* As is often the case in regulation of safety (see Fischhoff et al. 1981; Fischhoff 1983), the choices that governmental officials face in regulating public safety need to be identified. These include establishment of regulatory standards (i.e., minimum performance levels) and establishment performance objectives for lifelines or critical facilities. The framing of these choices is a critical aspect of societal decisions about seismic safety.

- *Expose the consequences of these choices and their trade-offs with respect to safety/risks, benefits, and costs.* The consequences should include consideration of externalities, interdependencies, and indirect effects. As discussed earlier, the tools for accomplishing this are those of economic loss estimation that build upon regional models of economies. But, as also indicated above, these frameworks are incomplete for these purposes.
- *Expose distributional aspects of the choices.* One limitation of such economic modeling is the highly aggregate nature of the results. Yet, elected officials often want to know "who wins and who loses" as a consequence of any governmental decision. This means that the distribution of the consequences — across different geographic areas and sectors of the economy — also need to be considered.
- *Express consequences for different levels of decision making*. A different aspect of the distributional consequences of societal choices has to do with scale with respect to differing political jurisdictions. City officials want to know what the consequences are for their city; state officials want to know the consequences at the state level. This means that the consequences of the choices at different levels of aggregation also need to be considered.
- *Inspire confidence in their approach and conclusions*. This may seem obvious, but it is an important lesson that has been lost in past debates over nuclear safety and high-level nuclear waste. This is not only an issue of the credibility of the results, but the trust that is placed in the entities that produce them, the fairness of the process, and the way in which the results are communicated.

5.3 CONSIDERING RESEARCH NEEDS

Several research issues are evident from the discussion of organizational and societal aspects of performance-based earthquake engineering:

- Development of measures for each of the decision considerations addressed in the preceding sections concerning decisions about seismic safety: (1) public safety — loss of life and injuries; (2) reparability of structures — cost of repair of a structure and replacement of damaged contents; (3) usability of a structure — forgone revenues and/or costs of replacing interrupted services.

- Understanding of the implications of different ways of presenting decision makers information from performance-based analyses and trade-offs among choices. This entails consideration of ways of presenting probabilistic information (i.e., expectations about outcomes over time), uncertainties about such estimates (i.e., use of confidence intervals or other means), differing incidence of costs and benefits of seismic improvements (i.e., timing of incidence), and relative risk comparison of alternatives (i.e., versus absolute estimates of consequences).
- Refinement of benefit-cost and regional economic analysis frameworks for use in informing choices about performance-based earthquake engineering.
- Understanding of how performance-based earthquake engineering contributes to more rigorous methods for making decisions about financial management of earthquake risks. This includes attention to the role of performance-based earthquake engineering in analyzing seismic risk for a portfolio of buildings (i.e., as part of probable maximum loss estimates) and in development of choices about appropriate financial instruments for sharing risk (i.e., securitization of risk and insurance options).
- Delineation of the regulatory and other choices that advances in performance-based earthquake engineering pose for code adoption and enforcement.
- Understanding the barriers to adoption and implementation of more rigorous approaches to performance-based earthquake engineering. A key part of this is identification of the value that more rigorous approaches to PBEE add to the design of structures relative to the costs of carrying out necessary analyses for the more rigorous approaches.

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