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Barriers to Adoption and Implementation of PBEE Innovations

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ABSTRACT

Performance-based earthquake engineering (PBEE) has gained prominence in the engineering community as an approach that allows for more transparent choices about desired earthquake performance of engineered structures. This report considers prospects for the adoption of PBEE innovations by the design community and for use of innovations in making decisions about seismic performance more generally. The relevant literature is considered and case studies are presented regarding innovations in seismic isolation, load and resistance factor design (LRFD), and performance-based earthquake engineering.

It is difficult at this point to gauge the speed with which innovations in performance-based earthquake engineering will be adopted and implemented. Although code guidelines addressing performance-based approaches have been developed, rigorous methods and techniques for performance-based earthquake engineering are still largely on the drawing board. New seismic provisions and some engineering practice, especially with respect to the rehabilitation of buildings, have incorporated performance-based concepts. However, many engineers are just learning about performance-based earthquake engineering. And, under current ways of doing business, building owners, insurers, and other stakeholders only rarely explicitly engage in discussions of desired performance levels.

Patterns in other earthquake innovations, reviewed in this report, suggest that it takes at least two decades to move beyond the initial threshold of early applications and guidelines to widespread adoption of the innovation. If that pattern holds for PBEE, and if one argues that the initial threshold was reached in the mid to late 1990s, it will be at least another 15 years before PBEE gains widespread currency. Even within a 15-to-20-year time frame, adoption and implementation are far from assured.

For PBEE innovations to gain widespread currency, a number of technical and decision-related challenges must be addressed. The challenges that PBEE faces for adoption and implementation are arguably more daunting than those previously confronting seismic isolation or load and resistance factor design. Nonetheless, there are important lessons from the history of each. Key barriers to the adoption and diffusion of innovations in seismic isolation were the

perceived high costs of carrying out seismic isolation, uncertainties about the technology, and a lack of standards or guidelines for the technology against which building officials and others could assess seismic isolation designs. Key barriers to the adoption and diffusion of LRFD were the lack of necessary computational power and computing routines to carry out the necessary calculations, lack of data concerning performance of structures under different loads and their resistance, and reluctance of practicing engineers to adopt the methodology.

The lessons reviewed here suggest that the key barriers and steps to overcoming them for PBEE are (1) overcoming uncertainty about the PBEE methodology and its benefits, (2) addressing concerns about the costs of employing the methodology, (3) addressing the complexity of the methodology, (4) legitimizing the methodology, (5) establishing a comparative advantage, and (6) facilitating early adoption.

At best, these steps will help facilitate adoption of PBEE by the engineering profession and help foster greater capacity for undertaking PBEE. However, these steps will not increase the demand for PBEE or bring about the more fundamental changes in thinking about earthquake risks by building owners, the financial community, or public officials that are necessary for PBEE to reach its fullest capabilities. These broader transformations of thinking require the design community to be at the leading edge of explaining to clients how to think about choices and tradeoffs in seismic design as they become more transparent with the application of performance-based earthquake engineering analyses.

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Introduction

Performance-based earthquake engineering (PBEE) has gained prominence in the engineering community as an approach that allows for more transparent choices about desired earthquake performance of engineered structures. The approach allows for the design of structures to meet objectives for earthquake performance that are selected by owners or other relevant decision makers subject to the constraints of minimum standards. By more clearly identifying and more precisely defining quantitative performance objectives, facilities can be designed more efficiently and built with greater confidence in their seismic integrity. Yet, the promise of performance-based earthquake engineering requires more than development of sound methodologies and analytic tools. Such advances will be left on the conceptual drawing boards unless they are adopted by the engineering profession and are effectively used to inform seismic safety decisions. Recognizing this, it is important to remember that the adoption of new methods and tools is not automatic. The availability of a methodology or tool does not guarantee that it will be effectively employed. In short, it is a long way from the research laboratory to actual practice.

The identification of potential adoption and implementation barriers provides a basis for recommending improvements to PBEE methodologies and tools. This also provides a foundation for thinking about ways to more effectively disseminate PBEE methodologies and tools. A first step for identifying potential barriers to adoption and implementation is to consider what prior research says about adoption and implementation of innovations. There is an extensive literature about this from which to draw, although none of it is specific to innovations in earthquake engineering. A second step is to consider patterns in adoption and implementation of previous innovations in earthquake engineering. The following discussion is organized with attention to the conceptual literature and case studies of earthquake engineering innovations.

1 The Diffusion of Innovations

The literature about the diffusion of innovations is striking in its diversity. Everett Rogers, in the latest edition of his classic book *The Diffusion of Innovations,* comments that a complete bibliography of the 3900 publications on the topic would constitute a book in itself (1995: 443). Among the 850 citations of diffusion studies in the Rogers' book, fewer than a dozen specifically address engineering innovations and none address innovations in earthquake engineering. Most of the research on diffusion of innovations addresses innovations in agriculture, consumer goods, education, medicine, and public health. Early studies on these topics date to the 1950s with broader attention by the academic community beginning in the 1970s.

The disparate literature addresses three broad topics. One topic of study is the reasons why firms or other entities adopt new innovations. Research about this question has led to discussion of the need being addressed, characteristics of innovations, and motivations of adopters. Consider, for example, the nonadoption of the Dvorak keyboard (see Rogers 1995: 8-11). Although a technically superior layout for a typewriter keyboard, the Dvorak keyboard never overcame the vested interests that manufacturers and others had in keeping the old design. A second topic that is commonly studied is the pattern of diffusion of innovations among potential adopters. This includes the speed of adoption and factors that affect different patterns of diffusion. A third topic within the broad literature is consideration of the origins of innovations. Research about this topic considers why innovations arise and how that affects later adoption. The first two topics are of most relevance to the discussion of innovations in earthquake engineering.

1.1 FACTORS AFFECTING ADOPTION OF INNOVATIONS

A starting point for addressing reasons for adoption of innovations is to consider what is meant by an innovation. Within the diffusion literature, "an innovation is an idea, practice, or object that is perceived as new by an individual or other unit of adoption" (Rogers 1995: 11). The key point of this definition is that innovations are not necessarily brand new breakthroughs, as they can also comprise new applications of existing knowledge. In the context of performance-based earthquake engineering, innovations may consist of methodologies that have not been previously widely used, different ways of thinking about performance targets or presentation of analytic results, or technological innovations such as new analysis tools.

1.1.1 Characteristics of Innovations

One line of research on the adoption of innovations considers characteristics of the innovation itself. Rogers (1995: 208) describes five attributes of relevance: (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability, and (5) observability. He defines each as follows. "Relative advantage" is the degree to which an innovation is perceived as being better than the idea that it supersedes. "Compatibility" is the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters. "Complexity" is the degree to which an innovation is perceived as relatively difficult to understand and use. "Trialability" is the degree to which an innovation may be experimented with on a limited basis. "Observability" is the degree to which the results of an innovation are visible to others. With the exception of complexity, greater amounts of each of these have been shown to be associated with greater degrees of adoption of innovations. Not surprisingly, increased complexity has been associated with lesser rates of adoption.

An important point about these characteristics is that they are not absolute. What matters is how potential adopters perceive the innovation. If the innovation is perceived as solving a problem better than existing methods, then it is more likely to be adopted. Consider the example of the printing press. As described by Macioti (1989), movable type could be found in China and Korea as early as the 13th and 14th centuries. The technology was not initially widely used in China because woodblock printing was more compatible with the Chinese writing system and ink was too watery to work well with movable metal type. The situation was different in Korea where shortages of hard wood prompted an acceleration of the adoption of the technology.

An important component of relative advantage is the cost of adoption and ease of use of an innovation, relative to alternative ways of doing business. One factor that distinguishes early adopters of innovations from later adopters is the formers' willingness to incur the typically larger up-front costs of being an early adopter. Mitropoulos and Tatum (1995) describe justification of costs of adoption of new CAD technology to senior managers in construction firms. The justification was less likely to be based on a formal cost-benefit analysis and more likely to be based on "informed intuition" that the technology would provide competitive benefits. Those marketing new technologies have learned the importance of helping firms lessen up-front costs of early adoption with breaks in pricing and by making available on-site technical assistance. An important aspect of this is the observability of the benefits of the innovation.

The degree of uncertainty about an innovation is affected by the remaining characteristics. By the nature of being new and involving change, the adoption of innovations tends to engender uncertainty. Because individuals and firms tend not to tolerate uncertainty well, they are often reluctant to be early adopters of innovations. The uncertainty will be lowered, and the individuals' willingness to adopt will be increased, if an innovation is more compatible with previous ways of doing business (i.e., involving little change), is not very complex, or if the innovation can be tested before full-scale use. One reason why innovations are more widely adopted once an initial threshold of adopters is passed is that the greater industry-wide diffusion reduces uncertainties for later adopters. For example, in studying adoption of new jet technologies by the aviation industry, Goel and Rich (1997) note that wider adoption of new technologies increase complementarities of ground equipment, availability of spare parts, and quality of training of flight crews and maintenance workers.

The growth of information technologies has called attention to an important additional factor not considered by Rodgers that affects user acceptance of information technology. The "ease of use" of the technology has been shown both in the marketplace and in academic studies to be an important consideration. Complexity may or may not undermine ease of use in that an innovation may be technically complex but be designed in such a way that it can be easily used. As discussed by Dillon and Morris (1996) in a survey of research about user acceptance of information technology, the field of human-computer interaction has broadened in recent years to broadly consider factors that affect the usability of information technology. Dillon and Morris cite the ISO standard 9241 (part 11) in defining the usability of an application as "the effectiveness, efficiency, and satisfaction with which specific users who are performing specific tasks in specific environments can use an application" (1996: 20).

1.1.2 Characteristics of Early Adopters

A second line of research about adoption of innovations considers the characteristics of adopters of innovations, focusing on differences between early adopters and later adopters of innovations. Much of the research focuses on characteristics of individuals — farmers, teachers, consumers, and so on — who choose product innovations or new ways of doing business. In general, the early adopters are better educated, more willing to take risks, and have more exposure to the media (see Rogers 1995: 252–280).

The literature that addresses differences among firms that are early and later adopters of innovations is of greater relevance to consideration of innovations in earthquake engineering. This literature highlights similar characteristics to those of individual early adopters, while also suggesting relevant organizational attributes. As summarized by O'Neill, Pouder, and Buchholtz (1998) in studying business adoption of new strategies such as downsizing or mergers, several organizational factors are potentially relevant (more generally see Rogers 1995: 371–404). One is an organization's receptivity to change and learning. Firms that are leaders in an industry are more willing to experiment and that, in turn, leads to greater rates of adoption of innovations. This is partly because such firms have more flexibility and resources with which to experiment, and partly because they fear losing their leader status. Countering the forces of willingness to learn and experiment is the organization drag imposed by bureaucratization and large size. As organizations grow they tend to atrophy, leading to less willingness to try out innovations.

Other research by Kitchell (1995) points to differences in market environments and corporate culture that distinguish early from later adopters of innovations. Firms in competitive markets must be risk-taking in order to cope with fast-changing events and uncertainties of the markets. As such, they are more likely to try out innovations if they perceive the innovations as providing a market advantage—if only for a short term. Such firms are also more likely to be actively seeking such advantages, making them more likely to be aware of innovations. However, not all firms in such markets can be early adopters. Some do not have the resources, while others do not have a corporate culture that is supportive of such risk-taking. As such, a corporate culture that promotes innovativeness is an important facilitator of such adoption.

1.2 FACTORS AFFECTING THE PATTERN OF ADOPTION

Some innovations diffuse quickly among potential adopters, while others either languish or die off entirely. Diffusion scholars have studied these patterns with a general finding that adoption tends to follow an S-shaped pattern as illustrated in Figure 1 (Rogers 1995: 11-12). Adoption is initially limited to early adopters and is relatively slow. Once a critical base is established, which typically amounts to 10 to 25 percent of potential adopters, the pace of adoption is relatively fast. Then, a point of saturation is reached where reluctant adopters either are slow to adopt or do not act.

The most common explanation for this pattern is what has been labeled the epidemic model of information diffusion (Geroski 2000). According to this explanation, the spread of technology is dependent on the speed with which potential users learn about that technology. Because much information technology rests on personal experiences to evaluate and communicate the benefits of the technology, word-of-mouth communication dominates in the same fashion that many epidemics spread by human contact. In early stages, few learn of and communicate the benefits of the technology. By this logic, Geroski (2000: 606) notes that diffusion is likely to be faster for simpler technologies, for populations which are densely packed and mixing is easy, and in situations where the new technology is clearly superior.

As Geroski (2000: 616) notes, however, the information diffusion explanation is limited and other explanations can be offered for the S-shaped pattern. Geroski suggests that the early, slower rates of adoption might be better explained by the need for legitimization of the technology for which key issues are whether it will work, whether it is superior to the alternatives, whether there is infrastructure to support adopters, and so on. Once legitimized either through formal endorsement (standards settings) or adoption by a critical mass of adopters, competitive forces propel later adopters to jump on the bandwagon in order to stay competitive. Yet, competition has an equilibrating effect in that competitive advantages wane as more firms adopt the new technology leading to a slowing of the rate of adoption.

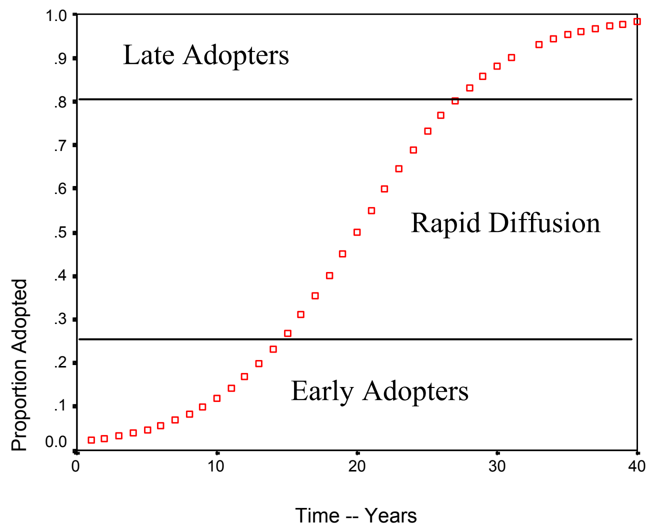

Figure 1. Typical diffusion pattern for innovations

Regardless of the underlying explanation of the S-shaped pattern of diffusion, a central element is what has been labeled the diffusion network. The relevant network is made of the interpersonal ties among individuals and firms that serve as information flows about innovations. Networks can comprise ties with individuals within a firm, among suppliers or competitors, or among professional trade associations or other organized interest groups (see Johnston and Linton 2000; Robertson et al. 1996). As discussed by Rogers (1995: 281–334), a central aspect of diffusion among such networks is the role of opinion leaders. These are individuals who lead in influencing others' opinions about innovations. Their influence will depend on how persuasive they are—or, more precisely, how enthusiastic they are—along with characteristics of the network of individuals or firms. More tightly packed networks with strong ties provide greater opportunities for sharing of information. More homogeneous networks comprising similar individuals or firms will have shared problems and experiences, leading to easier adaptation of innovations.

2 Diffusion of Innovations in Earthquake Engineering

The broad literature on the diffusion of innovations sets the stage for considering patterns of adoption and implementation of innovations in earthquake engineering. Three such innovations of relevance are seismic isolation (base isolation), load and resistance factor design (LRFD), and performance-based seismic design. The remainder of this section provides an overview of the patterns of these innovations followed by a more detailed discussion of each of the observed patterns.

2.1 OVERVIEW

Table 2.1 provides an overview summary of the stages of innovation and adoption for the three earthquake-engineering innovations.

Table 2.1 Patterns for earthquake engineering innovations

	Seismic Isolation / Base Isolation	Load and Resistance Factor Design	Performance-Based Seismic Design
Earliest version	1906 patent application	1914 Budapest design code	Early 1970s' HUD "Operation Breakthrough"
Modern conceptual groundwork began	Late 1970s' advances in rubber bearings	1947 rigorous theoretical basis by Freudenthal; 1960s' development of concepts of limit states	Evolution of LRFD 1980s into 1990s
Initial modern day application to buildings	1978 Clayton Building in New Zealand 1985 Foothills Law and Justice Center, San Bernardino County, CA	1970s' advances in reliability analysis and load modeling	Late 1990s repair of moment-resisting steel frame joints
Initial U.S. standard or guidelines	1989 SEOAC bluebook guideline 1989 CA hospital guidelines 1991 UBC 1991 AASHTO	1963 AIC concrete specification; 1986 AISC specification for steel structures; 8 other codes from 1991 – 1995	1992 — Department of Energy, Nuclear Performance Standards; 1995 – SEAOC Vision 2000 1995 — FEMA 267 SAC guidelines for welded 1997 FEMA 273/274 Seismic Rehabilitation
Current extent of diffusion	Worldwide use of isolation, but small percentage of engineered buildings	Widespread adoption of the design approach in codes and in education	Early stages of methodology and applications

Seismic isolation, according to Ian Buckle and Ronald Mayes, "is perhaps the most innovative development in Civil Engineering since the computer revolutionized structural engineering." Despite this, they comment: "[S]eismic isolation is not yet widely accepted as a valid alternative to conventional seismic resistant design. There is, however, growing evidence, that the methodology is gaining ground" (1990: 196). The pattern for this innovation is very much the S-shaped curve of diffusion scholars. Early versions were contained in patent applications in 1906 in the U.S. and 1909 in England. It was not until the 1970s, however, with advances in the design of rubber bearings that the approach became technically and economically feasible. This followed extensive research and application in New Zealand, with later application in the mid 1980s in Japan and the U.S. By the early 1990s, the innovation had reached the takeoff stage with use of seismic isolation for buildings and bridges throughout the world. Yet, that takeoff has been stalled in the United States. As Mayes' commented: "Although seismic isolation has been used in the United States for close to twenty years and is considered a relatively mature technology, there are not indications that its use is increasing….In contrast, China and Japan (with over 1100 buildings completed) design and build many isolated projects each year…" (2002: 1).

Load and Resistance Factor Design (LRFD), also known as "limit states design," is interesting because it serves as a precursor to key elements of the methodology for performance-based seismic design. Aspects of LRFD also date to the early 1900s with the plastic design of steel structures. The conceptual basis was advanced with development of reliability theory in the 1950s and with computational advances in the 1950s and 1960s that permitted development of initial approaches to probabilistic approaches to structural analysis. The development of standards was advanced with a collaboration of academics and industry from the late 1960s until the mid 1980s in carrying out research and developing standards. Standards development using LRFD concepts has been adopted for standards setting for steel, concrete, aluminum, bridge, and wood structures (see Galambos 1998 for an overview of the history of LRFD). Despite the widespread adoption of this approach, Galambos commented in 1998: "The full transition from ASD (allowable stress design) to LRFD will, however, not likely be complete yet for some ten more years" (1998: 2). In writing this, he argued that further dissemination requires wider education of practicing engineers about the design approach and development, and the testing of reliable software for LRFD for a range of structures.

In comparison to seismic isolation and LRFD, performance-based seismic design is in its infancy. The concepts of performance-based codes were advanced by the US Department of Housing and Urban Development with a housing code development program, "Operation Breakthrough," which began in the late 1960s and ended in the mid 1970s. The important analytic underpinnings were developed as extensions of LRFD in the late 1970s and early 1980s with attention to the quantification of seismic demands on structures as a function of different hazard levels. This thinking, in turn, led to subsequent research and discussion about ways of systematically cataloging the performance of structures. Not until the early 1990s with the publication of Department of Energy standards for nuclear power plants were the concepts more fully developed and incorporated into practical design for earthquake engineering. The response to the steel frame joint failures in the Northridge earthquake led to wider application of the concepts. As with the development of LRFD standards, the interplay of research and industry was critical for the SAC program as has been the case for the subsequent development of guidelines for the seismic rehabilitation of buildings. Although code guidelines addressing performance-based approaches have been developed, rigorous methods and techniques for performance-based earthquake engineering are still largely on the drawing board.

2.2 INNOVATION AND ADOPTION PATTERNS

With this historical background about innovations in seismic isolation, load and resistance factor design, and performance-based seismic design, it is useful to consider in more detail the pace of innovation and adoption for each innovation.

2.2.1 Innovation and Adoption for Seismic Isolation

Seismic isolation has been described as a design strategy that is based on the premise that "it is both possible and feasible to uncouple a structure from the ground and thereby protect it from the damaging effects of earthquake ground motions" (Buckle and Mayes 1990: 161). The key concepts for seismic isolation are the use of flexible mounting systems to isolate structures and damping mechanisms to dissipate the energy generated by an earthquake away from the structure. While several systems of isolation exist, the most predominant is the use of base-isolation techniques involving the separation of a structure from the ground with the use of rubber bearings. The historical discussion that follows draws from Buckle (1993), Buckle and Mayes (1990), Kelly (1998), and Mayes et al. (1990a).

The concepts of seismic isolation date to the late 19th century. The December 1891 issue of the journal published by the Architectural Institute of Japan contains a report of construction of a building involving an early form of base isolation. In 1906, Jacob Bechtold of Munich, Germany, made an application for a U.S. patent for an earthquake-proof building involving a mass of spherical bodies of hard material to carry the base plate. In 1909, a medical doctor from Scarborough, England, obtained a patent involving a layer of talc to isolate the walls and floors of a structure from ground disturbance; apparently inspired by a Japanese approach. Another patent application was filed in 1929 in New Zealand.

Wider use of seismic isolation approaches did not occur until advances were made in the 1970s in the devices that could be used to isolate structures. French engineers experimented in the early 1970s with elastometric bearings for protecting low-rise, lightweight structures. A school built in Mexico City in 1974 employed steel ball bearings, while about that time another school built in Skopjie, Yugoslavia, employed large blocks of natural rubber. The first bridge using base isolation was constructed in New Zealand in 1974. In the late 1970s more than a hundred prestressed concrete railway bridges were built for the Japanese bullet-train (Shinkansen) that incorporated sliding bearings and viscous dampers; providing a partial form of isolation.

Further advances in the design and manufacture of rubber bearings provided a relatively simple device for achieving base isolation. Rubber bearings have the added advantages that they are relatively easy to manufacture for desired levels of quality. The 1978 construction of an office building in New Zealand, the Clayton Building, was the first using natural rubber bearings as isolators. The first building constructed using these techniques in the U.S. was the Foothills Communities Law and Justice Center built in 1985 in San Bernardino County. The first large base-isolated building in Japan was completed in 1986. Seismic isolation has also been used in a number of settings for bridges, with notable developments in the late 1970s including the use of energy dissipators for the South Rangitikei Rail Bridge in New Zealand and for numerous bridges as part of the Japanese bullet-train system.

Worldwide adoption of base-isolation practices is now evident, although the rate of adoption of the technology in the United States has slowed from that of the early 1990s. (This is addressed more fully below in discussing impediments to seismic isolation.) Buckle and Mayes

(1990: 167) cite that as of the early 1990s seismically isolated structures had been built in at least 17 countries with another eight having active research programs. As of the year 2002, Mayes (2002) notes that there are in excess of 1100 seismically isolated buildings in Japan and approximately 80 in the United States. As one of the leading countries in the development and use of the technology, a number of buildings and bridges in New Zealand have been constructed or rehabilitated using base isolation, including the national Parliament Building in Wellington. The latter illustrates the value of seismic isolation for seismic retrofits that include the use of the technology in the retrofit of facilities in the United States (e.g., Salt Lake City and County Building; Los Angeles, Oakland, and San Francisco city halls, Lake Washington I-90 bridge). In these and other retrofit cases, isolation was used to reduce the load, thereby allowing the structure to remain unchanged. In cases in which the structure had monetary, architectural, or cultural intrinsic value, the seismic isolation approach has considerable merit.

The incorporation of seismic isolation techniques into earthquake engineering guidelines and codes paralleled, as well as propelled, the use of the approach in construction. The 1982 Code of Practice for the Design of Concrete Structures in New Zealand incorporated design recommendations for seismically isolated structures. The Structural Engineers Association of California adopted guidelines in an appendix to the 1989 SEAOC Bluebook. Guidelines for base-isolation of hospitals in California were developed by the state in 1989. Other early commentary about base isolation within codes and design guidelines in the United States included the Uniform Building Code (UBC) in 1991 and the American Association of State Highways and Transportation Officials (AASHTO) guidelines in 1991.

Despite the worldwide use of seismic isolation methods, the approach itself is only employed for a small percentage of newly engineered or rehabilitated structures. With respect to the state of diffusion as of the early 1990s, which has not qualitatively changed a decade later, Buckle and Mayes observe: "Despite a history which stretches back almost 90 years, seismic isolation is not yet widely accepted as a valid alternative to conventional seismic resistant design. There is, however, growing evidence that the methodology is gaining ground" (1990: 196). In updating the status of the adoption of seismic isolation approaches as of 2002, Mayes (2002) provides a mixed review in noting that the use of seismic isolation has continued to increase in China and Japan, while the rate of adoption of the technology has stalled in the United States.

Based on interviews with engineering professionals, Mayes (2002) attributes this slowing in the United States to a combination of perceptions that the technology is "expensive, complicated, and time consuming" and to the reality of overly burdensome requirements for certification of designs for seismically isolated facilities.

2.2.2 Innovation and Adoption of Load and Resistant Factor Design

Load and Resistance Factor Design (LRFD) is an approach that recognizes that a structure may have a number of different sources of load upon it and several different limit states for resisting those loads. The design goal under LRFD is to keep the expected load effects less than or equal to the expected resistance of the structural elements or structural system. Given the variety of potential load and resistance factors and potential responses for any structure, the development of probabilistic reliability framework has been central in the evolution of the LRFD approach. The LRFD methodology provides advances in addressing nonlinear responses of structures, multiple load combinations, and multiple sources of resistance of a structural system. The approach replaces the Allowable Stress Design (ASD) method that assumed linear responses and was more limited in the treatment of loads and resistance sources.

The history of LRFD as summarized here has been described by T. Galambos (1998), who has been a pioneer in developing this approach (also see Ellingwood 1998, 2000, 2001). As with seismic isolation, aspects of the concepts of LRFD date to the beginning of the 20th Century with the plastic design of steel structures. Kazinczy pioneered the plastic design of steel structures, which was used in the Budapest design code in 1914, as a precursor to reinforced and prestressed concrete structures. The concepts of reliability and uncertainty, which are central to LRFD, were developed by Mayer in 1926 and by engineers in the Soviet Union and Poland in the 1930s and 1940s.

A more rigorous theoretical basis for reliability-based structural design was provided by Freudenthal in 1947. The conceptual basis was advanced with the development of reliability theory in the 1950s. Computational advances in the 1950s and 1960s facilitated advances in estimating load and resistance factors. The First International Conference on Structural Safety and Reliability led to publication by the *ACI Journal* in the September-December 1969 issue of a set of papers on LRFD and structural safety. By the 1970s advances were being made in reliability analysis, modeling of loads, and data collection about seismic demands and resistance. One of the early efforts at disseminating this information was a technical session on the probabilistic design of concrete buildings that was held by the American Concrete Institute in 1971. The advances in analysis, modeling, and data were important for establishing a common set of demands placed on structures for subsequent analysis and codification.

The research of the 1960s and 1970s, along with industry participation, led to the development of several sets of standards by the 1980s for the use of LRFD. As discussed by Ellingwood (2000), one of the more extensive efforts was an academic-industry research program initiated in 1969 by the American Iron and Steel Institute (AISI) and the American Institute of Steel Construction (AISC). That effort led to publication in 1978 of a collection of papers explaining the technical basis for LRFD. This was followed by a period of trial and refinement of proposed standards for steel construction with an initial draft standard introduced for consideration in 1981. After several years of further refinement and debate, in 1986 an LRFD specification. was adopted for steel buildings in the U.S. An LRFD-like provision was promulgated in 1963 for concrete structures by the American Concrete Institute. Although the term "LRFD" was not used, the concepts were similar. This arguably was the first codified use of LRFD specifications with agreement about initial standards evolving more quickly than it did for steel standards.

Subsequent dissemination of the LRFD methodology and advances in "second-order" reliability methods were central to development specifications for other types of structures. Galambos (1998) lists eight different sets of LRFD-based standards that incorporate these advances (relevant dates in parentheses): cold-formed steel structures (1991), stainless steel structures (1991), aluminum structures (1994), steel building structures (1993), bridge structures (1994), concrete structures (1995), loads, load factors and combinations (1995), and wood structures (1995).

The adoption of these standards is clear indication of acceptance of LRFD principles by the engineering profession. That acceptance is further evidenced by the fact that LRFD is now the accepted methodology within engineering textbooks and with the availability of analytical tools for LRFD calculations. Galambos remarks:

> It appears that most structural design specifications in the USA will have LRFD versions in effect by the year 2000. Almost all structural engineers under 40 years of age will have by then received education in the LRFD methods in their engineering training. It is also likely that more and more new structures will be designed by LRFD, especially seismic structures, composite systems and unusual structures (1998: 3).

Yet, in the same set of remarks, Galambos notes that "the full transition from ASD [Allowable Stress Design] to LRFD will, however, not likely be complete for some ten more years."

2.2.3 Innovation and Adoption of Performance-Based Seismic Design

Performance-based seismic design—also known as "performance-based earthquake engineering"—has gained prominence in the engineering community as an approach that in principle allows for more transparent choices about desired earthquake performance of engineered structures. The approach allows for the design of structures to meet objectives for earthquake performance that are selected by owners or other relevant decisionmakers subject to the constraints of minimum standards. For example, a building owner can choose whether it is worth the extra investment in seismic engineering to protect contents from major damage or assure a reasonable level of business continuity in addition to minimizing potential loss of life. Or, an owner can choose to rehabilitate an existing, vulnerable structure to a meet a life-safety performance standard in a more cost-effective way than possible under traditional codes.

At present, PBEE represents a conceptual approach, an evolving analysis and design methodology, and an evolving set of analytic tools for implementing the methodology. The conceptual approach is to allow for differentiation in seismic performance objectives based on more than just differences in types of facility or occupancy group. This also reflects a continued evolution in design philosophy in moving from prescriptive- to performance-based design. The evolving methodology, which is being actively developed in engineering research centers in several countries, is a more rigorous approach to earthquake engineering that clearly and quantitatively specifies different levels of performance as a basis for seismic design. This draws from and extends key notions of load and factor resistance design, especially in the application of inelastic design principles, probabilistic treatment of different hazard sources and demands on structural systems, and treatment of uncertainties in the design and engineering of facilities. The evolving analytic tools for implementing the methodology consist of analytic and computing routines.

The seismic provisions of building codes, as with the codes more generally, have always been concerned with the performance of structures. Codes, as well, are often the result of delicate compromises between interests with differing views of appropriate standards, approaches, or materials. The preface to the 1946 edition of the UBC expresses the ambitions in language that today belies the complexity of modern codes:

> The Uniform Building Code is dedicated to the development of better building construction and greater safety to the public, through the elimination of needless red tape, favoritism and local politics by uniformity in building laws; to the granting of full justice to all building materials on the fair basis of the true merits of each material; and to the development of a sound economic basis for the future growth of cities through unbiased and equitable dealing with structural design and fire hazards (UBC, 1946, p.4)

The seismic provisions of modern codes have been based on a philosophy of protecting life-safety with vague articulation of this objective and limited explanation of how specific provisions achieve the objective. Although the preface to the 1946 UBC implies that codes are also aimed at providing a level of economic security, such protection is only an indirect consideration in modern code provisions.

New insights about earthquake damage to buildings, based largely on empirical observation of the effects of major earthquakes, have led to substantial revisions in seismic provisions and seismic design approaches over time (see Applied Technology Council 1995). The net result has been the creation of a set of provisions that have minimized the loss of life during earthquakes in this country. However, the resultant code provisions have often been characterized as rather ad hoc (in responding to past events), complex, and prescriptive. The performance-based approach is desirable because it overcomes limitations of current prescriptive codes that fail to clearly identify and precisely define quantitative performance objectives. The choice of design procedures for meeting performance objectives as part of performance-based codes is particularly important when considering the rehabilitation of buildings for which it is typically uneconomical to fully meet existing code provisions.

The concept of a performance standard is as old as the Code of Hammurabi of ancient Babylon for which a contractor was subject to death if a building he constructed later fell down. While perhaps saying more about the origins of construction litigation, this simple "golden rule" clearly established a desired performance of a structure. Perhaps because of litigation and the need for legally defensible actions, building codes have evolved in this country with highly prescriptive provisions concerning specific requirements for the selection, use, and installation of different building materials and structural systems.

As discussed by Ellingwood (2001), the performance concept in modern building construction dates to the 1960s when the U.S. Department of Housing and Urban Development sponsored an innovative housing demonstration program, Operation Breakthrough. This demonstration program was intended to showcase new approaches to design, materials, and construction techniques for low-income housing. A key component of the initiative was work undertaken in the late 1960s and early 1970s by engineers at the National Bureau of Standards, to create guidelines for evaluating the applicability of different designs and materials as they relate to various aspects of a building (e.g., safety, serviceability, entrance/egress). A performance-based approach was employed in setting forth for each aspect of a building a set of goals, a set of criteria for assessing adherence to those goals, an evaluation procedure for the assessment, and commentary about the criteria and evaluation procedures. Ellingwood cites a variety of considerations that undermined further development and application of these guidelines. These include concerns about enforcement of relatively open-ended codes, in comparison to prescriptive ones, provisions; the lack of analytic tools for carrying out requisite analyses; and the reluctance of the engineering profession to embrace the approach; given their concerns about the value added of the approach.

Also in the early 1970s the fire safety community was interested in promoting the use of smoke detectors in residences—something that was not required until much later. As discussed by Bukowski (2001), a committee of the National Fire Protection Association proposed a system of four "Levels of Protection" in the 1974 edition of the NFPA fire protection code. This represented the first delineation in code guidelines of building owners choosing different levels of performance. Subsequent testing to see whether these indeed provided adequate protection led to the definition of a performance standard based on "escape time" from a building of three minutes. That testing resulted in a determination that smoke detectors were necessary on each floor of a residence to achieve the desired standard. The use and development of performance-based approaches to fire protection standards has been central to subsequent development of fire codes.

Interest in performance-based approaches to seismic design and engineering has come from two sources. The primary demand has come from recognition of the difficulty of applying new code provisions to the rehabilitation of existing facilities or structures. Simply put, applying new provisions is often prohibitively expensive and arguable in terms of desirability. Federal funding for the creation of a set of rehabilitation guidelines, the FEMA 273 guidelines (Applied Technology Council 1997), allowed for alternative ways of meeting desired performance objectives and provided a path for resolving this dilemma. This allowed for lower-cost alternatives in many instances than possible under existing prescriptive approaches.

A second source of demand has come from owners and operators of high-valued facilities — computer centers, hospitals, electric utilities — for which it is important to consider the functionality of the facilities in the aftermath of an earthquake. Although modern building code provisions have distinguished among different uses (occupancy classes) of buildings and have specified more stringent requirements for higher-rated uses, such delineation does not adequately convey desired performance. The first application of the PBSD approach as part of building guidelines came with the development by the Department of Energy of standards for seismic (and "natural hazards") performance of nuclear facilities — DOE Standard 1020 of 1992. These provisions established different classes of structures and different performance objectives depending on the class and extent of seismic hazards. Those objectives were specified in terms of qualitative characterizations of life safety and continued operations, as well as with quantifiable goals of maximum tolerable levels of radiation exposure.

The 1989 Loma Prieta and 1994 Northridge earthquakes further propelled interest in performance-based seismic design with recognition of the tremendous financial and economic stakes of urban earthquakes. Fundamental questions have been raised by the insurance industry about the potential enormous costs to governments for disaster relief and recovery, the impacts on the national and regional economies, and the impacts on business productivity and employment. These events also awakened facility owners and businesses to the realization that, even when buildings are built to modern code specifications, their businesses can be interrupted for weeks if not months ——sometimes leading to financial ruin. Few realize the basic fact that current seismic regulations and design procedures are focused on preventing loss of life in earthquakes. Because codes do not explicitly address non-life-threatening damage to facilities and infrastructure, assuring continuity of services, or minimizing repair time and costs, they are at present limited means for addressing economic losses from earthquakes.

Two activities emanating from the Northridge earthquake have been instrumental in the development of performance-based seismic design. One was an activity funded by FEMA and undertaken by the Structural Engineers Association of California (SEOAC) titled the "Vision 2000 Project." This project considered the application of the performance-based concepts that were developed as part of the previously noted FEMA 273 provisions for the rehabilitation of existing facilities or structures. The resultant SEOAC guidelines (1995) proved influential in setting forth a matrix that characterized desired performance for different levels of hazards and building classes. These concepts were later incorporated as commentary in the 1997 NEHRP seismic guidelines.

The second activity of relevance to performance-based seismic design that followed the Northridge earthquake was a response to the extensive damage in that event to moment-resistant steel frame structures (see Malley et al. 2000). The discovery of unexpected fractures of framing connections for more than 150 moment-resisting steel frame buildings—including hospitals, governmental buildings, private offices, residential structures, and commercial buildings—called into question existing code provisions and created an urgent need for a program for repair and assessment of such structures. A six-year, $12 million project to address this problem was undertaken with FEMA funding as a joint venture among three professional and educational organizations: the Structural Engineers Association of California, the Applied Technology Council, and the California Universities for Research in Earthquake Engineering. An intensive research program led to the development of interim guidelines for the evaluation, repair, modification, and design of welded-steel moment steel frame structures, published as FEMA 267

(SAC Joint Venture 1995) and later updated as FEMA 267A (SAC Joint Venture 1997). Subsequent testing and review led to the publication of a final set of guidelines as FEMA 351 (SAC Joint Venture 2000). These guidelines constituted the first widespread application of performance-based design principles that included quantified performance for the behavior of steel-frame buildings and their components, and methods for assessing the reliability of the predicted performance of different designs.

The limitations of the prescriptive approach to building codes have also propelled the private, code-writing entities in this country to rethink code provisions. Interest in developing a more workable set of provisions led to a multiyear effort undertaken by a consortium of the three national code-writing entities and the International Code Council to develop a performance-based building code. The result is a performance-based code published in December 2001 as the *ICC Performance Codes for Buildings and Facilities* (International Code Council 2001). The intent is specified in the statement of purpose of the code, Section 10.1: "[T]o provide appropriate health, safety, welfare, and social and economic value, while promoting innovative, flexible and responsive solutions that optimize the expenditure and consumption of resources." The code provisions establish minimum performance levels for a cross-classification of four groups of facilities (delineated by use and occupancy) and four categories of design events (delineated by levels of risk). For the resultant 16 combinations different "maximum levels of damage to be tolerated" are specified. As clearly stated in the code documentation, "the performance code is intended as a framework document that creates a method more closely reflecting society's expectations of building and facility performance…" (International Code Council 2001: 85). At present, the ICC is an alternative set of provisions to the more traditional International Building Code.

Also relevant, as noted above, are developments in performance-based approaches in the fire safety community. The National Fire Prevention Association (NFPA) has promulgated performance-based code provisions for fire and life-safety (the 2000 edition of NFPA 101, Life Safety Code) and is in the process of completing a performance-based design option to the NFPA-promulgated building code (the 2002 NFPA 5000, Building Code). The performance-based design provisions make a distinction among three different performance levels (serviceability, immediate occupancy, and collapse prevention) as applied to different occupancies and potential forces upon a structure. In introducing the performance-based design provisions, Harrington (2002) comments:

> The PBD option offers designers more flexibility, and requires a greater level of sophistication than prescriptive design….Given the required level of sophistication, PBD options are likely to be reserved for large, complicated building projects in which the prescriptive approach doesn't offer the necessary design flexibility….The option provides for safe building design since it's grounded in science, yet offers flexibility not always afforded by its prescriptive counterpart….By incorporating the PBD option into our new Building Code, NFPA shows it's facing the twenty-first century head on.

2.2.4 Summary: Prospects for Diffusion of PBEE

It is difficult at this point to gauge the speed with which innovations in performance-based earthquake engineering will be adopted and implemented. Although code guidelines addressing performance-based approaches have been developed, rigorous methods and techniques for performance-based earthquake engineering are still largely on the drawing board. New seismic provisions and some engineering practice, especially with respect to rehabilitation of buildings, have incorporated performance-based concepts. But, many engineers are just learning about performance-based earthquake engineering. And under current ways of doing business, building owners, insurers, and other stakeholders only rarely explicitly engage in discussions of desired performance levels.

Patterns in other earthquake innovations, reviewed here, suggest that it takes at least two decades to move beyond the initial threshold of early applications and guidelines to widespread adoption of the innovation. If that pattern holds for PBEE, and if one argues that the initial threshold was reached in the mid to late 1990s, it will be at least another 15 years before PBEE gains widespread currency. As discussed in the next section, even within a 15 to 20 year time frame, such adoption and implementation is far from assured.

3 Overcoming Challenges for PBEE

For PBEE innovations to gain widespread currency a number of hurdles must be overcome. These hurdles and the experiences for the other previous earthquake innovations in overcoming similar hurdles are considered in what follows (also see Tobin 1998; Mayes 2002). This discussion leads to commentary about specific actions that will help enhance the prospects for adoption and implementation of PBEE innovations.

3.1 CHALLENGES FOR PBEE

The development of performance-based earthquake engineering confronts a number of daunting technical and decision-related challenges. The technical issues revolve around the ability to predict the effects of earthquakes upon structures, to translate those effects into predictable physical damage states, and in turn to translate those damage states into consequences in such terms as loss of life, injuries, building functionality, and repairability. The decision-related challenges entail design of a methodology that is useful in terms of providing meaningful categories of choices, information about the costs of achieving different outcomes, and confidence in the part of decision-makers that the buildings will perform as stated (see May 2002).

Achieving the benefits of PBEE advances is far from automatic as they entail fundamental changes in engineering practice and in decisionmaking about seismic risks. The engineering profession will be required to fulfill a broader consultative role in explaining the stakes involved in making choices about earthquake risks, the relevant choices, and advice about the implications of those choices. These choices, in turn, will require building owners, investors, public officials, and other stakeholders to think differently about decisions regarding the management of earthquake risks.

At present, it is not common for facility designers or owners to think about differing seismic safety goals except when building specialized facilities such as computer and data centers, valuable production facilities, and critical facilities such as hospitals and power plants. More typically, seismic risk and safety are by-products of decisions about the design and construction of a facility. Aesthetic and functional design properties are first specified. Structures 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.

3.2 IMPLEMENTATION ISSUES

For PBEE to be effective, the design professions—architects, engineers, and professionals responsible for the design of structural and nonstructural elements—will need to be equipped to understand and take advantage of advances in performance-based earthquake engineering. Each will need to understand the philosophy of performance-based design and develop new skill sets specific to their profession. Architects will need to better appreciate the relationships between building configuration, structural features, and nonstructural components of facilities. Facility designers will need to understand how modifications in the use of a structure affect its ability to withstand earthquake damage and maintain functionality. Earthquake engineers will need to be well versed in the methodology of performance-based earthquake engineering as applied to new and existing structures.

The design professions are understandably often reluctant to embrace new innovations (May and Stark 1992). Under current liability provisions, the risks associated with problems in design and construction fall heavily on the design engineer and contractors. This serves as a deterrent to acceptance of new innovations or approaches, especially if they are not codified as accepted practice, because these innovations entail additional risk for the design professional. Moreover, in promoting new approaches, the design professional potentially incurs greater costs for design and client education.

A key issue from a decisionmaker's perspective is the cost of PBEE in comparison to more traditional design approaches. Proponents of PBEE argue that one of the benefits of the methodology is that it makes transparent the costs of achieving different seismic performance objectives. In addition, they argue, it makes choices possible as with the seismic rehabilitation experience that would not be possible under more traditional approaches. Given this, it is difficult to compare the costs of PBEE design with traditional design. Yet, decision-makers are concerned about the costs of the actual PBEE analyses and the delays involved in obtaining additional approvals for "nonstandard" approaches (i.e., additional peer review, testing, and special approvals). In the short term for early adopters of PBEE innovations, at the least these will likely cost more than traditional engineering analysis and advice.

Another issue is the degree to which the building regulatory system is able to adjust to the PBEE approach. The regulatory system in the United States consists of a set of model codes that are adopted by state legislatures and typically enforced, if at all, by local governments. The development of the model codes is through a consensus process by three private, regionally based building code organizations. Owing in large part to a concerned federally funded effort to develop guidelines for seismic code provisions, the private code development process in the United States has been generally good about incorporating advances in seismic design into code provisions.

The three model code organizations have recently produced a common code (the International Performance Code) that is the first model building code in the United States to include performance-based design concepts of the type envisioned by PBEE. The PBEE concepts are also being incorporated into the National Fire Protection Association's performance-based design option for their 2002 NFPA 5000, Building Code. Although code-writers are advancing application of PBEE concepts, the question remains how well those who implement codes—state agencies, local building code authorities, building officials, and inspectors—are able to adapt to these provisions. Implementation of past advances has often fallen short, especially as it relates to the rehabilitation of existing buildings. All too often, building officials or inspectors do not understand key provisions, or are too quick to accept the advice of unqualified engineers.

A final larger set of considerations is the choices that governmental officials face in regulating seismic safety (see May 2001). These include the establishment of regulatory standards (i.e., minimum performance levels) for all structures, establishment of desired performance objectives for public facilities, and establishment of performance objectives for lifelines or critical facilities. The need to specify these objectives presents the fundamental Catch-22 for public officials. On the one hand, determining desired levels of performance is fundamentally a value judgment that presumably requires some form of collective decisionmaking. On the other hand, 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.

3.3 ADDRESSING THESE CHALLENGES: LESSONS FROM OTHER INNOVATIONS

The challenges that PBEE faces for adoption and implementation are arguably more daunting than for those previously confronting seismic isolation or load and resistance factor design. Nonetheless, there are important lessons from the history of each of the latter two earthquake innovations about factors that facilitated or hindered the adoption of each. These are considered in this section, while keeping in mind the generic factors affecting diffusion of innovations that were discussed earlier in this report: relative advantage, compatibility, complexity, trialability, observability, uncertainty, and ease of use.

3.3.1 Overcoming Barriers for Seismic Isolation

Key barriers to the adoption and diffusion of innovations in seismic isolation were the high perceived costs of carrying out seismic isolation, uncertainties about the technology, and a lack of standards or guidelines for the technology against which building officials and others could assess seismic isolation designs. Most of these have been addressed over time with some success, thereby enhancing the prospects for diffusion of seismic isolation technologies. Yet, as noted by Mayes (2002) seismic isolation is still perceived by many practicing professionals in the United States to be “expensive, complicated, and time-consuming.”

The costs of seismic isolation, as is true for most seismic design, depend on the specifics of the situation. A lot depends, as well, as to whether one considers the up-front costs of the technology, which tends to be a bit more expensive, or the life-cycle costs associated with the life of a given building or structure. As noted by Mayes (2002), a key difficulty in making such cost comparisons is the incommensurability of the performance goals of conventional and base-isolated designs. The former emphasize life-safety, while the latter typically involve a more stringent standard of continued operation. This difference in goals complicates cost comparisons.

One group of highly experienced engineers in using seismic isolation estimates that seismic isolation has a cost premium for UBC-designed buildings of 1 to 5 percent, but that it can be 5 to 10 percent less expensive for essential facilities that require higher design force levels (Mayes et al. 1990b: 260). For a fire command and control facility of the Los Angeles fire department Mayes (2002) cites a savings of 6 percent for the costs of base-isolated design compared to the costs of a conventional life-safety design, a savings that resulted mainly from the reduced seismic hardening of key contents when using base isolation. As this example illustrates, the experience with seismic isolation of high-valued facilities has been a key in a comparative performance advantage of seismic isolation for such facilities. It also suggests why base isolation has been more often used for essential and high-valued facilities than for other types of facilities.

An especially important development in the history of seismic isolation in this country was the 1985 construction of the first base-isolated building in the U.S., the Foothill Communities Law and Justice Center of San Bernardino County, California. As noted by other commentators (Olson and Lambright 1990), this building played an important role in gaining acceptance of the seismic isolation technology among the engineering profession as well as among prospective clients in the U.S. In the language of diffusion of innovations, this building addressed the trialability, relative advantage, cost, and uncertainty of the technology.

Of particular interest is why San Bernardino County would be an early adopter of the technology given the uncertainties and potential risks that were involved. That history has been related by Robert Rigney (1986), the county official who was largely responsible for the decision to base isolate the facility. Rigney was the county chief administrative officer who also had served as chair of the California Seismic Safety Commission. Consistent with organizations that are early adopters evidencing receptivity to change and learning, Rigney comments: “This is a County that takes great pride in winning and boasts of winning awards from the National

Association of Counties annual convention for innovation… The County has the right atmosphere for a favorable decision involving innovation… The decision makers of the County, the Board of Supervisors, were intrigued by the idea of being the first in a new field and were inclined to try it if there was not a heavy financial impact and if the engineering community would support it" (1986: 64–5). The decision, however, was not a straightforward one as much had to be learned in order to overcome the obstacles of unknown costs, uncertain comparative advantage, complexity, and other uncertainties. Even then, there was continued skepticism on the part of the insurance company for the building architect and among some within the design and engineering community.

The learning process for this county was facilitated by funding from the National Science Foundation that enabled the relevant decisionmakers to visit base-isolated structures in Japan and New Zealand and to visit laboratories developing the technology. Rigney comments that this fact-finding was "a necessary ingredient … [giving the decision-makers] the typical satisfaction of the purchaser of an automobile who slams the door to listen to the solid clunk, kick the tires, and adjust the mirrors before he is satisfied in investing his money in such a product" (1986: 66). Put in the language of the diffusion of innovations, this experience enhanced the observability of the technology while also reducing some of the uncertainties associated with it. Also important to this decision were several comparative cost analyses, independent review of alternative designs by a panel of experts, and NSF involvement in funding the bearing tests. The NSF and expert roles provided important legitimization to the technology in general and the design in particular for the Foothill building.

Also important for the legitimization of seismic isolation was the development of seismic standards for the technology. These included guidelines issued in 1989 by the Structural Engineers Association of California and other guidelines issued in 1989 by the California Office of Statewide Health Planning and Development (OSHPD). Both of these served to validate the technology as well as to provide a basis for evaluating the use of base isolation. These further enhanced the compatibility of the technology with alternative approaches. Subsequent design guidelines were developed as part of the UBC in 1991 for buildings, as part of the AASHTO guidelines in 1991 for bridges, and by the Structural Engineers of Northern California guidelines in 1993 for the design and implementation of energy dissipators.

While code provisions have been important for legitimizing seismic isolation, the requirements in the United States, at least, have arguably stifled adoption of the technology. Mayes (2002) is particularly critical of this in stating that "rather conservative and burdensome provisions in the building code" inhibit rather than encourage more widespread use of the technology. He cites, in particular, changes since 1994 in Uniform Building Code provisions concerning design requirements for the use of seismic isolation that increase the types of structures requiring dynamic time history analyses, increases in required design forces, extends extensive testing requirements of prototypes, and adds overly burdensome peer requirements.

As noted earlier, the diffusion of the seismic isolation technology has been more extensive in Japan and in New Zealand than in the United States. The diffusion of the technology in Japan, having overcome initial hurdles, has been rapid in comparison to the United States — especially in recent years. Kelly (1998) attributes this to the extensive expenditure of governmental funds on research and development of seismic isolation technology, the aggressive marketing of the technology by large construction companies, and a building approval process that understands the technology. Also relevant is that in Japan large construction companies undertake a more holistic design-build approach. This facilitates more innovation in design approaches, since the Japanese firms have the ability to trade off design and construction costs. When the two phases are separated, as typically the case in the United States, design costs are usually highly constrained and engineers typically do not have the flexibility to experiment with novel approaches.

Many of the barriers to seismic isolation still exist in at least some form given the still high perceived up-front costs of the technology, the sense that it is only appropriate for essential facilities, and remaining uncertainties over the technology. Yet, the technology has been effectively employed in the United States and has been more widely used in a number of other countries.

3.3.2 Overcoming Barriers for Load and Resistant Factor Design

Key barriers to the adoption and diffusion of LRFD were the lack of necessary computational power and analytic routines to carry out the necessary calculations, lack of data concerning performance of structures under different loads and their resistance, and reluctance of practicing engineers to adopt a methodology. This reluctance stemmed from the initial difficulty of carrying out the methodology given lack of easy-to-use computer routines, the added costs to design of conducting the required analyses, and the perceived reluctance of clients to pay those added costs. Unlike seismic isolation, for which the physical presence of base-isolated buildings served to demonstrate the feasibility of the technology, the benefits of LRFD were less observable. Nonetheless, the history of LRFD shows increasing acceptance of the need for the approach and of its applicability.

Three factors were critical in advancing the acceptance of LRFD. One critical factor was the development of workable LRFD methods and analytic routines that made LRFD a usable approach to seismic design. The latter were made possible by advances in both programming and in computing power. Without these, the second-generation inelastic analysis of LRFD would not be common.

A second critical factor was the development of the necessary data for deriving empirical relationships between seismic loads and the seismic resistance of different materials. This entailed extensive observation and laboratory experimentation. A key factor in making this possible was the academic-industry-professional research program undertaken from 1979 to 1985 for steel structures. Ellingwood describes this effort as "the paradigm for a collaboration of those in reliability research, a particular construction technology, and professional practice to work together to improve the process by which building structures are engineered" (2000: 109). This learning, much like the learning associated with experiences with seismic isolation, provided an important basis for gaining acceptance of the LRFD methodology among the design and engineering community.

A third critical factor was the development for a variety of construction materials of guidelines or standards for applying the LRFD methodology. In some instances, as was the case for the steel standards, debate over the possible outcomes of applying the LRFD methodology were a serious roadblock to gaining necessary consensus for moving standards along. This concern was partially addressed by efforts to calibrate LRFD approaches, where comparable, with conventional approaches. In other instances, as was the case for concrete standards, the profession was more accepting of the approach from the outset, thereby allowing for a more rapid process — still covering years — to refine and adopt standards. In any case, the guidelines, and standards that followed, provided important legitimization of the LRFD design methodology that was further accelerated by incorporation of the approach into several earthquake engineering textbooks.

Many of the initial barriers to adoption of the LRFD methodology have been eliminated as evidenced by the widespread acceptance of the methodology in existing guidelines, in engineering education, and in earthquake engineering practice. Critical factors facilitating the diffusion of LRFD were advances in computing and analytic routines for LRFD, compilation of essential data for establishing relevant protocols, issuance of standards and guidelines that incorporate LRFD, and education of a cadre of engineers with experience in the methodology.

3.4 APPLYING THESE LESSONS TO PBEE

Much needs to be accomplished in the research world concerning the PBEE methodology in order for it to move more fully from concept to practical application. This report does not address the challenges for refining the methodology, which is a subject for other reports by the Pacific Earthquake Engineering Research Center. The key point of this report is that implementation of PBEE applications will not occur, except in isolated cases, unless key barriers that are common to innovations in general and past earthquake engineering innovations in particular are overcome. The lessons reviewed here suggest that the key barriers and steps to overcoming them for PBEE are

- Overcoming uncertainty about the methodology and its benefits. This was a factor in both seismic isolation and LRFD for which practical applications and examples were important for addressing this barrier. In the case of PBEE, this requires clear and understandable explanation of the methodology accompanied by realistic applications of the methodology.

- Addressing concerns about the costs of employing the methodology. As was true for LRFD and is true today for seismic isolation, the concerns expressed by practicing engineers are that PBEE adds to the costs of design and that clients will be reluctant to pay those added costs given limited tangible benefits. An understanding of the costs of carrying out PBEE analyses is clearly essential for overcoming this barrier—whether more costly or not—along with clear evidence of the added value (benefits) of the PBEE methodology. Part of this is development of an understanding, as in the case of base isolation, of the circumstances for which PBEE methods are appropriate and those for which it is less appropriate.

- Addressing the complexity of the methodology and of required analysis procedures. Overcoming such complexity also requires clear and understandable explanation of the methodology, perhaps including simplified versions for some circumstances. Critical for this, as was the case for dissemination of LRFD, is development of user-friendly analytical routines for carrying out the necessary analyses for PBEE. A clear danger, which has hampered implementation of both LRFD and seismic isolation, is that the required analysis and quality assurance procedures within relevant codes for acceptance of PBEE designs will themselves be prohibitively complex and costly relative to the value added of the performance-based design.

- Legitimizing the methodology. Incorporation of the innovation into seismic guidelines and standards was essential for acceptance of seismic isolation and of LRFD. This will also be necessary for PBEE to be viewed as an acceptable, if not preferred, methodology for seismic design. Clearly, codification of the PBEE methodology, is not automatic—as is evident in the extreme from the 15-year period for LRFD to be incorporated into steel code provisions. At present PBEE concepts are being incorporated into building codes (e.g., International Performance Code, NFPA 2002 Building Code, SEAOC 1999 guidelines). But, these provisions are not consistent and fall far short of the expectation of reliable quantification of prospective performance.

- Establishing comparative advantage. Convincing evidence, in the form of well-documented case studies, needs to be developed to demonstrate that PBEE provides at least as reliable and useable results as more traditional design and engineering methods. If that is not always the case, as noted above, the circumstances for which PBEE is appropriate and of less value need to be clearly identified.

- Facilitating early adoption. The willingness of San Bernardino County to employ base isolation for the Foothill Communities Center serves as a prime example of the effects of early adoption of an engineering innovation. As suggested in the above review of the literature about early adopters, some organizations are more likely to fulfill this role than others. Nonetheless, the diffusion of PBEE methodologies will be enhanced if such prospective engineering organizations can be identified and steps taken to ease their initial adoption of the nascent PBEE methodology. This may include special funding, technical assistance, or recognition for these efforts, much as the computer industry facilitates early adopters of new computing technologies. Another important point, which is analogous to the computer industry as well, is the use of evangelists to promote the benefits of new technologies.

These steps will help facilitate adoption of PBEE by the engineering profession and help create greater capacity for undertaking PBEE. However, these steps will not increase the demand for PBEE or bring about the more fundamental changes in thinking about earthquake risks by building owners, the financial community, or public officials that are necessary for PBEE to reach its fullest capabilities. These are broader transformations of thinking about earthquake risks that require the design community to be at the leading edge of explaining to clients how to think about choices and tradeoffs in seismic design as they become more transparent with the application of performance-based earthquake engineering analyses.

4 Conclusions

The promise of performance-based earthquake engineering requires more than development of sound methodologies and analytic tools. Such advances will be left on the conceptual drawing boards unless they are adopted by the engineering profession and are effectively used to inform seismic safety decisions. This report has considered prospects for adoption of PBEE innovations by the design community and for use of the innovations in making decisions about seismic performance more generally. The relevant literature concerning adoption of innovations has been considered and case studies have been presented regarding innovation in seismic isolation, load and resistance factor design, and performance-based earthquake engineering.

It is difficult at this point to gauge the speed with which innovations in performance-based earthquake engineering will be adopted and implemented. Although code guidelines addressing performance-based approaches have been developed, rigorous methods and techniques for performance-based earthquake engineering are still largely on the drawing board. New seismic provisions and some engineering practice, especially with respect to the rehabilitation of buildings, have incorporated performance-based concepts. However, many engineers are just learning about performance-based earthquake engineering. And, under current ways of doing business, building owners, insurers, and other stakeholders only rarely explicitly engage in discussions of desired performance levels.

Patterns in other earthquake innovations, reviewed in this report, suggest that it takes at least two decades to move beyond the initial threshold of early applications and guidelines to widespread adoption of the innovation. If that pattern holds for PBEE, and if one argues that the initial threshold was reached in the mid to late 1990s, it will be at least another 15 years before PBEE gains widespread currency. Even within a 15-to-20-year time frame, such adoption and implementation are far from assured.

For PBEE innovations to gain widespread currency a number technical and decision-related challenges must be addressed. The challenges that PBEE faces for adoption and implementation are arguably more daunting than those previously confronting seismic isolation or load and resistance factor design. Nonetheless, there are important lessons from the history of each. Key barriers to the adoption and diffusion of innovations in seismic isolation were the high perceived costs of carrying out seismic isolation, uncertainties about the technology, and a lack of standards or guidelines for the technology against which building officials and others could assess seismic isolation designs. Key barriers to the adoption and diffusion of LRFD were the lack of necessary computational power and computing routines to carry out the necessary calculations, lack of data concerning performance of structures under different loads and their resistance, and reluctance of practicing engineers to adopt the methodology.

Much still needs to be accomplished concerning the PBEE methodology in order for it to move more fully from concept to practical application. The lessons reviewed here suggest that the key barriers and steps to overcoming them for PBEE are (1) overcoming uncertainty about the PBEE methodology and its benefits by illustrating case application of the methodology; (2) addressing concerns about the costs of employing the methodology by developing an understanding of relevant costs and factors that affect them; (3) addressing the complexity of the methodology; (4) legitimizing the methodology by working to develop standards and guidelines that endorse the approach; (5) establishing a comparative advantage by developing an understanding of the circumstances for which PBEE is a preferred methodology; and (6) facilitating early adoption by leading engineering organizations.

These steps will help facilitate adoption of PBEE by the engineering profession and help create greater capacity for undertaking PBEE. However, these steps will not increase the demand for PBEE or bring about the more fundamental changes in thinking about earthquake risks by building owners, the financial community, or public officials that are necessary for PBEE to reach its fullest capabilities. These broader transformations of thinking about earthquake risks require the design community to be at the leading edge of explaining to clients how to think about choices and tradeoffs in seismic design as they become more transparent with the application of performance-based earthquake engineering analyses.

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