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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. Although code provisions containing performance-based concepts have been adopted in several countries, rigorous methods and techniques for performance-based earthquake engineering are still largely on the drawing board. For PBEE innovations to gain widespread currency a number technical and decision-related challenges must be addressed. These challenges are arguably more daunting than those previously confronting seismic isolation or load and resistance factor design. The lessons reviewed here from those experiences 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.

1 INTRODUCTION

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 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.

At present, PBEE represents both a conceptual approach and an evolving design 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 change in design philosophy from prescriptive- to performance-based design. The evolving methodology is a more rigorous approach to earthquake engineering that clearly and quantitatively specifies different levels of performance as a basis for seismic design. 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 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 ways from the research laboratory to actual practice.

This paper considers potential barriers to the adoption and implementation of PBEE methodologies and tools. There are four parts to the discussion. The challenges for decision-making that PBEE poses are first considered. This is followed by a brief discussion of the literature on adoption and diffusion of innovations. The third part of the paper contrasts the PBEE experiences to date with the history of seismic isolation and history of load and resistance factor design. The final part of the paper considers lessons for overcoming barriers to adoption and implementation of PBEE innovations.

2 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 by decision-makers that the buildings will perform as stated.

Achieving the benefits of PBEE advances is far from automatic as they entail fundamental changes in engineering practice and in decision-making about seismic risks (see May 2003). 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 centres, 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.

For PBEE to be effective, the design professions—architects, engineers, and professionals responsible for the design of structural and non-structural 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 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.

Another issue is the degree to which the building regulatory system is able to adjust to the PBEE approach. Due 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 in the United States 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 (International Code Council 2001). The PBEE concepts are also being incorporated into the National Fire Protection Associations' 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 they relate to the rehabilitation of existing buildings. This problem is not unique to the United States and is a central consideration for countries (Australia, Canada, England and Wales, Japan, Netherlands, New Zealand, and the United States) that have incorporated performance-based concepts into building code provisions (see Beller et al. 2002).

A larger set of considerations is the choices that governmental officials face in regulating seismic safety (see May 2001). These include establishment of regulatory standards (i.e. minimum performance levels) for all structures, establishment of desired performance objectives for public facilities, and establishment 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 decision-making. 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 PATTERNS IN ADOPTION OF INNOVATIONS

The extensive literature concerning adoption and implementation of innovations provides a backdrop for considering the prospects for performance-based earthquake engineering. That literature is briefly reviewed in this section.

3.1 Diffusion of innovations

Innovations are either new breakthroughs, or more often, 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, new ways of thinking about performance targets or presentation of analytic results, or technological innovations such as new analysis tools.

The literature about diffusion of innovations provides insights concerning opportunities and obstacles to adoption and implementation. Diffusion scholars find that adoption tends to follow an "S-shaped" pattern as illustrated in Figure 1 for one hypothetical innovation. As discussed by 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.

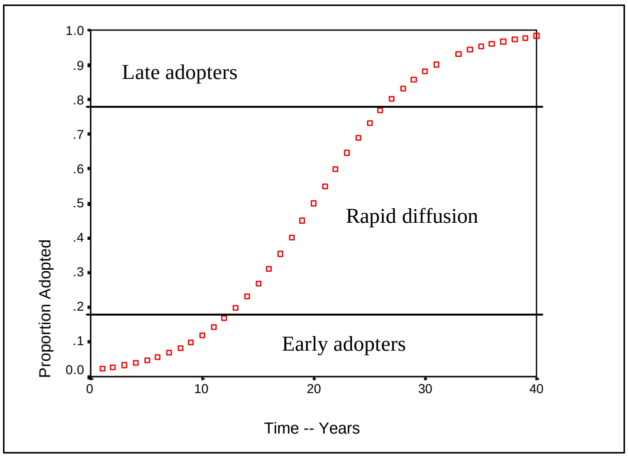

Figure 1. Typical pattern for diffusion of innovations

The most common explanation for this pattern is what has been labelled the epidemic model of information diffusion (Geroski 2000). According to this, 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. A central element in all of this is a diffusion network made of the interpersonal ties among individuals and firms that serve as information flows about innovations. Networks can be comprised of ties with individuals within a firm, among suppliers or competitors, or among professional trade associations or other organized interest groups.

3.2 Factors affecting adoption of innovations

One line of research on adoption of innovations considers characteristics of the innovation itself. Rogers (1995: 208) describes five attributes that affect adoption of innovations: (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. Increased complexity has been associated with lesser rates of adoption.

Another line of research addresses differences among firms that are early and later adopters of innovations. 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 adoption of new business strategies, several organizational factors are potentially relevant. One is an organization's receptivity to change and learning. Ironically, the research suggests that highly successful organizations tend to be more resistant to change, although there are plenty of counter examples to this general point. 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.

4 PATTERNS FOR INNOVATIONS IN EARTHQUAKE ENGINEERING

The broad literature on 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 (PBEE). Table 1 provides an overview summary of the stages of innovation and adoption as these relate to buildings, based on secondary accounts of each of the engineering innovations.

4.1 Seismic isolation

Seismic isolation is a concept that is 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 US 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 US. 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 noted by Mayes in commenting: “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).

4.2 Load and resistance factor design

Load and Resistance Factor Design (LRFD), also known as limit states design, is interesting 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. 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 standard setting for steel, concrete, aluminum, bridge, and wood structures (Galambos 1998). 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 further dissemination requires wider education of practicing engineers about the design approach and development and testing of reliable software for LRFD for a range of structures (also see Ellingwood 2002).

Table 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 US 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

4.3 **Performance-based earthquake engineering**

In comparison to seismic isolation and LRFD, performance-based seismic design is in its infancy. 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 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 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 concepts of performance-based codes were advanced in the United States 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 (Ellingwood 2001). 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 cataloguing 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 subsequent development of guidelines for seismic rehabilitation of buildings.

Interest in performance-based approaches to seismic design and engineering in the United States 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 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 centres, hospitals, and utility facilities–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 specified more stringent requirements for higher-rated uses, such delineation does not adequately convey desired performance.

4.4 Prospects for diffusion of PBEE innovations

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 provisions addressing performance-based concepts have been adopted in several countries, 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.

5 OVERCOMING CHALLENGES FOR PBEE

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. 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.”

Much needs to be accomplished in the research world concerning the PBEE methodology in order for it to move more fully form concept to practical application. The key point of this paper 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 initially for LRFD and continues to be true today for seismic isolation, there is a concern that has been expressed by practicing engineers 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 in the United States (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 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*. 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 prospective early adopters 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.

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 with the application of performance-based earthquake engineering analyses

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