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GROUND MOTION HAZARD EVALUATION FOR PERFORMANCE-BASED EARTHQUAKE ENGINEERING DESIGN OF TALL BUILDINGS

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ABSTRACT

Tall buildings in high seismic regions are being designed using performance-based earthquake engineering (PBEE) principles under alternative design provisions that may be allowed in the current building codes. Still-evolving PBEE design criteria for tall buildings generally require that these buildings be designed for collapse prevention under a very rare earthquake (with a long recurrence interval, on the order of 2,475 years in the United States). Alternative design criteria for tall buildings generally permit deviations from prescriptive building code provisions, thus allowing for greater building heights, more use of high strength materials, and less structural redundancy among other things. Because of the deviations from prescriptive provisions, nonlinear response history analysis is required. However, when using probabilistic seismic hazard analysis, the ground motions developed for very rare earthquakes are dominated by uncertainties. There is great difficulty in identifying or developing realistic strong ground motion time histories for these rare events. In addition, trying to account for source-to-site effects such as basin, near-source, and directivity effects becomes increasingly complex. Developing representative ground motion time histories may involve scaling or modification of actual time histories, in either the time or frequency domains, to match the target design response spectrum. Changes in the methods to define more realistic ground motions for design are needed.

Introduction

In the planning and design of tall buildings, especially in economically trying times, the design profession is challenged to provide constructability, sustainability, safety, and affordability in taller and taller buildings. Many of these new tall buildings are pioneering efforts are pushing the limits on height, slenderness, and light weight materials. In high seismic regions, the task of design of tall buildings is ever more challenging because of seismic requirements. Although there is not an established definition of “tall building,” this paper will generally refer to buildings as having a height of 160 feet (about 47 meters) above grade as being “tall buildings.”

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The 2006 International Building Code or "IBC" (International Code Council, 2006) is the current governing building code in the United States, and is essentially the de facto national building code. The IBC provides regulations applying "…to the construction, alteration, movement, enlargement, replacement, repair, equipment, use and occupancy, location, maintenance, removal and demolition of every building or structure or any appurtenances connected or attached to such buildings or structures." The seismic design provisions of the IBC are the requirements of "ASCE 7" (American Society of Civil Engineers, 2006) which are incorporated by reference. The IBC governs the design of all normal building structures ranging from the most simple to the most sophisticated structural systems, and from short to tall in height.

It is generally accepted that knowledgeable design professionals have come to believe that the design of tall buildings using the current building code does not allow for the best use of structural systems and building materials to provide safe and predictable performance in high seismic regions. The building code contains many prescriptive requirements, limitations on permissible structural systems and restrictions on building height. As the building code is intended to provide regulations and guidance for design of all structures, it has been calibrated for the lower rise construction that is much more prevalent in the building stock. Also, the prescriptive requirements such as the requirements for structural detailing are intended to protect the public from a broader and less sophisticated design community than those in the specialized tall building design community, which arguably has more resources and a deeper understanding of complex structures and analytical techniques. It is generally accepted that a tall building designed in strict accordance with the building code is more costly and likely more difficult to construct, without the benefit of necessarily being a safer structure.

Alternative Design Procedures for Tall Buildings

Both the IBC and ASCE 7 documents permit the use of "alternate materials and methods of construction" to those prescribed in their respective seismic requirements with the approval of the regulatory agency having jurisdiction. Thus the use of Performance-Based Earthquake Engineering (PBEE) techniques may be used in the design of tall buildings. PBEE allows the opportunity to use new and innovative technologies in the structure and may remove arbitrary height limitations set by the code.

In general, the use of PBEE for the design of tall buildings will require nonlinear time history structural analysis. In addition, the PBEE process of developing design criteria, design ground motions, building modeling, and structural analysis will likely require peer review by an independent panel of experts (with the approval of the building department or jurisdictional agency).

As there is the need for guidance for alternative design procedures for PBEE as applied to tall buildings, several initiatives have been underway to provide such guidance. In 2005, the Los Angeles Tall Buildings Structural Design Council (LATBSDC) published an alternative procedure for a performance-based approach for seismic design and analysis of tall buildings in the Los Angeles, California (LATBSDC, 2005); a revision and update of the 2005 document was published in 2008 (LATBSDC, 2008) and subsequent revisions have also been published (LATBSDC, 2009).

Following the publication of the 2005 LATBSDC document, discussions about the application of PBEE in other seismic regions, including San Francisco, California, were under way. At the request of the City of San Francisco Department of Building Inspection, a document entitled Recommended Administrative Bulletin on the Seismic Design and Review of Tall Buildings Using Non-Prescriptive Procedures was developed and published by the Structural Engineers Association of Northern California (SEAONC, 2007). This document is the basis of Administrative Bulletin 083 (AB-083), issued by the City of San Francisco Department of Building Inspection to guide tall building design using alternative procedures. AB-083 is not a purely performance-based guideline for seismic design, but is rather closely tied to the San Francisco Building Code in an effort to address whether a non-prescriptive design meets the code standard of "at least equivalent" seismic performance.

The Pacific Earthquake Engineering Research Center (PEER) at Berkeley, California has undertaken the "Tall Buildings Initiative" to develop guidelines for seismic design of tall buildings using PBEE design principles. The Tall Buildings Initiative (TBI) intends to develop a framework for seismic design of tall buildings, summarized in a final guidelines document containing principles and specific criteria for tall building seismic design. The document is intended to support ongoing guidelines and code-writing activities of collaborating organizations, as well as being a stand-alone reference for designers of tall buildings. Information may be found at http://peer.berkeley.edu/tbi/index.html. The Tall Buildings Initiative draft guidelines are available at this website and are expected to be published in final form in the near future.

Specification of Ground Motions for Design

The specification of the ground motions is the most important input for performance-based engineering analysis and design in high seismic regions. The ground motions will govern the design of the lateral resisting system of the building in high seismic regions. Wind will more than likely govern the design of the lateral resisting system in low and moderate seismic regions, rather than seismic forces.

The LATBSDC and AB-083 guideline documents both recommend that three-dimensional nonlinear response history (NLRH) analyses of the tall building be performed for the Maximum Considered Earthquake (MCE) ground motions; this level of hazard is to ensure that the tall building would have a very low probability of collapse during an extreme event. MCE ground motions are defined in Chapter 21 of ASCE 7. The MCE ground motions have both probabilistic and deterministic criteria, with the probabilistic criteria specified as corresponding to the risk of a 2 percent probability of being exceeded within a 50-year period (return period of 2,475 years).

In addition to the MCE ground motions, the LATBSDC document recommends an evaluation for a service level design earthquake. The purpose of the service level design earthquake is to validate the building's structural and nonstructural components and attachments retain their general functionality during and after a smaller and more frequent design earthquake that is very likely to occur during the lifetime of the tall building. The service level design earthquake has been defined as an event having a 50 percent probability of being exceeded in 30 years (43-year return period). Repairs, if necessary, are expected to be minor and could be performed without substantially affecting the normal use and functionality of the building. It is not intended that the structure remain fully linear elastic for the service level ground motions. The serviceability analysis is permitted to indicate minor yielding of ductile elements of the primary structural system provided such results do not suggest appreciable permanent deformation in the elements, or structural damage to the elements requiring more than minor repair. The AB-083 guideline also has a similar serviceability evaluation requirement. The TBI guidelines will likely also have a serviceability evaluation requirement, but the service level design earthquake may be defined differently.

Ground Motion Response Spectra

This discussion of ground motions will be limited to the MCE ground motions as it is likely that three-dimensional NLRH analyses would be required for the evaluation of collapse prevention if performing a PBEE evaluation. ASCE 7 (ASCE, 2006) Chapter 21 provides procedures for the determination of site-specific ground motions for seismic design. According to ASCE 7, the ground motion hazard analysis shall account for the regional tectonic setting, geology, and seismicity, the expected recurrence rates and maximum magnitudes of earthquakes on known faults and source zones, the characteristics of ground motion attenuation, near source effects, if any, and the effects of subsurface site conditions on ground motions.

ASCE 7 allows for the ground motions to be determined by a combination of probabilistic and deterministic methods to define the MCE elastic spectral response accelerations. The probabilistic MCE response accelerations are taken as the spectral response accelerations represented by a 5 percent damped acceleration response spectrum having a 2 percent probability of being exceeded within a 50-year period; this is determined by probabilistic seismic hazard analysis or "PSHA" (Cornell, 1968). The deterministic MCE response acceleration at each period per ASCE 7 is calculated as 150 percent of the largest median 5 percent damped spectral response acceleration computed at that period for characteristic earthquakes on all known active faults within the region. The site specific MCE spectral response acceleration at any period is taken as the lesser of the probabilistic and deterministic MCE spectral response accelerations. However, the ordinates of the deterministic MCE ground motion response spectrum cannot be taken as being lower than the minimum deterministic spectrum as determined by factors in ASCE 7.

Since time histories are to be used in the NLRH analyses, it is common practice that the probabilistic MCE spectral response be used rather than the hybrid probabilistic MCE spectral response with a deterministic MCE cap as would be determined if following the IBC and ASCE 7. Because of the extremely long probabilistic MCE recurrence interval, the epistemic uncertainty of the PSHA will be quite large due to the lack of full knowledge about generation and propagation of ground motions.

An example of a 5 percent damped probabilistic MCE response spectrum (performed by a PSHA) for a site in downtown Los Angeles is shown in Fig. 1. The site is Site Class "C" as defined in the IBC code with a soil shear wave velocity in the upper 30 meters of about 360 meters per second. The United States Geological Survey fault model (USGS, 2002) was used in the PSHA analysis which was performed by the computer program EZ-FRISK (Risk Engineering, 2007). Three attenuation relations from the Next Generation Attenuation (NGA) project (Power et al., 2008) were used in the analysis: Boore and Atkinson (2008); Campbell and Bozorgnia (2008); and Chiou and Youngs (2008). Each of the attenuation relations was weighted equally to develop an average recommended spectrum. The NGA attenuation relations allow for the determination of spectral accelerations up to a period of 10 seconds; earlier attenuation relations that were used prior to the development of the NGA relations were reliable up to periods of 5 seconds or less. Near-source and basin effects were not considered in the PSHA analyses for this example.

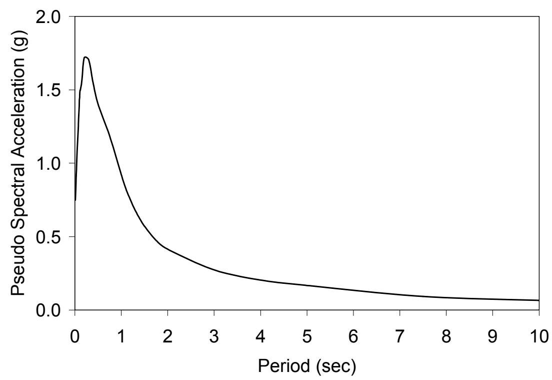

Figure 1. Probabilistic MCE response spectrum for site in downtown Los Angeles (5 percent critical damping)

The PSHA analysis considers a multitude of earthquake occurrences, and produces an integrated description of seismic hazard representing all specified events. Thus the resulting response spectrum includes relatively large spectral ordinates across a wide range of structural periods, not typical of a single earthquake shaking event, which tends to have a response spectrum much more narrowly focused across a smaller range of periods. The deaggregation of the seismic hazard for the downtown Los Angeles site for various periods is shown in Fig. 2. From the deaggregation analysis, it is obvious that different magnitude events on different fault systems at different distances contribute to the overall seismic hazard in downtown Los Angeles. It is also apparent that as the structural period of interest changes, the source of hazard also changes; in particular, as the period increases, larger magnitude earthquake events on more distant faults contribute more to the seismic hazard. At short periods, the seismic risk is dominated by smaller magnitude earthquakes on faults located close to the site.

Ground Motion Time Histories

Chapter 16 of ASCE 7 provides guidance on the development of ground motion acceleration time histories for linear and nonlinear response history analyses. ASCE 7 specifies that a suite of not less than three appropriate ground motions be used in the analysis. If at least seven ground motions are analyzed, in general, the average forces and drifts may be used; if less than seven ground motions are analyzed, the design member forces and design story drift shall be taken as the maximum value determined from the analyses.

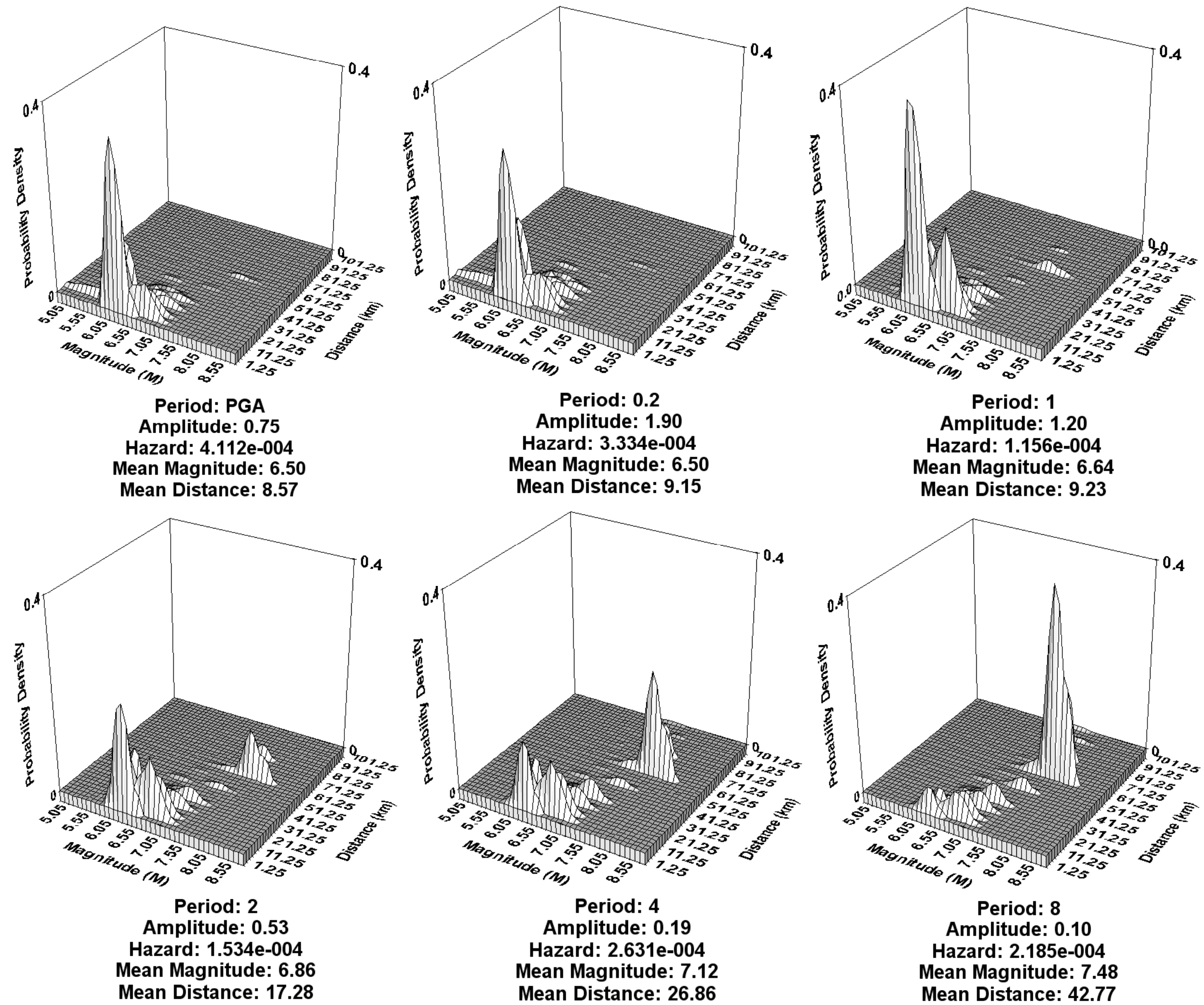

Figure 2. Deaggregation of seismic hazard for MCE for site in downtown Los Angeles for periods of 0.0 sec (PGA), 0.2 sec, 1.0 sec, 2.0 sec, 4.0 sec, and 8.0 sec; distances in kilometers

If possible, each ground motion consists of a horizontal acceleration history (pair of orthogonal components), selected from an actual recorded event. The records should be from events having magnitudes, fault distance, and source mechanisms that are consistent with those that control the MCE response spectrum. If a sufficient number of appropriate recorded ground motion pairs are not available, ASCE 7 allows for simulated ground motion pairs to be used. For two-dimensional analysis, the ground motions are to be scaled such that the average of the 5 percent damped response spectra for the suite of motions is not less than the design spectrum for the site for periods ranging from $0.2T$ to $1.5T$, where T is the natural period of the structure in the fundamental mode for the direction of response being analyzed. For three-dimensional analysis, the square root of the sum of the squares (SRSS) spectrum of the 5 percent-damped response spectra is computed for each pair of horizontal ground motion components; each pair of motions is to be scaled such that for each period between $0.2T$ and $1.5T$, the average of the SRSS spectra from all horizontal component pairs does not fall below 1.3 times the corresponding ordinate of the design response spectrum by more than 10 percent.

To perform the spectral matching for the time histories, there are basically two commonly used approaches: (1) multiply the time histories by a constant factor to meet the requirements of ASCE 7; (2) modify the frequency content of the time histories such that the requirements of ASCE 7 are matched (spectral matching). For the second method, usually each time history is modified such that its spectrum is closer to the target spectrum. From a practical point of view, matching by arithmetic scaling of the time histories is extremely difficult because of the nature of the MCE response spectrum. The MCE spectrum for a region like Los Angeles does not represent any singular earthquake event; rather, it is the blending of multiple events with smaller and larger earthquake magnitudes, occurring on different types of faults, at varying distances from the site of interest. Fig. 3 shows the MCE spectrum with spectra from several recorded time histories in recent earthquakes that are typically used for matching; only one of the horizontal components is shown for each time history in Fig. 3.

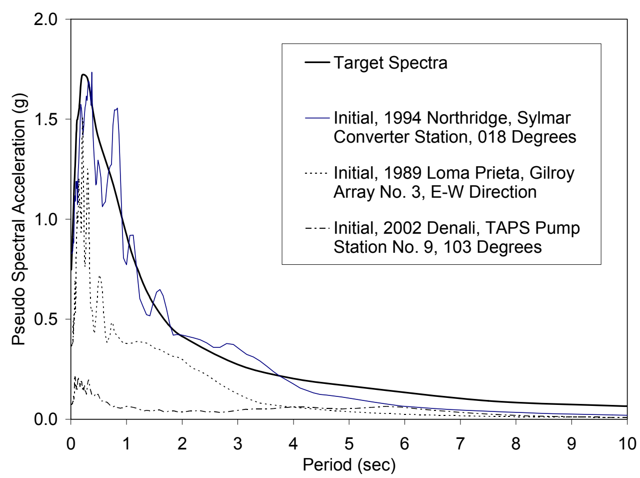

Figure 3. MCE spectrum with original response spectra from several recorded events

Because of the breadth of the $0.2T$ to $1.5T$ period range that the target spectrum is to be met, arithmetic scaling often results in the time histories being so amplified that the energy content of the matched time histories is unrealistically high at most periods. Most commonly, spectral matching is performed to match the target spectrum by the RSPMATCH procedure (Abrahamson, 1998), a time domain method which adds wavelets to the time histories near the time of the peak response while maintaining the main non-stationary characteristics of the original time history.

The selection of candidate time histories for matching to the target MCE spectrum can be challenging. The records are to be from events having magnitudes, fault distance, and source mechanisms that are consistent with those that control the MCE. Despite the increase in number of available time histories with more earthquakes and more databases such as the NGA database (Chiou, Darragh, Gregor and Silva, 2008), there are still deficiencies in the available records in meeting the code's requirements. In particular, records for large magnitude events in the near and far field are still lacking. Many earlier time histories do not have reliable information for longer periods beyond 2 to 5 seconds. As can be seen in Figure 3, no single event response spectra can represent well the conglomerated nature of the MCE target spectrum. Significant modifications of the seed time histories are needed such that the spectra match the MCE target spectrum for tall buildings which may have fundamental periods greater than 5 seconds. In the case of the distant Denali event, significant large amplification of the shorter period motions is added to the event to meet the target spectrum, which would create a very unrealistic time history.

Fig. 4 illustrates the results of the downtown Los Angeles MCE response spectrum matching on one horizontal component of one of the seed time history records. The acceleration-, velocity- and displacement-time histories are shown for the original seed and matched spectra.

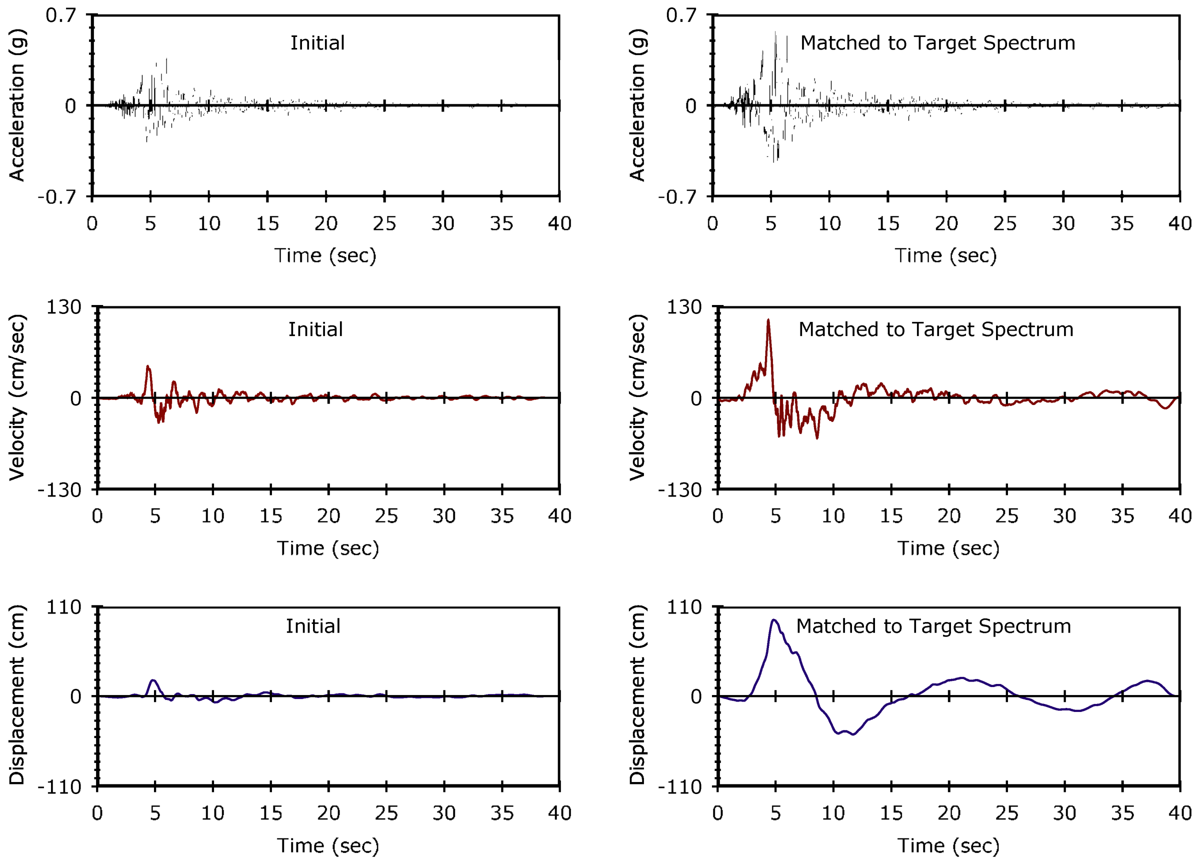

Figure 4. Original and Matched Time Histories for MCE - From 1994 Northridge earthquake, Sylmar Converter Station, Component 018 degrees

It should be noted that if near-source or basin effects are to be incorporated into the ground motion analysis, then the time histories would need to be from those records that have these effects in the original recordings. This could further limit the number of records available for matching to the target spectrum.

Other Ground Motion Considerations

From the author's experience there are other issues related to ground motions that present challenges. As mentioned earlier, there are definite deficiencies in the available earthquake time histories that can be used in design. There is still a lack of large to great magnitude ground motion recordings, particularly in the near source region.

Characterization of near-source directivity in the ground motions is still crude. Although consideration of near source directivity effects has been incorporated in PSHA applications (such as EZ-FRISK) to be able to compute fault normal and fault parallel directivity components, the mathematical formulations do not presently take into consideration the orientation of the normal and parallel components and accumulate the effects regardless of fault orientation to the site; thus PSHA fault normal components may be conservatively estimated. Also, the most common method used to determine directivity effects is the combination of the seminal works by Somerville et al. (1997) and Abrahamson (2000). Current research on near-source directivity being conducted as part of the NGA project indicates that the impact of directivity may not be as great as predicted by Somerville et al. and Abrahamson (Bozorgnia, 2009); the results of this research are expected to be published in the near future.

The current practice of having earthquake time histories meet a minimum target spectrum of ground motions determined by a PSHA procedure leads to time histories that are neither realistic nor reasonable. As the uniform hazard spectrum represents the contributions of hazard from various sources at different distances from a site over the entire range of periods of interest, it cannot be represented by a single earthquake time history unless there is massive modification of the time history in the time and/or frequency domain, which would lead to excessive energy content at many periods that would not be present in a typical time history (because of the minimum scaling requirements in the building code). A possible solution to this situation would be to specify a suite of ensemble ground motions representing different scenario earthquakes which would affect the various modes of vibration of the structure. This would require much more computational effort than is currently used with present procedures and may not be practical or economical at this time. This may also require the use of synthetic time histories as there may not be sufficient recorded time histories available.

Conclusions

The specification of the ground motions is an important part of PBEE design of tall buildings in high seismic regions. When nonlinear response history analyses are required, the seismic input (design spectrum and time histories) will determine the adequacy of the design for collapse prevention and serviceability. The specification of the ground motion input is an imperfect science and there are inadequacies in the procedures and technologies used in the development of the ground motion response and the time histories. Changes in time history specification are needed to provide better representation of design ground motions.

References

Abrahamson, N.A., 1998. Non-stationary spectral matching program RSPMATCH. Pacific Gas &

Electric Company Internal Report.

American Society of Civil Engineers, 2006. Minimum Design Loads for Buildings and Other Structures, ASCE Standard ASCE/SEI 7-05, USA.

Boore, D.M. and G.M. Atkinson, 2008. Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s. *Earthquake Spectra*, **24:1**, 99-138.

Bozorgnia, Y, 2009. Personal Communication.

Campbell, K.W. and Y. Bozorgnia, 2008. NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s. *Earthquake Spectra*, **24:1**, 139-171.

Chiou, B., R. Darragh, N. Gregor, and W. Silva, 2008. NGA Project Strong-Motion Database. *Earthquake Spectra*, **24:1**, 23-44.

Chiou, B.S.-J. and R.R. Youngs, 2008. An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthquake Spectra*, **24:1**, 173-215.

Cornell, C.A.. 1968. Engineering Seismic Risk Analysis. *Bulletin of the Seismological Society of America,* **58,** 1583-1606.

International Code Council, 2006. 2006 International Building Code. ICC, USA.

Los Angeles Tall Buildings Structural Design Council, 2005. An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region. LATBSDC, Los Angeles, CA USA.

Los Angeles Tall Buildings Structural Design Council, 2008. An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region, 2008 Edition. LATBSDC, Los Angeles, CA USA.

Los Angeles Tall Buildings Structural Design Council, 2009. 2009 Revisions to an Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region. LATBSDC, Los Angeles, CA USA.

Power, M., B. Chiou, N. Abrahamson, Y. Bozorgnia, T. Shantz, and C. Roblee, 2008. An Overview of the NGA Project. *Earthquake Spectra*, **24:1**, 3-21.

Structural Engineers Association of Northern California, 2007. Recommended Administrative Bulletin on the Seismic Design & Review of Tall Buildings Using Non-Prescriptive Procedures. San Francisco, CA USA.

United States Geological Survey, 2002. Seismic Hazard Mapping Project. U.S. Geological Survey Open-File Report 02-467, Version 1.0.