

CHALLENGES IN SPECIFYING GROUND MOTIONS FOR DESIGN OF TALL BUILDINGS IN HIGH SEISMIC REGIONS OF THE UNITED STATES

Marshall Lew,¹ Farzad Naeim,² Martin B. Hudson³ and Boris O. Korin⁴

¹ Senior Principal, MACTEC Engineering and Consulting, Inc., Los Angeles, CA USA

² Vice President and General Counsel, John A. Martin & Associates, Los Angeles, CA USA

³ Chief Engineer, MACTEC Engineering and Consulting, Inc., Los Angeles, CA USA

⁴ Senior Engineer, MACTEC Engineering and Consulting, Inc., Los Angeles, CA USA

ABSTRACT :

Many tall buildings in high seismic regions of the United States are being designed using performance-based earthquake engineering principles under alternative design provisions allowed in the current building code. Still-evolving 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). Alternative design criteria for tall buildings generally specify some 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. However, because of the deviations from prescriptive provisions, nonlinear time history analysis is required. 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 response spectrum. Alternatively, artificial time histories may be generated to match the target response spectrum. Advances in ground motion simulations of time histories for model events also hold some promise. There is a great challenge in specifying the ground motions for realistic analysis to result in safe and economical design of tall buildings in high seismic regions.

KEYWORDS: GROUND MOTIONS, TALL BUILDINGS, PERFORMANCE-BASED EARTHQUAKE ENGINEERING

1. DESIGN OF TALL BUILDINGS

The recent resurgence in tall building construction in the United States has been a challenge to the design profession in its quest to provide safety, constructability, sustainability, and affordability in ever taller buildings, many of which are pioneering efforts having no prior peer or similar model. In high seismic regions, the task of design of tall buildings is ever more challenging because of the seismic requirements. Although there is not a formal definition of “tall building”, we will generally refer to buildings as having a height of 160 feet (about 47 meters) above grade as being “tall buildings.”

In the United States, the basic building code is the 2006 International Building Code or “IBC” (International Code Council, 2006) which has been adopted almost universally as the 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 is included by reference. With such a broad-reaching scope, the IBC applies to all structures ranging from the most simple to the most sophisticated structural systems, and from short to super tall in height.

Design professionals have come to believe that the design of tall buildings using the current U.S. building code does not allow for the best use of structural systems and building materials to provide safe and predictable performance when subjected to strong earthquake ground motions. 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 design community than those in the tall building design community, which has more resources and a deeper understanding of complex structures and analytical techniques. A tall building designed in strict accordance with the building code is generally believed to be more costly and likely more difficult to construct than the same building designed using alternative design procedures, without the benefit of necessarily being a safer structure.

2. ALTERNATIVE DESIGN PROCEDURES FOR TALL BUILDINGS

The IBC and ASCE 7 documents permit the use of “alternate materials and methods of construction” to those prescribed in their seismic requirements with the approval of the regulatory agency having jurisdiction. Thus the door is open to the use of Performance-Based Earthquake Engineering (PBEE) techniques in the design of tall buildings. In general, the use of PBEE for the design of tall buildings will require nonlinear time history analysis. In addition, the PBEE process of developing design criteria, design ground motions, building modeling, and structural analysis will likely be peer reviewed 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 produced an alternative procedure for a performance-based approach for seismic design and analysis of tall buildings (LATBSDC, 2005); this alternative procedure was revised and updated in 2008 (LATBSDC, 2008).

Following the publication of the 2005 LATBSDC document, discussions about the application of PBEE were being discussed in other locations, including the City of San Francisco. 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 presented by the Structural Engineers Association of Northern California (SEAONC, 2007). This document is the basis of Administrative Bulletin 083 (AB-083), issued by the 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.

At the present time, the Pacific Earthquake Engineering Research Center (PEER) is leading the Tall Buildings Initiative to develop PBEE design criteria for safe and usable tall buildings following future earthquakes. The Tall Buildings Initiative 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 high-rise buildings. Information about the Tall Buildings Initiative may be presently found at http://peer.berkeley.edu/research/tall_building.html.

3. GROUND MOTIONS

The specification of the ground motions is undoubtedly the most important input for performance-based engineering analysis and design in high seismic regions. The ground motions in high seismic regions will most

probably govern the design of the lateral resisting system of the building. In low and moderate seismic regions, the design of the lateral resisting system will likely be governed by wind rather than seismic forces.

Both the LATBSDC and AB-083 documents recommend that three-dimensional nonlinear response history (NLRH) analyses be performed for the Maximum Considered Earthquake (MCE) ground motions to ensure that the building would have a very low probability of collapse during an extreme event. The 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 exceedance within a 50-year period, corresponding to a return period of 2,475 years.

The LATBSDC document recommends an evaluation to validate that the building's structural and nonstructural components and attachments will retain their general functionality during and after a service level design earthquake. The service level design earthquake is defined as an event having a 50 percent probability of being exceeded in 30 years, which corresponds to an event with a 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. AB-083 also has a similar serviceability evaluation requirement.

3.1. 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. 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 with a probabilistic seismic hazard analysis or "PSHA" (Cornell, 1968). The deterministic MCE response acceleration at each period 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 ordinates of the deterministic MCE ground motion response spectrum cannot be taken as being lower than the ASCE 7 defined minimum deterministic spectrum. The site specific MCE spectral response acceleration at any period is taken as the lesser of the probabilistic and deterministic MCE spectral response accelerations.

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 with a deterministic MCE cap. 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, California is shown in Figure 1. The site is Site Class "C" as defined in the IBC code with a soil shear wave velocity in the top 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; prior attenuation relations were reliable up to periods of no more than 5 seconds. Near-source and basin effects were not considered in the PSHA analyses for this example.

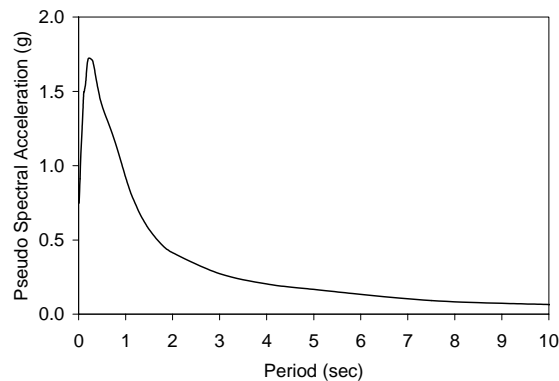


Figure 1 Probabilistic MCE response spectrum for site in downtown Los Angeles (5 percent damping)

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. A deaggregation of the seismic hazard for the downtown Los Angeles site at various periods is shown in Figure 2. From the deaggregation analysis, it can be seen clearly that different 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, some events on other faults become more significant; in particular, as the period increases, larger magnitude earthquake events on more distant faults contribute more to the seismic hazard than at short periods. At short periods, the seismic risk is dominated by smaller magnitude earthquakes on faults located close to the site.

3.2. 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 are to be taken as the maximum value determined from the analyses.

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 the numbers 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 used 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.

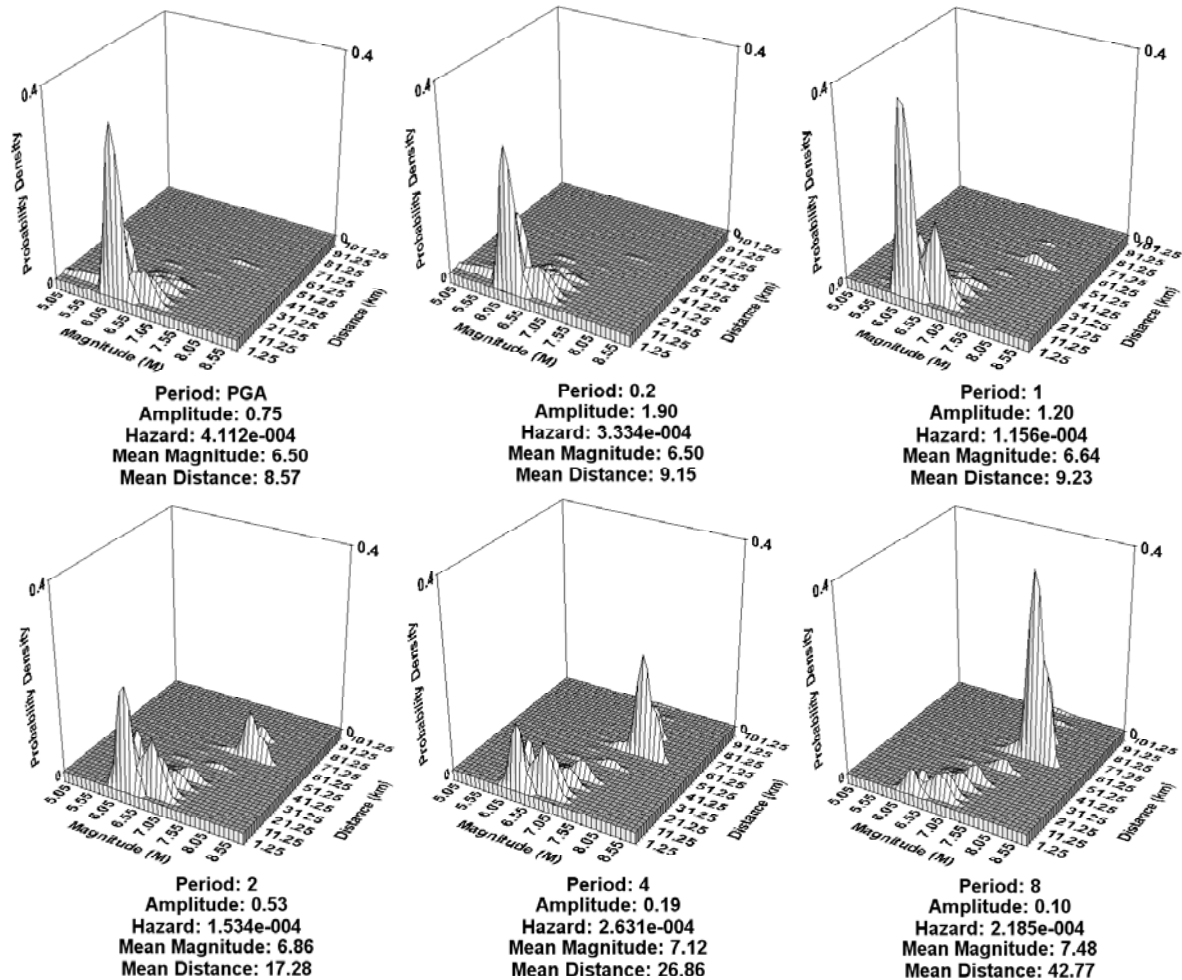


Figure 2 Deaggregation of seismic hazard for MCE for site in downtown Los Angeles for periods of 0.0 sec (PGA), 0.2 sec, 1.0 sec, 2.0 sec, 4.0 sec, and 8.0 sec; distances in kilometers

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, each time history is modified such that its response spectrum is closer to the target spectrum. From a practical point of view, matching by arithmetic scaling of the time histories in an attempt to match the target design spectrum 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. Figure 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 Figure 3.

Because of the breadth of the $0.2T$ to $1.5T$ period range that the target spectrum is to meet, 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 (Abrahamson, 1998) procedure, 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.

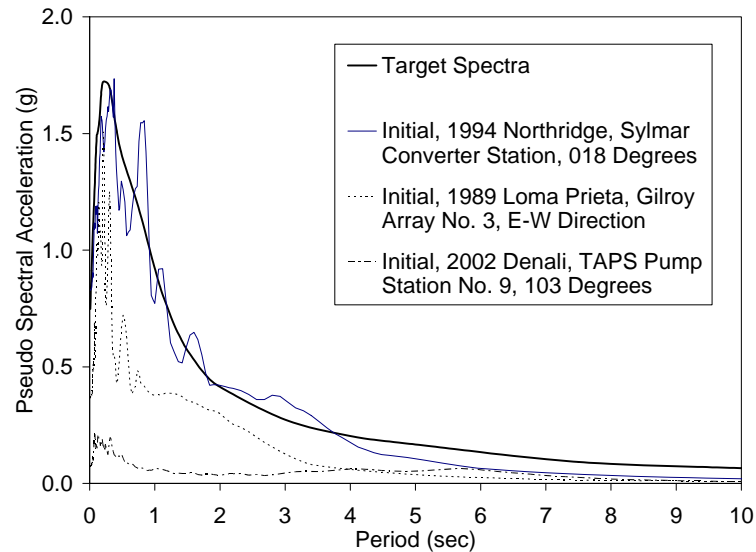


Figure 3 MCE spectrum with original response spectra from several recorded events

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 gaps in the available records in meeting the code's requirements. There are still deficiencies in the quantity of records for large magnitude events in the near and far field. 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, creating a very unrealistic pair of horizontal time histories.

Figure 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.

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 limit the number of records available for matching to the target spectrum.

4. CONCLUSIONS

There indeed are challenges in specifying ground motions for the design of tall buildings in high seismic regions of the United States. These challenges would be similar in high seismic regions of other parts of the world. Using a performance-based earthquake engineering approach, protection against structural collapse for a rare earthquake event is a paramount concern. Nonlinear time history analysis is needed to provide a realistic assessment of collapse prevention and provide an economical design. The use of PBEE for the analysis and design of tall buildings can provide justification to use new construction materials and techniques that may be prohibited by building codes that have many prescriptive requirements that are targeted towards more common structure types and perhaps less reliable design and construction methodologies.

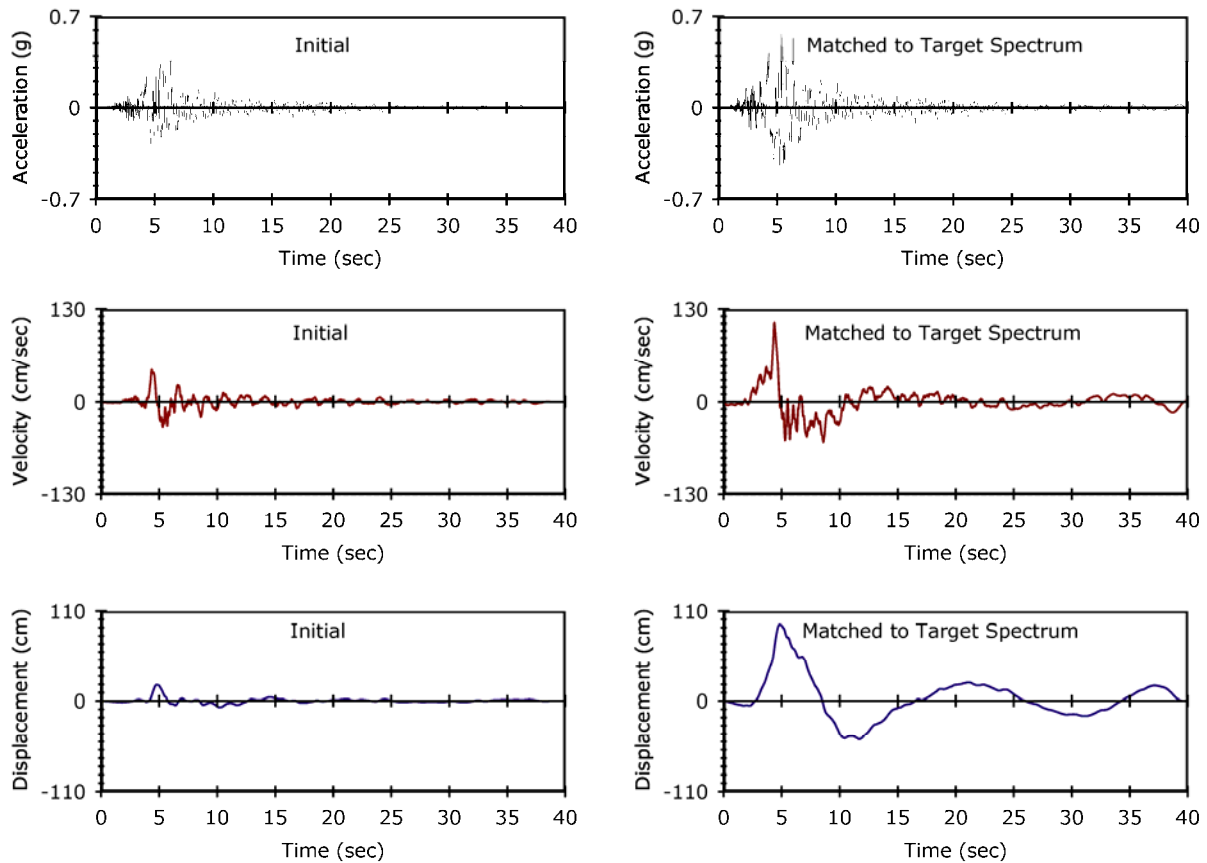


Figure 4 Original and Matched Time Histories for MCE
From 1994 Northridge earthquake, Sylmar Converter Station, Component 018 degrees

The specification of the ground motions, however, is not a simple task. The difficulties arise from having to predict ground motions for very long recurrence intervals of about 2,500 years, so the results include much uncertainty due to our lack of full knowledge about generation and propagation of seismic waves, as well as the seismicity of the individual faults and region and the tectonics. The use of PSHA to predict ground motion provides a uniform hazard spectrum that accounts for all sources at all distances; however, it represents multiple events and not any single earthquake event.

Thus, selection of appropriate time histories to use as seeds requires much thought and insight to be representative of the MCE ground motions. It will be impossible to find existing time histories that will have response spectra similar to the MCE spectrum at all periods of interest for the wide period range required for tall buildings. As deaggregations of the MCE ground motions show, different types of earthquake events at different distances may govern portions of the hazard at different structural periods. If that is the case, it could be argued that the use of scenario earthquakes to describe the different ground motions for the given risk level should be used. The scenario earthquakes would at least need to represent the different types of ground motion from different sources at varying distances. For the example from Los Angeles, ground motions representative of close-in or near-field, moderate magnitude events would be needed to model the motions expected at short structural periods; similarly, ground motions representative of far field or distant, large magnitude events would be needed to model the motions expected at long structural periods. The motions would need to be selected such that all significant structural periods are representative; moreover, as the structures will have nonlinear behavior and structural periods will shift and likely lengthen during earthquake excitation, the motions must have some

broad band content or more time histories would be needed. However, this would require that the NLRH analyses be performed for much more than the three or seven time history sets currently used for tall building design. Alternatively, a Monte Carlo analysis could be performed with numerous ground motion simulations. The computer software and hardware available at the time of this writing make these types of analyses impractical for all but the most critical structures.

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.
- 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.
- 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.