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Dealing in Practice with Selecting and Modifying Earthquake Ground Motions for Nonlinear Analysis

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DEALING IN PRACTICE WITH SELECTING AND MODIFYING EARTHQUAKE GROUND MOTIONS FOR NONLINEAR ANALYSIS

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ABSTRACT

Nonlinear earthquake analyzes of structures are increasingly required by building codes and other seismic design regulations. An essential component of these analyses is that the geotechnical engineer has to provide the structural engineer with a set of strong motion time histories, typically three or seven sets containing two orthogonal horizontal components, and one vertical component if needed. The procedure for selecting the seed time histories and modifying them to match the design response spectrum involves several steps including development of seismological criteria, earthquake deaggregation analysis, and spectral matching.

This procedure for selecting and modifying earthquake ground motions is explained based on three example projects in the San Diego region; i.e., seismic retrofit of an existing hospital complex, seismic retrofit of an existing historic bridge, and seismic design of a harbor facility. Challenges and identified issues encountered in practice will be discussed and some suggestions will be proposed.

INTRODUCTION

Selecting and modifying earthquake ground motions is a big challenge for practitioners. On one hand, most of the methods are still under research and testing; and on the other hand seismic design codes do not provide enough guidance. In addition the impact on structures behavior from using different time histories is not fully understood yet. However despite all these limitations practitioners have the urgency of providing answers and specific solutions to project needs.

This paper intends to show how geotechnical practitioners deal with this big challenge by describing three specific projects in which there was the need of selecting and modifying earthquake ground motion records. One project is the seismic retrofit of a hospital complex, another project is the seismic retrofit of an historic bridge, and the last project is the seismic design of a new harbor facility.

As a preamble some important steps in the process of selecting and modifying earthquake ground motion records are briefly discussed. These include identification of earthquake ground motion records databases, earthquake deaggregation, determination of the target spectrum, modification of earthquake ground motion records, and readily available software.

Strong Motion Records Databases

Several databases are available over the Internet mainly at US and Japan websites. The databases provide the user several search options for earthquake time histories including seismological characteristics, site conditions, and/or records characteristics. Some of the most important databases are presented and briefly described in this section.

PEER-NGA. This database is an update and extension to the PEER Strong Motion Database, first published in 1999. The NGA database includes a larger set of records, more extensive meta-data, and some corrections to information in the original database. At this time, the NGA site contains only acceleration time history files. The PEER-NGA database is accessible at http://peer.berkeley.edu/nga/.

Cosmos Virtual Data Center. Cosmos stands for Consortium of Organizations for Strong-Motion Observation Systems and the core members are the United States Geological Survey (USGS), California Geological Survey, US Army Corps of Engineers and US Bureau of Reclamation. The database is available at http://db.cosmos-eq.org/scripts/default.plx.

Kyoshin Network K-NET. This database is managed by the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED) and contains an impressive number of Japanese earthquake records. The database is accessible at http://www.k-net.bosai.go.jp/. It is required registration to download records.

Earthquake Deaggregation

Earthquake deaggregation (Bazzurro and Cornell 1999, McGuire 1995) is an important tool for understanding seismic hazard and selecting earthquake ground motion records. Deaggregating the total hazard into contributions based on distance and magnitude facilitates the identification of the scenario design earthquake(s) from thousands of earthquakes that comprise a seismic hazard model. Deaggregation at different periods of vibration will enable the detection of different possible design earthquakes. The resulting magnitude and distance from a deaggregation analysis will be instrumental for finding the most suitable earthquake records from a database.

Target Spectrum

There are typically two ways of defining a target spectrum, i.e., uniform hazard spectrum (UHS), and conditional mean spectrum (CMS).

Uniform Hazard Spectrum. This spectrum is one of the final results of a probabilistic seismic hazard analysis (PSHA). PSHA calculates spectral accelerations for a given range of periods. Then a rate of exceedance is identified, and all spectral accelerations are plotted versus their corresponding periods. The resulting envelope curve is called uniform hazard spectrum (UHS) because each spectral ordinate has an equal rate of being exceeded (McGuire 2004, Baker 2008). Hence this spectrum may be the result from different earthquake events with different magnitudes and distances and should not be interpreted as the response spectrum from a single ground motion excitation. The use of the UHS is widespread in practice and in many seismic design codes.

Conditional Mean Spectrum. Because a UHS is not representative of the spectrum from any single ground motion, it is contended that an UHS is an unsuitable and unsatisfactory ground motion target. Baker (2009) proposes that the CMS is a better target and useful tool for selecting ground motion records as input to dynamic analysis. The CMS provides the mean response spectrum, conditioned on occurrence of a target spectral acceleration ordinate at a period of interest. Baker (2009) describes a simple four-step procedure to construct the CMS, and a method for selecting and scaling ground motions to match this spectrum. The CMS appears as a promising approach and may become widespread in practice of seismic design of buildings.

Common Methods for Modifying Strong Motion Records

Two of the most common methods used in practice for performing modification of strong motion records are spectral matching and scaling.

Spectral Matching. This method adjusts the original record in the time domain by adding wavelets to it (Lilhanand and Tseng 1988). The spectral matching can be performed with a given level of convergence tolerance for the maximum deviation from the target spectrum. Spectral matching reduces substantially the number of time histories needed for the analysis, but the cost is using less realistic time histories. Real earthquake spectra are not smoothed and target spectra tend to be smoothed. Real, unmodified strong motion records have response spectral peaks and valleys that impact the nonlinear response of structures. Two types of spectral matching can be identified, i.e., “loose” and “tight” matching. “Loose” spectral matching roughly follows the shape of the target smoothed spectrum but leaves peaks and valleys in the matched spectrum. “Tight” spectral matching produces a smoothed matched spectrum eliminating peaks and valleys minimizing variability but introducing bias in the nonlinear response. Matching difficulties can be observed especially at long periods. Modified strong motion records should be baseline corrected in time domain (residual displacements eliminated) after the spectral matching.

Scaling of strong motion records. This method applies scale factors to modify the amplitudes of the original ground motion records without altering the frequency content. Naeim et al. (2004) proposed a method using a genetic algorithm (Goldberg 1989). This algorithm treats a union of a given number of records, say seven, and corresponding scaling factors as a single “individual.” Then an optimum “individual” is obtained through “mating,” “natural selection,” and “mutation.” In an alternative approach, Kottke and Rathje (2008) developed a semi-automated procedure that selects and scales ground motion records by adjusting individual scale factors for the motions to fit the amplitude and standard deviation of the target spectral shape.

Available Software

Some of the most common available computer programs are identified and a short description for each one is provided.

SigmaSpectra. This is a computer program that selects suites of earthquake ground motions from a library. The median of the suite matches a target response spectrum at all defined periods, and then scales the standard deviation of the suite with the target standard deviation. The methodology used in SigmaSpectra is described by Kottke and Rathje (2007) and Kottke and Rathje (2008). The methodology selects and linearly scales recorded acceleration time histories and does not explicitly deal with frequency-domain or time-domain spectral matching techniques. The program is free at http://www.caee.utexas.edu/prof/rathje/research.html.

RspMatch. This program utilizes an algorithm that adjusts the original strong motion record in the time domain by adding wavelets to it. The spectral matching can be performed to a user specified convergence tolerance for the maximum deviation from the target spectrum (Abrahamson 1992, Abrahamson 1998). The new version of the program, RspMatch2005, enables the strong motion records to be matched to the pseudo-acceleration or displacement spectral ordinates as well as the spectrum of absolute acceleration, and additionally allows the matching to be performed simultaneously to a given spectrum at several damping ratios (Hancock et al. 2006).

RASCAL. This program performs spectral matching by scaling the Fourier amplitude of each individual frequency using the ratio of spectral acceleration of the record to the target spectral acceleration (Silva and Lee 1987). This program utilizes random vibration theory to calculate peak values of acceleration and velocity in addition to response spectra for specified earthquake source and propagation path parameters. The method combines the phase spectra from observed strong motion records to a theoretical Brune modulus (Brune 1970, 1971). The program can produce acceleration time histories whose response spectrum matches a specified target spectrum.

Design Ground Motion Library (DGML). This is an interactive tool for selecting strong motion records from the PEER-NGA database (Youngs et al. 2009). The selection is based on user-specified criteria including design response spectra, magnitude, distance, style of faulting, V_{S30} (average shear wave velocity in the upper 30 meters of a soil profile), and records with or without pulses. Also DGML provides linear scaling factors for record application. The target spectrum may be the building code spectrum, NGA ground motion based spectrum, or user-developed spectrum of any shape. Additionally there is an option for conditional mean spectrum. As of September 2009, PEER is in the process of transferring DGML to a web-based tool.

SEISMIC RETROFIT OF A HOSPITAL COMPLEX

The seismic retrofit of a hospital complex in southern California required site-specific probabilistic and deterministic seismic hazard analyses, kinematic and foundation damping soil-structure evaluation, upper and lower bound foundation capacity and stiffness determination, and seismic pressures evaluation for existing retaining and basement walls. These geotechnical evaluations were performed for two different earthquake hazard levels, i.e., Basic Safety Earthquake 1 (BSE-1; 10% probability of exceedance in 50 years) and Basic Safety Earthquake 2 (BSE-2; 2% probability of exceedance in 50 years), and two performance levels, i.e., Life Safety Performance and Collapse Prevention Performance Levels (Meneses et al. 2009).

Project site characterization included collection of information on the subsurface soil conditions, foundation conditions and seismic geologic hazards. A comprehensive review of available previous geotechnical studies was performed and a number of boring logs for the site were compiled from these studies. With this available subsurface information, geologic reconnaissance and mapping, and experience with the site and nearby projects, a map was prepared of surface geology and geologic cross sections.

Seismic measurements using active and passive surface wave techniques were performed for the current study to supplement the previous subsurface data. The purpose of this survey was to provide a shear wave velocity (V_{S30}) profile to a depth of 30 m, to be used for seismic site classification and for evaluation of small strain stiffness properties of the site soils. Figure 1 presents the V_S profile utilized for seismic site class determination, seismic hazard study, and foundation stiffness.

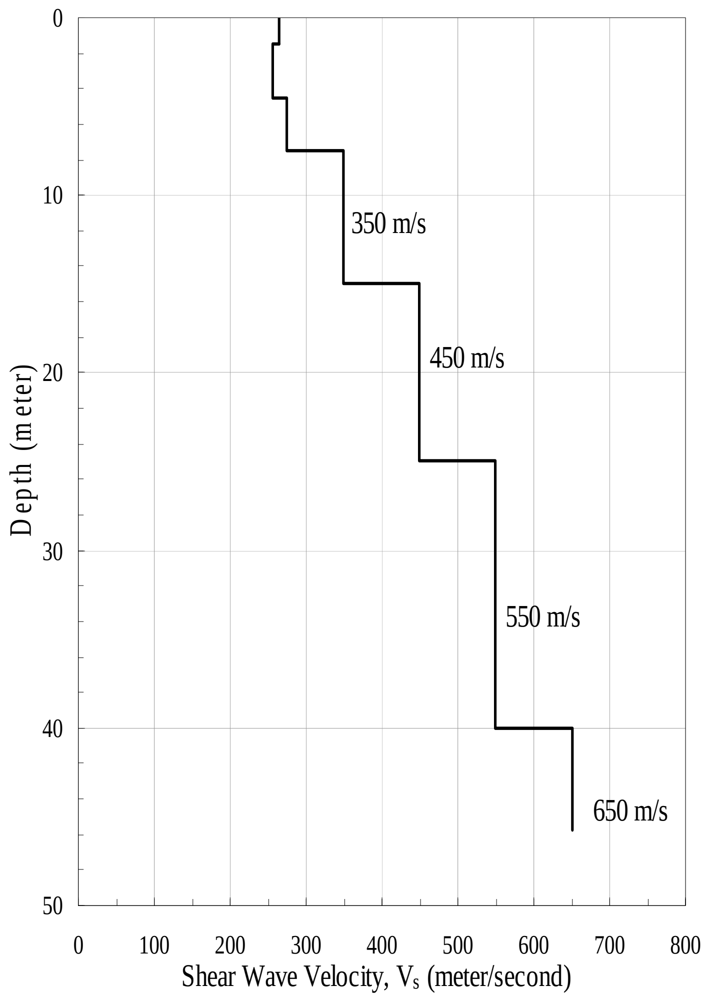

Figure 1. Representative shear wave velocity V_S profile for the project site.

Ground Motion Development

The project site is a seismically active area and is likely to experience ground shaking as a result of earthquakes on nearby or more distant faults. The Rose Canyon fault zone is located approximately 4.3 km west of the project site and contributes the most to the seismic ground shaking hazard at the site.

Based on the shear wave velocity measurements made as part of this study, the average shear wave velocity in the upper 30 meters of the site (V_{S30}) is 385 m/sec, which corresponds to Site Class C (shear wave velocity of 366 to 762 m/s) per Section 1613A.5.2 of the 2007 California Building Code (CBC).

Site-specific ground motion hazard evaluations using probabilistic and deterministic seismic hazard analysis (PSHA and DSHA) methods were performed. The purpose of this study was to develop the site-specific ground motion criteria in terms of spectral accelerations by using a seismic source model and the subsurface soil conditions encountered at the site.

The BSE-1 and BSE-2 response spectra for 5 percent damping are presented graphically in Figure 2.

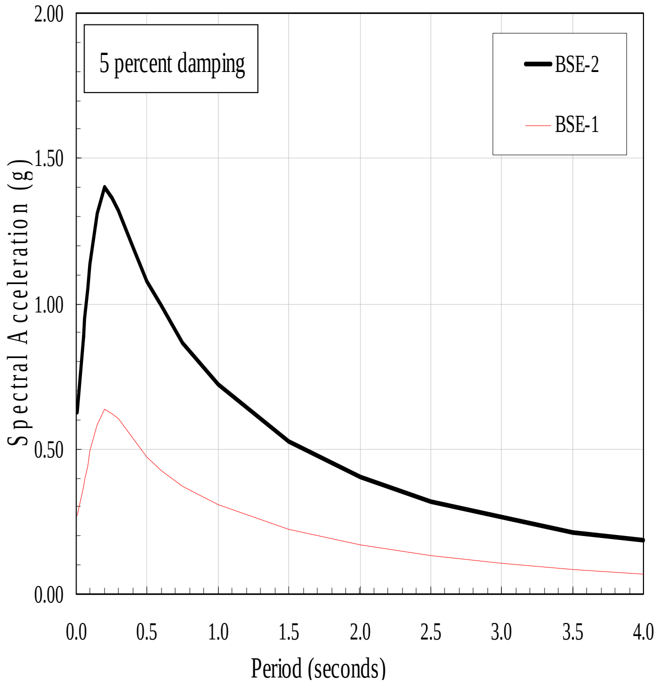

Figure 2. BSE-1 and BSE-2 response spectra for the project site.

DEVELOPMENT OF EARTHQUAKE TIME HISTORIES

Seven sets (each containing two orthogonal horizontal components and one vertical component) of ground motion time histories were developed. These sets were selected from recorded seismic events and spectrally matched within 5 percent of the response spectra associated with the BSE-1 and the BSE-2 design events.

Deaggregation of the PSHA resulted in mode values of distance and moment magnitude of 3.75 km and 6.95 respectively for periods up to 1 second for the BSE-1 and up to 2 seconds for the BSE-2 event. In general, the dominant magnitude for this site ranges from 6.95 to 7.25 at a distance of approximately 3.75 km.

The most significant criteria for the selection of time histories include site-source distance (3.75 km), forward directivity effects, faulting mechanism (strike-slip), magnitude (7.0), and spectral shape (frequency content). Utilizing these criteria the PEER Strong Motion NGA Database available at http://peer.berkeley.edu/nga was used to select strong motion records. For the BSE-1 event, time histories include three forward-directivity events, three backward-directivity events and one neutral-directivity event. For the BSE-2 event, time histories include four forward-directivity events, two backward-directivity events and one neutral-forward directivity event.

Spectral matching of the selected time histories was performed using the computer program RSPMATCH. The spectral matching was performed with a 5% of convergence tolerance for the maximum deviation from the target spectrum. All records were baseline corrected in time domain (residual displacements were eliminated) after the spectral matching.

For each dataset, the square root of the sum of the squares (SRSS) of the 5%-damped site-specific spectra of the horizontal components was constructed. The datasets were modified such that the average values of the SRSS spectra are not lower than 1.3 times the target spectra. Figure 3 shows response spectra of all matched horizontal time histories for the BSE-2 event.

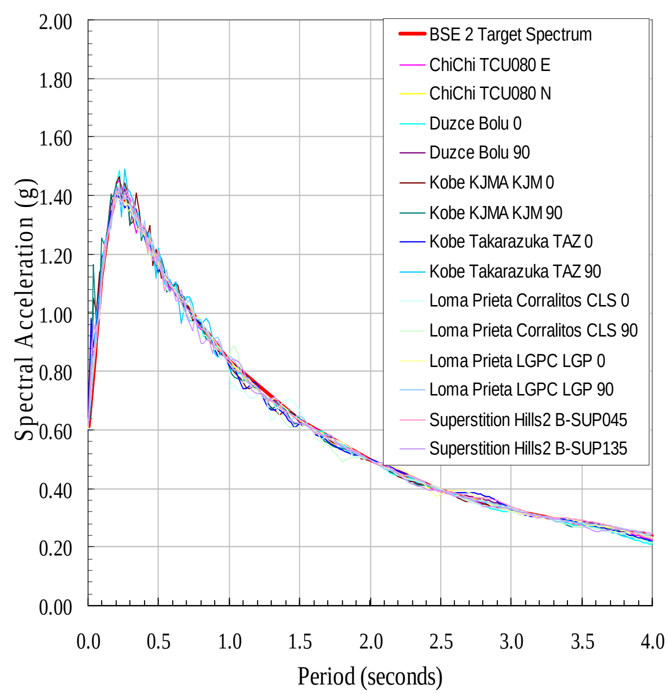

Figure 3. Response Spectra of All Matched Horizontal Time Histories for the BSE-2 event.

The bridge is located along the coast of the Pacific Ocean, as close as 60 m from the high tide line. It is situated at the north end of an alluvial valley, with the northern-most quarter of the bridge ascending the valley's sloping boundary. The bridge spans over a state park access road and the San Diego Northern Railway (SDNR) line. It was constructed with three bents skewed at 63 degrees from the longitudinal axis of the bridge that accommodate the railroad and its embankment.

The design seismic performance criteria were established keeping in mind that the bridge is not a critical lifeline structure. The retrofit design was developed with the performance expectation that after a major design level earthquake the bridge would sustain significant damage and would probably be closed to traffic. The bridge may or may not be repairable after the event, but structural collapse should not occur and life safety should be protected. The design seismic event was defined as the "Safety Evaluation Earthquake" (SEE), and was taken as the greater of a 1,033-year return period probabilistic seismic hazard analysis-based ground motion and the median deterministic seismic hazard analysis ground motion (Gingery et al. 2009).

PSHA and DSHA for rock

Both probabilistic and deterministic seismic hazard analyses (PSHA and DSHA, respectively) were performed to characterize the seismic hazard for a hypothetical rock outcrop at the site.

For the probabilistic analyses, a seismic source model based on the model used in developing probabilistic seismic hazard maps by California Geological Survey (CGS) for the State of California (Petersen et al., 1996, Cao et al., 2003) was used. In addition, faults located in Baja California, Mexico were added to the seismic source model (Rockwell 2002).

Attenuation relationships were selected to characterize the strong ground motions for both the PSHA and DSHA. Four of the five relationships from the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation of Ground Motion (NGA) project were used: Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008) and Chiou and Youngs (2008). These attenuation relationships were specifically developed to characterize strong ground motions from shallow crustal events in western North America. All four selected attenuation relationships utilize estimates of V_{S30} (i.e., average shear wave velocity in the upper 30-meters of the soil); a bedrock shear wave velocity of 1,070 meters per second was used in the analyses. Since the project site was in close proximity to the Rose Canyon fault, rupture directivity and directionality (near-source effects) were considered in the analyses in accordance with the recommendations by Somerville et al. (1997) and Abrahamson (2000).

Both the PSHA and DSHA were performed using the seismic hazard analysis computer software EZ-FRISK (Risk Engineering, 2008). The DSHA was determined to be governed by the Rose Canyon fault (maximum moment magnitude of 7.2), which is located approximately 3.1 km west of the site. Comparisons between the 1,033-year probabilistic and median deterministic response spectra showed that the deterministic spectrum was larger at all periods that were analyzed. The dominance of the median deterministic response spectrum is attributed to the relatively low slip rate (1.5 mm/year) of the Rose Canyon fault. Therefore, the SEE design earthquake was based on the DSHA results.

Time history selection, spectral matching, rotation

Three earthquake horizontal acceleration time histories were selected from the PEER-NGA ground-motion database. These time histories were chosen based on their relative consistency with the scenario SEE event with respect to fault rupture mechanism, distance to site, moment magnitude, site bedrock conditions and duration of strong shaking. Since the site-source geometry is conductive to forward directivity, two of the three time histories selected included forward rupture directivity effects (Bray and Rodriguez-Marek 2004). The three selected time histories were:

- The Duzce, Turkey earthquake of 1999, Bolu recording station (includes forward directivity);
- The Landers, California earthquake of 1994, Joshua Tree recording station (backward directivity); and
- The Loma Prieta earthquake of 1989, Los Gatos Presentation Center (LGPC) recording station (includes forward directivity).

The selected horizontal time histories were transformed through a simple vector rotation to major principal and minor principal orientations (Somerville 2002). The major and minor principal axes were selected with consideration to polar plots of peak and spectral acceleration, velocities and displacements. Geographical fault orientations as described in Bray and Rodriguez-Marek (2004) were also considered. In general, the principal major axis was taken as the orientation that produced the greatest Peak Ground Displacement (PGD), and the minor principal axis was taken as orthogonal to the major axis (Lam and Law 2000). The major and minor principal axes were assumed to be the fault normal and fault parallel directions, respectively, of the recorded ground motion.

The horizontal time histories, rotated to major and minor principal axes, were fitted (i.e., spectrally matched) in the time domain to the design bedrock target fault-normal and fault-parallel spectra, respectively, using the computer program RSPMATCH. This spectral matching was done relatively loosely (within 5% of the target) to preserve as much as possible the characteristics of the time histories. All acceleration time history records were baseline corrected (i.e. elimination of residual displacements) following the spectral matching using a high-pass Butterworth filter to remove very long period ground motion (i.e. greater than 20 second period) and/or addition/subtraction of a best-fit polynomial of the acceleration time history. Response spectra of the matched time histories are plotted on Figure 4 for both the fault-normal and fault-parallel components along with the design SEE target bedrock outcrop spectra for comparison.

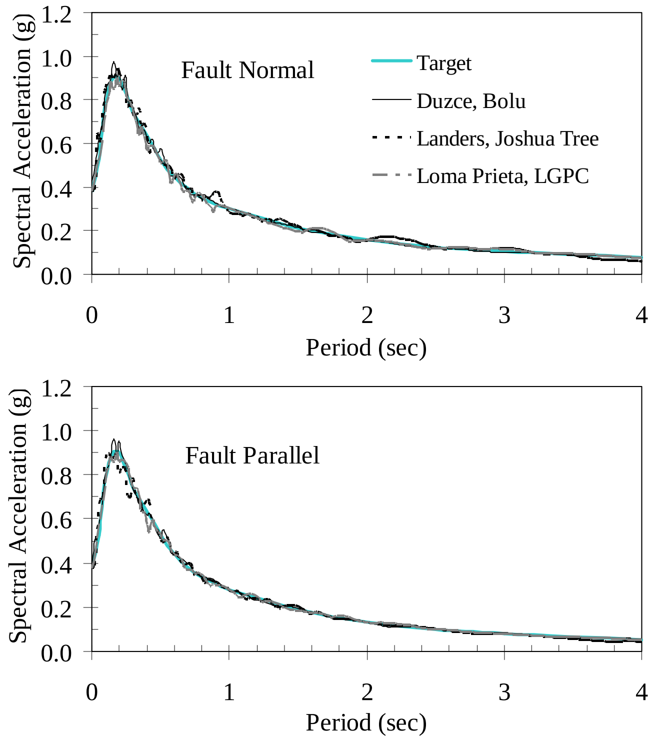

Figure 4. Fault normal and fault parallel spectrally matched response spectra for the hypothetical bedrock outcrop.

Site response analyses

One-dimensional equivalent linear site response analyses were performed to propagate the design bedrock ground motion to the ground surface and foundation levels. The site response analyses were performed using the computer program SHAKE2000 (Schnabel et al. 1972, Ordonez 2006). Soil non-linearity is accounted for using strain-dependent modulus degradation and damping curves. The program iterates until compatible effective strain levels are obtained for each sub layer within the model.

Because the subsurface soil conditions and ground surface elevations vary across the site, the analyses were performed for five representative site zones. Generalized soil profiles were developed for these five sites zones. The base of the site response models was taken at the top of the unweathered Lusardi Formation at approximately elevation -38 m where the measured shear wave velocity was approximately 1,067 meters per second. Shear modulus (G/G_{max}) and damping versus shear strain curves were estimated using Roblee and Chiou (2004) for soil materials and Schnabel (1973) for rock in the SHAKE2000 analysis. The shear wave velocity (V_s) used in our profiles was interpreted from the shear wave velocities measurements and from correlations with CPT and SPT measurements. The value G_o is the maximum shear modulus at very small strains calculated from $G_o = \rho\ V_s^2$ where ρ is the soil density. Figure 5 shows a V_s profile for Abutment 1, one of the five soil profiles.

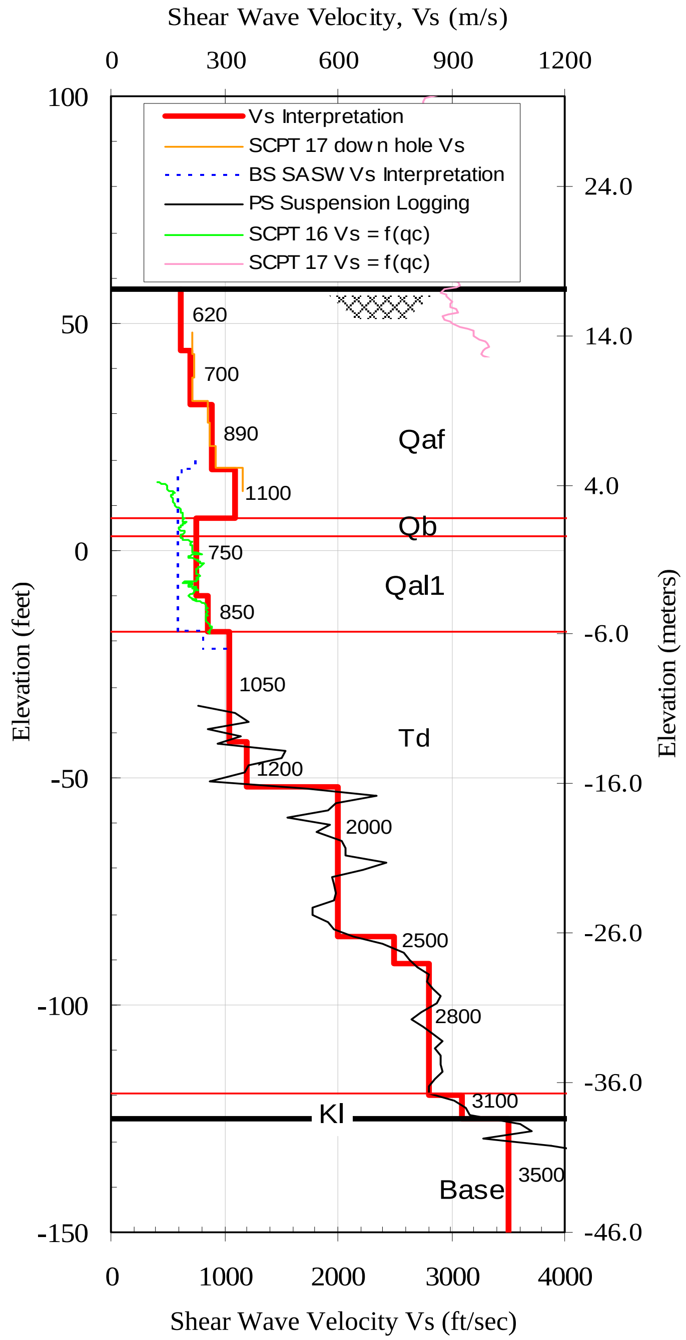

Figure 5. Measured and interpreted shear wave velocity profile at Abutment 1 profile.

The SEE (Safety Evaluation Earthquake) design bedrock outcrop earthquake time histories were used as input to the site response analyses. Each of the five profiles was subjected to the fault normal (FN) and fault parallel (FP) components of the three design SEE bedrock outcrop motions for a total of 30 site response runs. The time histories were applied at the base of the site response model (bedrock level) as an "outcropping" motion. Time histories extracted from the site response analysis at the foundation levels were provided to the project structural engineers for use in dynamic modeling of the bridge. Free-field, elastic, five percent damping, response spectra were calculated for these foundation input motions. Figure 6 shows fault normal spectra at the foundation level for Abutment 1.

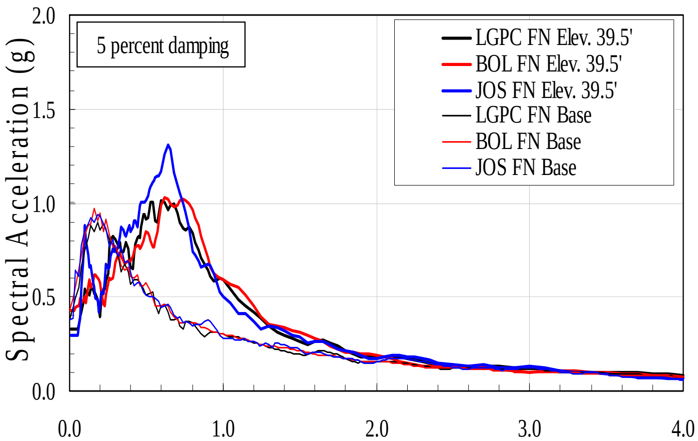

Figure 6. Example fault normal response spectra for the bedrock and foundation elevations.

SEISMIC DESIGN OF A HARBOR FACILITY

The project site is located within a relatively flat site in Baja California, Mexico. The site is characterized at an elevation of -16m mean sea level as medium dense to very dense sand. Measurements of P wave velocities reported are 2,600 – 3,630 m/s, which correspond approximately to S wave velocities of 1,390 – 1,940 m/s. For the purpose of this analysis we assume a shear wave velocity of 1,300 m/s.

A probabilistic seismic hazard analysis (PSHA) was performed for the site as per Port of Los Angeles (POLA) 2004 Seismic Code. The PSHA developed 5 percent damped, uniform-hazard, elastic acceleration response spectra at an elevation of -16m at the site. Near source effects (Abrahamson 2000, Somerville et al. 1997, Somerville 2002) were incorporated by developing fault normal response spectra. Two levels of design earthquake motions were considered: *Operating Level Earthquake*, *OLE* (50 percent probability of exceedance in 50 years), and *Contingency Level Earthquake*, *CLE* (10 percent probability of exceedance in 50 years). Response spectra were developed for each of these two levels of design earthquakes. Deaggregation of the PSHA was performed to develop scenario magnitude and site-source distance pairs for the design earthquakes.

Under a Pacific Earthquake Engineering Research (PEER) Center project entitled "Next Generation Attenuation of Ground Motions (NGA)," five teams have developed and presented new attenuation relationships for shallow crustal earthquakes in Western North America. These relationships are Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), and Idriss (2008). Prior to these NGA relationships, four of the most used relationships and widely accepted by seismologists for shallow crustal earthquakes in Western North America were the ones presented by Boore et. al. (1997), Abrahamson and Silva (1997), Campbell and Bozorgnia (2003), and Sadigh et. al. (1997).

The NGA attenuation relationships are also applicable to sources in Baja California, Mexico. For this project we used four NGA models listed in Table 2.

Table 2. NGA Relationships Used in the Seismic Hazard Analysis

Attenuation Relationship	Seismic Source
Abrahamson-Silva (2008)	Fault/Background
Boore and Atkinson (2008)	Fault/Background
Campbell and Bozorgnia (2008)	Fault/Background
Chiou and Youngs (2008)	Fault/Background

All four of these NGA relationships use estimates of V_{S30} (average shear wave velocity in the top 30m) as input. We used the shear wave velocity of 1,300 meter per second (4,265 feet per second) in our analyses. The NGA Idriss (2008) relation was not used because this V_{S30} is beyond its range of applicability (V_{S30} = 1,500 to 2,000 feet per second).

We used the commercially available computer program EZ-FRISK (Risk Engineering, 2008) for our analysis. Figure 7 shows the linear plots for the OLE and CLE response spectra.

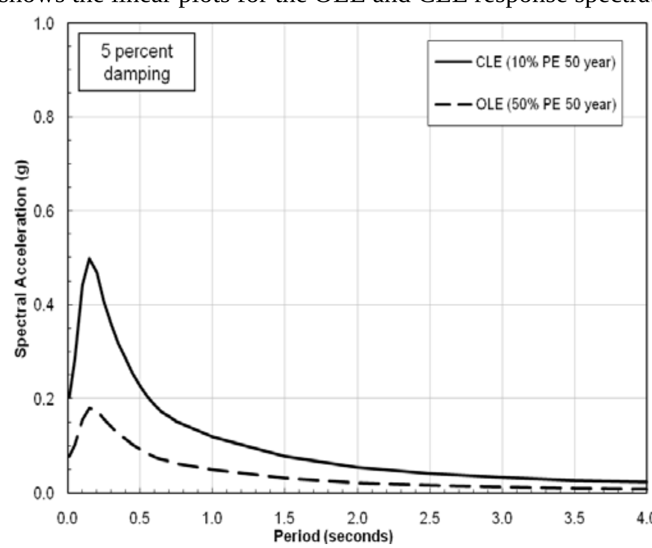

Figure 7. Probabilistic Response Spectra

The most significant criteria for the selection of time histories included site-source distance (13.75 km), magnitude (7.65), directivity effects, and spectral shape. Utilizing the "target" criteria above, Kleinfelder searched the PEER –NGA Strong Motion Database and selected the strong motion records shown in Tables 6 through 9. Table 6 and 7 show the characteristics of the selected earthquakes to match the OLE and CLE target response spectra respectively.

Table 6. Selected Earthquakes for OLE

Earthquake	Date	Magnitude	Mechanism
Kocaeli, Turkey	8/17/1999	7.4	Strike-slip
Chi-Chi, Taiwan	9/21/1999	7.6	Reverse
Hector Mine, CA	10/16/1999	7.1	Strike-slip
Landers, CA	06/28/1992	7.3	Strike-slip
Manjil, Iran	06/20/1990	7.4	Strike-slip

Table 7. Selected Earthquakes for CLE

Earthquake	Date	Magnitude	Mechanism
Kocaeli, Turkey	8/17/1999	7.4	Strike-slip
Chi-Chi, Taiwan	9/21/1999	7.6	Reverse
Hector Mine, CA	10/16/1999	7.1	Strike-slip
Landers, CA	06/28/1992	7.3	Strike-slip
Manjil, Iran	06/20/1990	7.4	Strike-slip
Loma Prieta, CA	10/17/1989	7.0	Oblique

Table 8 and 9 show the stations from which the strong motion records were selected to match the OLE and CLE target response spectra respectively.

Table 8. Selected Time Histories for OLE

Earthquake	Station	Comp.	Dist. (km)	V_{s30} (m/s)	PGA (g)
Chi-Chi, Taiwan	CHY029	E	11.0	544.7	0.28
Chi-Chi, Taiwan	TCU048	N	13.6	551.0	0.18
Manjil, Iran	Abbar	L	12.6	724.0	0.52
Kocaeli, Turkey	Arcelik	0°	13.5	523.0	0.22
Kocaeli, Turkey	Gebze	0°	11.0	792.0	0.24
Landers, CA	Joshua	0°	11.0	379.3	0.27
Hector Mine, CA	SCSN 0	0°	11.7	684.9	0.27

Table 9. Selected Time Histories for CLE

Earthquake	Station	Comp.	Dist. (km)	V_{s30} (m/s)	PGA (g)
Chi-Chi, Taiwan	CHY029	E	11.0	544.7	0.28
Loma Prieta, CA	Gilroy Array 1	0°	9.6	1428.0	0.41
Manjil, Iran	Abbar	L	12.6	724.0	0.52
Kocaeli, Turkey	Arcelik	0°	13.5	523.0	0.22
Kocaeli, Turkey	Gebze	0°	11.0	792.0	0.24
Landers, CA	Joshua	0°	11.0	379.3	0.27
Hector Mine, CA	SCSN 0	0°	11.7	684.9	0.27

Spectral Matching

Spectral matching of the selected time histories was performed using the program RSPMATCH. The spectral matching was performed with a 5% of convergence tolerance for the maximum deviation from the spectrum target. All records were baseline corrected (residual displacements were eliminated) after the spectral matching.

Figure 8 shows the response spectra of the original time histories selected to match the CLE response spectrum. The CLE response spectrum is also plotted on Figure 8 for comparison.

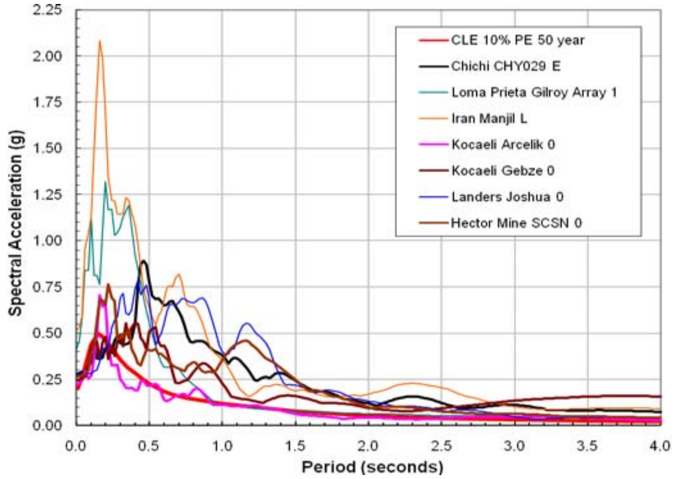

Figure 8. Response spectra of original time histories for CLE event

In addition, response spectra of the original selected time histories were normalized to the CLE peak ground acceleration for comparison. Comparison of normalized response spectra aids in visualizing spectral shapes of selected time histories. Figure 9 shows the normalized response spectra of the original time histories selected to match the CLE response spectrum.

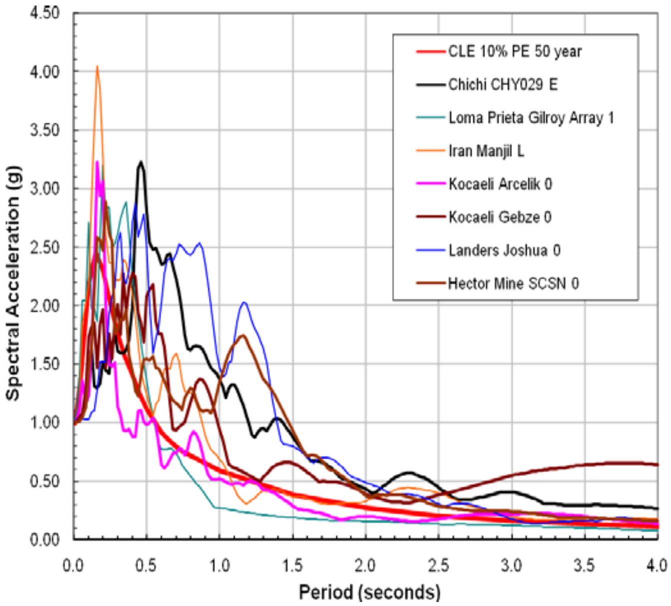

Figure 9. Normalized response spectra of original time histories for CLE event

Figure 10 shows the response spectra of spectral matched time histories for the CLE event.

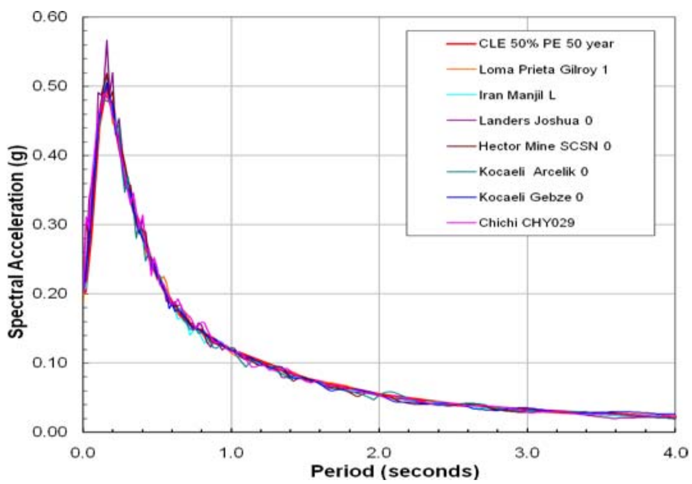

Figure 10. Response spectra of matched time histories for CLE event

Two sets of spectrum-matched earthquake time histories were developed in our study. One set of seven time histories was developed to match the Operating Earthquake Level (OLE) response spectrum, and another set of seven time histories was developed to match the Contingency Earthquake Level (CLE) response spectrum.

CONCLUSIONS AND RECOMMENDATIONS

Dealing in practice with selecting and modifying earthquake ground motion records for nonlinear analysis of structures and site response is a big challenge for geotechnical practitioners. Guidelines are not clearly established, most methods are still under research and structural response to different time histories is not completely understood. Early involvement with regulatory agencies is highly recommended to understand what they are expecting from the analysis and to avoid delays with projects. Third party reviewers also play an important role and should be involved as much as possible during the entire process of selecting and modifying earthquake records. Agreement in methods, procedures and assumptions is critical. In the last few years there have been substantial progress in research and seismic codes and geotechnical practitioners are encouraged to stay current with latest knowledge and get more involved in seismic design code development.

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