3

Earthquake Ground Motion

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Most of the effort in seismic design of buildings and other structures is focused on structural design. This chapter addresses another key aspect of the design process—characterization of earthquake ground motion. Section 3.1 describes the basis of the earthquake ground motion maps in the *Provisions* and in ASCE 7. Section 3.2 has examples for the determination of ground motion parameters and spectra for use in design. Section 3.3 discusses and provides an example for the selection and scaling of ground motion records for use in response history analysis.

3.1 BASIS OFEARTHQUAKE GROUND MOTION MAPS

This section explains the basis of the new Risk-Targeted Maximum Considered Earthquake (MCE_R) ground motions specified in the 2009 *Provisions* and mapped in ASCE 7-10. In doing so, it also explains the basis for the uniform-hazard ground motion (S_{SUH} and S_{1UH}) maps, risk coefficient (C_{RS} and C_{R1}) maps and deterministic ground motion (S_{SD} and S_{1D}) maps in the 2009 *Provisions.* These three sets of maps are combined to form the Site Class B MCE_R ground motion (S_S and S_1) maps in ASCE 7-10. The use of S_S and S_1 ground motions in the 2009 *Provisions* and ASCE 7-10 to derive a design response spectrum remains the same as it is in ASCE 7-05.

This section also explains the basis for the new Peak Ground Acceleration (PGA) maps in the 2009 *Provisions* and ASCE 7-10 and the new equations for vertical ground motions. The basis for the long-period transition (T_L) maps in the 2009 *Provisions* and ASCE 7-10, which are identical to those in ASCE 7-05, is also reviewed. In fact, we start with a review of these maps and the Maximum Considered Earthquake (MCE) ground motion maps in ASCE 7-05.

3.1.1 ASCE 7-05 Seismic Maps

The bases for the seismic ground motion (MCE) and long-period transition (T_L) maps in Chapter 22 of ASCE 7-05 were established by, respectively, the Building Seismic Safety Council (BSSC) Seismic Design Procedures Group, also referred to as Project '97, and Technical Subcommittee 1 (TS-1) of the 2003 Provisions Update Committee. They are reviewed briefly in the following two subsections.

3.1.1.1 Maximum Considered Earthquake (MCE) Ground Motion Maps

The MCE ground motion maps in ASCE 7-05 can be described as applications of its site-specific ground motion hazard analysis procedure in Chapter 21 (Section 21.2), using ground motion values computed by the USGS National Seismic Hazard Mapping Project (in Golden, CO) for a grid of locations and/or polygons that covers the US. In particular, the 1996 USGS update of the ground motion values was used for ASCE 7-98 and ASCE 7-02; the 2002 USGS update was used for ASCE 7-05. The site-specific procedure in all three editions calculates the MCE ground motion as the lesser of a probabilistic and a deterministic ground motion. Hence, the USGS computed both types of ground motions, whereas otherwise it would have only computed probabilistic ground motions. Brief reviews of how the USGS computed the probabilistic and deterministic ground motions are provided in the next few paragraphs. For additional information, see Leyendecker et al. (2000).

The USGS computation of the probabilistic ground motions that are part of the basis of the MCE ground motion maps in ASCE 7-05 is explained in detail in Frankel et al. (2002). In short, the USGS combines research on potential sources of earthquakes (e.g., faults and locations of past earthquakes), the potential magnitudes of earthquakes from these sources and their frequencies of occurrence, and the potential ground motions generated by these earthquakes. Uncertainty and randomness in each of these components is accounted for in the computation via contemporary Probabilistic Seismic Hazard Analysis (PSHA), which was originally conceived by Cornell (1968). The primary output of PSHA computations are so-called hazard curves, for locations on a grid covering the US in the case of the USGS computation.

Each hazard curve provides mean annual frequencies of exceeding various user-specified ground motions amplitudes. From these hazard curves, the ground motion amplitudes for a user-specified mean annual frequency can be interpolated and then mapped. The results are known as uniform-hazard ground motion maps, since the mean annual frequency (or corresponding probability) is uniform geographically.

For ASCE 7-05 (as well as ASCE 7-02 and ASCE 7-98), a mean annual exceedance frequency of 1/2475 per year, corresponding to 2% probability of exceedance in 50 years, was specified by the aforementioned BSSC Project '97. That project also specified that the ground motion parameters be spectral response accelerations at vibration periods of 0.2 seconds and 1 second, for 5% of critical damping. For the average shear wave velocity at small shear strains in the upper 100 feet (30 m) of subsurface below each location ($v_{S,30}$), the USGS decided on a reference value of 760 m/s. The BSSC subsequently decided to regard this reference value, which is at the boundary of Site Classes B and C, as corresponding to Site Class B. Justifications for the decisions summarized in this paragraph are provided in the *Commentary* of FEMA 303, FEMA 369 and FEMA 450.

The USGS computation of the deterministic ground motions for ASCE 7-05 is detailed in the FEMA 303 *Commentary*. As defined by Project '97 and subsequently specified in the site-specific procedure of ASCE 7-05 (Section 21.2.2), each deterministic ground motion is calculated as 150% of the median spectral response acceleration for a characteristic earthquake on a known active fault within the region. The specific characteristic earthquake is that which generates the largest median spectral response acceleration at the given location. As for the probabilistic ground motions, the spectral response accelerations are at vibration periods of 0.2 seconds and 1 second, for 5% of critical damping. The same reference site class (see preceding paragraph) is used as well. Though not applied to probabilistic ground motions, lower limits of 1.5g and 0.6g are applied to the deterministic ground motions.

As mentioned at the beginning of this section, the lesser of the probabilistic and deterministic ground motions described above yields the MCE ground motions mapped in ASCE 7-05. Thus, the MCE spectral response accelerations at 0.2 seconds and 1 second are equal to the corresponding probabilistic ground motions wherever they are less than the lower limits of the deterministic ground motions (1.5g and 0.6g, respectively). Where the probabilistic ground motions are greater than the lower limits, the deterministic ground motions sometimes govern, but only if they are less than their probabilistic counterparts. On the MCE ground motion maps in ASCE 7-05, the deterministic ground motions govern mainly near major faults in California (like the San Andreas), in Reno and in parts of the New Madrid Seismic Zone. The deterministic ground motions that govern are as small as 40% of their probabilistic counterparts.

3.1.1.2 Long-Period Transition Period (T_L) Maps

The details of the procedure and rationale used in developing the T_L maps in ASCE 7-05; and now in ASCE 7-10 and the 2009 *Provisions*, are found in Crouse et al. (2006). In short, the procedure consisted of two steps. First, a relationship between T_L and earthquake magnitude was established. Second, the modal magnitude from deaggregation of the USGS 2% in 50-year ground motion hazard at a 2-second period (1 second for Hawaii) was mapped. The long-period transition period (T_L) maps that combined these two steps delimit the transition of the design response spectrum from a constant velocity ($1/T$) to a constant displacement ($1/T^2$) shape.

3.1.2 MCE$_R$ Ground Motions in the *Provisions* and in ASCE 7-10

Like the MCE ground motion maps in ASCE 7-05 reviewed in the preceding section, the new Risk-Targeted Maximum Considered Earthquake (MCE$_R$) ground motions in the 2009 *Provisions* and ASCE 7-10 can be described as applications of the site-specific ground motion hazard analysis procedure in Chapter 21 (Section 21.2) of both documents. For the MCE$_R$ ground motions, however, the USGS values (for a grid of site and/or polygons covering the US) that are used in the procedure are from its 2008 update. Still, the site-specific procedure of the *Provisions* and ASCE 7-10 calculates the MCE$_R$ ground

motion as the lesser of a probabilistic and a deterministic ground motion. The definitions of the probabilistic and deterministic ground motions in ASCE 7-10, however, are different than in ASCE 7-05. The definitions were revised for the 2009 *Provisions* and ASCE 7-10 by the BSSC Seismic Design Procedures Reassessment Group (SDPRG), also referred to as Project '07. Three revisions were made:

1) The probabilistic ground motions are redefined as so-called risk-targeted ground motions, in lieu of the uniform-hazard (2% in 50-year) ground motions that underlie the ASCE 7-05 MCE ground motion maps,

2) the deterministic ground motions are redefined as 84^{th}-percentile ground motions, in lieu of median ground motions multiplied by 1.5; and

3) the probabilistic and deterministic ground motions are redefined as maximum-direction ground motions, in lieu of geometric mean ground motions.

In addition to these three BSSC redefinitions of probabilistic and deterministic ground motions, there is a fourth difference in the ground motion values computed by the USGS for the 2009 *Provisions* and ASCE 7-10 versus ASCE 7-05:

4) The probabilistic and deterministic ground motions were recomputed using updated earthquake source and ground motion propagation models, e.g., the Unified California Earthquake Rupture Forecast (UCERF, Version 2; Field et al., 2008) and the Next Generation Attenuation (NGA) ground motion models[4].

Each of the above four differences between the basis of the MCE ground motions (in ASCE 7-05) and that of the MCE_R ground motions (in the 2009 *Provisions* and ASCE 7-10) is explained in more detail below. Also explained are the differences in the presentation of MCE_R ground motions between the 2009 *Provisions* and ASCE 7-10; the numerical values of the MCE_R ground motions in the two documents are otherwise identical.

3.1.2.1 Risk-Targeted Probabilistic Ground Motions

For the MCE ground motion maps in ASCE 7-05, recall (from Section 3.1.1) that the underlying probabilistic ground motions are specified to be uniform-hazard ground motions that have a 2% probability of being exceeded in 50 years. It has long been recognized, though, that "it really is the probability of structural failure with resultant casualties that is of concern; and the geographical distribution of that probability is not necessarily the same as the distribution of the probability of exceeding some ground motion" (p. 296 of ATC 3-06, 1978). The primary reason that the distributions of the two probabilities are not the same is that there are geographic differences in the shape of the hazard curves from which uniform-hazard ground motions are read. The *Commentary* of FEMA 303 (p. 289) reports that "because of these differences, questions were raised concerning whether definition of the ground motion based on a constant probability for the entire United States would result in similar levels of seismic safety for all structures".

The changeover to risk-targeted probabilistic ground motions for the 2009 *Provisions* and ASCE 7-10 takes into account the differences in the shape of hazard curves across the US. Where used in design, the risk-targeted ground motions are expected to result in buildings with a geographically uniform mean annual frequency of collapse, or uniform risk. The BSSC, via Project '07, decided on a target risk level corresponding to 1% probability of collapse in 50 years. This target is based on the average of the mean annual frequencies of collapse across the Western US (WUS) expected to result from design for the

[4] See the February 2008 *Earthquake Spectra* "Special Issue on the Next Generation Attenuation Project," Volume 24, Number 1.

probabilistic ground motions in ASCE 7-05. Consequently, in the WUS the risk-targeted ground motions in the 2009 *Provisions* and ASCE 7-10 are generally within 15% of the corresponding uniform-hazard (2% in 50-year) ground motions. In the Central and Eastern US, where the shapes of hazard curves are known to differ from those in the WUS, the risk-targeted ground motions generally are smaller. For instance, in the New Madrid Seismic Zone and near Charleston, South Carolina ratios of risk-targeted to uniform-hazard ground motions are as small as 0.7.

The computation of risk-targeted probabilistic ground motions for the MCE_R ground motions in the 2009 *Provisions* and ASCE 7-10 is detailed in *Provisions* Part 1 Sections 21.2.1.2 and C21.2.1 and in Luco et al. (2007). While the computation of the risk-targeted ground motions is different than that of the uniform-hazard ground motions specified for the MCE ground motions in ASCE 7-05, both begin with USGS computations of hazard curves. As explained in Section 3.1.1, the uniform-hazard ground motions simply interpolate the hazard curves for a 2% probability of exceedance in 50 years. In contrast, the risk-targeted ground motions make use of entire hazard curves. In either case, the end results are probabilistic spectral response accelerations at 0.2 seconds and 1 second, for 5% of critical damping and the reference site class.

3.1.2.2 84th-Percentile Deterministic Ground Motions

For the MCE ground motion maps in ASCE 7-05, recall (from Section 3.1.1) that the underlying deterministic ground motions are defined as 150% of median spectral response accelerations. As explained in the FEMA 303 *Commentary* (p. 296),

> *Increasing the median ground motion estimates by 50 percent [was] deemed to provide an appropriate margin and is similar to some deterministic estimates for a large magnitude characteristic earthquake using ground motion attenuation functions with one standard deviation. Estimated standard deviations for some active fault sources have been determined to be higher than 50 percent, but this increase in the median ground motions was considered reasonable for defining the maximum considered earthquake ground motions for use in design.*

For the MCE_R ground motions in the 2009 *Provisions* and ASCE 7-10, however, the BSSC decided to define directly the underlying deterministic ground motions as those at the level of one standard deviation. More specifically, they are defined as 84th-percentile ground motions (since it has been widely observed that ground motions follow lognormal probability distributions). The remainder of the definition of the deterministic ground motions remains the same as that used for the MCE ground motions maps in ASCE 7-05. For example, the lower limits of 1.5g and 0.6g described in Section 3.1.1 are retained.

The USGS applied a simplification specified by the BSSC in computing the 84th-percentile deterministic ground motions for the 2009 *Provisions* and ASCE 7-10. The 84th-percentile spectral response accelerations were approximated as 180% of median values. This approximation corresponds to a logarithmic ground motion standard deviation of approximately 0.6, as demonstrated in the *Provisions* Part 1 Section C21.2.2. The computation of deterministic ground motions is further described in *Provisions* Part 2 Section C21.2.2.

3.1.2.3 Maximum-Direction Probabilistic and Deterministic Ground Motions

Due to the ground motion attenuation models used by the USGS in computing them[5], overall the MCE spectral response accelerations in ASCE 7-05 represent the geometric mean of two horizontal components of ground motion. Most users of ASCE 7-05 are unaware of this fact, particularly since the discussion notes on the MCE ground motion maps incorrectly state that they represent “the random horizontal component of ground motion.” For the 2009 *Provisions* and ASCE 7-10, the BSSC decided that it would

[5] See the January/February 1997 *Seismological Research Letters* “Special Issue on Ground Motion Attenuation Relations,” Volume 68, Number 1.

be an improvement if the MCE_R ground motions represented the maximum direction of horizontal spectral response acceleration. Reasons for this decision are explained in *Provisions* Part 1 Section C21.2.

Since the attenuation models used in computing the 2008 update of the USGS ground motions also represent (overall) "geomean" spectral response accelerations, for the 2009 *Provisions* and ASCE 7-10 the BSSC provided factors to convert approximately to "maximum-direction" ground motions. Based on research by Huang et al. (2008) and others, the factors are 1.1 and 1.3 for the spectral response accelerations at 0.2 seconds and 1.0 second, respectively. The basis for these factors is elaborated upon in the *Provisions* Part 1 Section C21.2. They are applied to both the USGS probabilistic hazard curves from which the risk-targeted ground motions (described in Section 3.1.2.1) are derived and the USGS deterministic ground motions (described in Section 3.1.2.2).

3.1.2.4 Updated Ground Motions from USGS (2008)

For the MCE ground motion maps in ASCE 7-05, recall (from Section 3.1.1) that the underlying probabilistic and deterministic ground motions are from the 2002 USGS update. As mentioned above, the MCE_R ground motions in the 2009 *Provisions* and ASCE 7-10 are instead based on the 2008 update of the USGS ground motion values. This update is documented in Petersen et al. (2008) and supersedes the 1996 and 2002 USGS ground motions values. It involved interactions with hundreds of scientists and engineers at regional and topical workshops, including advice from working groups, expert panels, state geological surveys, other federal agencies and hazard experts from industry and academia. Based in large part on new published studies, the 2008 update incorporated changes in both earthquake source models (including magnitudes and occurrence frequencies) and models of ground motion propagation. The UCERF and NGA models mentioned above are just two examples of such changes. The end results are updated ground motions that represent the "best available science" as determined by the USGS from an extensive information-gathering and review process.

It is important to note that the 2008 USGS hazard curves and uniform-hazard maps (posted at http://earthquake.usgs.gov/hazards/products/conterminous/2008/), like their 2002 counterparts, represent the "geomean" ground motions discussed in the preceding subsection. Only the MCE_R ground motions and their underlying probabilistic and deterministic ground motions represent the maximum direction of horizontal spectral response acceleration.

3.1.2.5 Differing Presentation of MCE_R Ground Motions in the Provisions *and in ASCE 7-10*

Though their numerical values are identical, the MCE_R ground motions specified in the *Provisions* and in ASCE 7-10 are presented differently. As replacements to the MCE ground motion maps in ASCE 7-05, ASCE 7-10 presents (in Chapter 22) contour maps of the MCE_R ground motions for Site Class B, which are still denoted S_S and S_1 for the 0.2- and 1.0-second spectral response accelerations, respectively. Like the MCE ground motions in ASCE 7-05, the MCE_R ground motions mapped in ASCE 7-10 are accessible electronically via a USGS web application (see http://earthquake.usgs.gov/designmaps/).

In contrast, *Provisions* Section 11.4 presents equations to calculate MCE_R ground motions (S_S and S_1) for Site Class B using maps (in Chapter 22) of uniform-hazard 2% in 50-year ground motions (denoted S_{SUH} and S_{1UH}), so-called risk coefficients (denoted C_{RS} and C_{R1}); and deterministic ground motions (denoted S_{SD} and S_{1D}, not to be confused with the design ground motions S_{DS} and S_{D1}). The risk coefficient maps show the ratio of the risk-targeted probabilistic ground motions (described in Section 3.1.2.1) to corresponding 2% in 50-year ground motions like those used to derive the MCE ground motion maps in ASCE 7-05. The intent of the equations and three sets of maps presented in the *Provisions* is transparency in the derivation of the MCE_R ground motions. The mapped values of the uniform-hazard ground motions, risk coefficients and deterministic ground motions are all accessible electronically via http://earthquake.usgs.gov/designmaps/.

3.1.3 PGA Maps in the *Provisions* and in ASCE 7-10

The basis of the Peak Ground Acceleration (PGA) maps in the *Provisions* and in ASCE 7-10 nearly parallels that of the MCE ground motion maps in ASCE 7-05 described in Section 3.1.1.1. More specifically, the mapped PGA values for Site Class B are calculated as the lesser of uniform-hazard (2% in 50-year) probabilistic and deterministic PGA values that represent the geometric mean of two horizontal components of ground motion. Unlike in ASCE 7-05, though, the deterministic values are defined as 84^{th}-percentile ground motions rather than 150% of median ground motions. This definition of deterministic ground motions parallels that which is described above for the MCE_R ground motions in the 2009 *Provisions* and ASCE 7-10. The deterministic PGA values, though, are stipulated to be no lower than 0.5g, as opposed to 1.5g and 0.6g (respectively) for the MCE_R 0.2- and 1.0-second spectral response accelerations. All of these details of the basis of the PGA maps are provided in ASCE 7-10 Section 21.5; the *Provisions* do not contain a site-specific procedure for PGA values.

The USGS-computed PGA values for $v_{S,30}$ = 760m/s that are mapped, like their MCE_R ground motion counterparts in the *Provisions* and in ASCE 7-10, are from the 2008 USGS update. Also like their MCE_R ground motion counterparts, the 84^{th}-percentile PGA values have been approximated as median values multiplied by 1.8.

While the values on and format of the PGA maps in the *Provisions* and in ASCE 7-10 are identical, the terminology used to label the maps (and values) is different in the two documents. In the *Provisions*, they are referred to as "MCE Geometric Mean PGA" maps. In ASCE 7-10, they are labeled "Maximum Considered Earthquake Geometric Mean (MCE_G) PGA" maps. The MCE_G abbreviation is intended to remind users of the differences between the basis of the PGA maps and the MCE_R maps also in ASCE 7-10, namely that the PGA values represent the geometric mean of two horizontal components of ground motion, not the maximum direction; and that the probabilistic PGA values are not risk-targeted ground motions, but rather uniform-hazard (2% in 50-year) ground motions.

3.1.4 Basis of Vertical Ground Motions in the *Provisions* and in ASCE 7-10

Whereas ASCE 7-05 determines vertical seismic load effects via a single constant fraction of the horizontal short-period spectral response acceleration S_{DS}, the 2009 *Provisions* and ASCE 7-10 determine a vertical design response spectrum, S_{av}, that is analogous to the horizontal design response spectrum, S_a. The S_{av} values are determined via functions (for four different ranges of vertical period of vibration) that each depend on S_{DS} and a coefficient C_v representing the ratio of vertical to horizontal spectral response acceleration. This is in contrast to determination of S_a via mapped horizontal spectral response accelerations. The coefficient C_v, in turn, depends on the amplitude of spectral response acceleration (by way of S_S) and site class. These dependencies, as well as the period dependence of the equations for S_{av}, are based on studies by Bozorgnia and Campbell (2004) and others. Those studies observed that the ratio of vertical to horizontal spectral response acceleration is sensitive to period of vibration, site class, earthquake magnitude (for relatively soft sites) and distance to the earthquake. The sensitivity to the latter two characteristics is captured by the dependence of C_v on S_S.

The basis of the equations for vertical response spectra in the *Provisions* and in ASCE 7-10 is explained in more detail in the commentary to Chapter 23 of each document. Note that for vertical periods of vibration greater than 2 seconds, Chapter 23 stipulates that the vertical spectral response accelerations be determined via a site-specific procedure. A site-specific study also may be performed for periods less than 2 seconds, in lieu of using the equations for vertical response spectra.

3.1.5 Summary

While the new Risk-Targeted Maximum Considered Earthquake (MCE_R) ground motions in the *Provisions* and in ASCE 7-10 are similar to the MCE ground motions in ASCE 7-05, in that they both represent the lesser of probabilistic and deterministic ground motions, there are many differences in their

development. The definitions of the probabilistic and deterministic ground motions that underlie the MCE_R ground motions were revised by the BSSC Seismic Design Procedures Reassessment Group (SDPRG, or Project '07); and the hazard modeling upon which these ground motions are based was updated by the USGS (in 2008). In particular, the underlying probabilistic ground motions were redefined as so-called risk-targeted ground motions, which led to the new "MCE_R ground motion" terminology.

The basis of the new Peak Ground Acceleration (PGA) maps in the *Provisions* and in ASCE 7-10 nearly parallels that of the 0.2- and 1.0-second MCE spectral response accelerations in ASCE 7-05 (with one important exception); new equations for vertical ground motion spectra are based on recent studies of the ratio of vertical to horizontal ground motions. The long-period transition (T_L) maps in the new documents are the same as those in ASCE 7-05.

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3.2 DETERMINATION OF GROUND MOTION VALUES AND SPECTRA

This example illustrates the determination of seismic design parameters for a site in Seattle, Washington. The site is located at 47.65ºN latitude, 122.3ºW longitude. Using the results of a site-specific geotechnical investigation and the procedure specified in *Standard* Chapter 20, the site is classified as Site Class C. (This is the same site used in Design Example 6.3.)

In the sections that follow design ground motion parameters are determined using ASCE 7-05, the 2009 *Provisions* and ASCE 7-10. Using the 2009 *Provisions*, horizontal response spectra, vertical response spectra and peak ground accelerations are computed for both design and maximum considered earthquake ground motions.

3.2.1 ASCE 7-05 Ground Motion Values

ASCE 7-05 Section 11.4.1 requires that spectral response acceleration parameters S_S and S_1 be determined using the maps in Chapter 22. Those maps are too small to permit reading values to a sufficient degree of precision for most sites, so in practice the mapped parameters are determined using a software application available at www.earthquake.usgs.gov/designmaps. That application requires that longitude be entered in degrees east of the prime meridian; negative values are used for degrees west. Given the site location, the following values may be determined using the online application (or read from Figures 22-1 and 22-2).

$S_S = 1.306$
$S_1 = 0.444$

Using these mapped spectral response acceleration values and the site class, site coefficients F_a and F_v are determined in accordance with Section 11.4.3 using Tables 11.4-1 and 11.4-2. Using Table 11.4-1, for $S_S = 1.306 > 1.25$, $F_a = 1.0$ for Site Class C. Using Table 11.4-2, read $F_v = 1.4$ for $S_1 = 0.4$ and $F_v = 1.3$ for $S_1 \geq 0.5$ for Site Class C. Using linear interpolation for $S_1 = 0.444$,

$$F_v = 1.4 + \frac{0.444 - 0.4}{0.5 - 0.4}(1.3 - 1.4) = 1.356$$

Using Equations 11.4-1 and 11.4-2 to determine the adjusted maximum considered earthquake spectral response acceleration parameters,

$$S_{MS} = F_a S_S = 1.0(1.306) = 1.306$$
$$S_{M1} = F_v S_1 = 1.356(0.444) = 0.602$$

Using Equations 11.4-3 and 11.4-4 to determine the design earthquake spectral response acceleration parameters,

$$S_{DS} = \frac{2}{3} S_{MS} = \frac{2}{3}(1.306) = 0.870$$
$$S_{D1} = \frac{2}{3} S_{M1} = \frac{2}{3}(0.602) = 0.401$$

Given the site location read Figure 22-15 for the long-period transition period, T_L = 6 seconds.

3.2.2 2009 *Provisions* Ground Motion Values

Part 1 of the 2009 *Provisions* modifies Chapter 11 of ASCE 7-05 to update the seismic design ground motion parameters and procedures as described in Section 3.1.2 above. Given the site location, the following values may be determined using the online application (or read from *Provisions* Figures 22-1 through 22-6).

S_{SUH} = 1.305
S_{1UH} = 0.522
C_{RS} = 0.988
C_{R1} = 0.955
S_{SD} = 1.5
S_{1D} = 0.6

"UH" and "D" appear, respectively, in the subscripts to indicate uniform hazard and deterministic values of the spectral response acceleration parameters at short periods and at a period of 1 second, S_S and S_1. C_{RS} and C_{R1} are the mapped risk coefficients at short periods and at a period of 1 second. S_{1D} should not be confused with S_{D1}, which is computed below.

The spectral response acceleration parameter at short periods, S_S, is taken as the lesser of the values computed using *Provisions* Equations 11.4-1 and 11.4-2.

$S_S = C_{RS} S_{SUH}$ = 0.988(1.305) = 1.289
$S_S = S_{SD}$ = 1.5

Therefore, S_S = 1.289.

The spectral response acceleration parameter at a period of 1 second, S_1, is taken as the lesser of the values computed using *Provisions* Equations 11.4-3 and 11.4-4.

$S_1 = C_{R1}\, S_{1UH} = 0.955(0.522) = 0.498$
$S_1 = S_{1D} = 0.6$

Therefore, $S_1 = 0.498$.

Using these spectral response acceleration values and the site class, site coefficients F_a and F_v are determined in accordance with Section 11.4.3 using Tables 11.4-1 and 11.4-2 (which are identical to the Tables in ASCE 7-05). Using Table 11.4-1, for $S_S = 1.289 > 1.25$, $F_a = 1.0$ for Site Class C. Using Table 11.4-2, read $F_v = 1.4$ for $S_1 = 0.4$ and $F_v = 1.3$ for $S_1 \geq 0.5$ for Site Class C. Using linear interpolation for $S_1 = 0.498$,

$$F_v = 1.4 + \frac{0.498 - 0.4}{0.5 - 0.4}(1.3 - 1.4) = 1.302$$

Using *Provisions* Equations 11.4-5 and 11.4-6 to determine the MCE_R spectral response acceleration parameters,

$$S_{MS} = F_a S_S = 1.0(1.289) = 1.289$$
$$S_{M1} = F_v S_1 = 1.302(0.498) = 0.649$$

Using *Provisions* Equations 11.4-7 and 11.4-8 to determine the design earthquake spectral response acceleration parameters,

$$S_{DS} = \frac{2}{3} S_{MS} = \frac{2}{3}(1.289) = 0.859$$
$$S_{D1} = \frac{2}{3} S_{M1} = \frac{2}{3}(0.649) = 0.433$$

Given the site location read *Provisions* Figure 22-7 for the long-period transition period, $T_L = 6$ seconds.

3.2.3 ASCE 7-10 Ground Motion Values

The seismic design ground motion parameters and procedures in Chapter 11 of ASCE 7-10 are consistent with those in the 2009 *Provisions*. Given the site location, the following values may be determined using the online application (or read from ASCE 7-10 Figures 22-1 and 22-2).

$S_S = 1.289$
$S_1 = 0.498$

Using these spectral response acceleration values and the site class, site coefficients F_a and F_v are determined in accordance with Section 11.4.3 using Tables 11.4-1 and 11.4-2 (which are identical to the Tables in ASCE 7-05 and in the 2009 *Provisions*). Using Table 11.4-1, for $S_S = 1.289 > 1.25$, $F_a = 1.0$ for Site Class C. Using Table 11.4-2, read $F_v = 1.4$ for $S_1 = 0.4$ and $F_v = 1.3$ for $S_1 \geq 0.5$ for Site Class C. Using linear interpolation for $S_1 = 0.498$,

$$F_v = 1.4 + \frac{0.498 - 0.4}{0.5 - 0.4}(1.3 - 1.4) = 1.302$$

Using Equations 11.4-1 and 11.4-2 to determine the MCE$_R$ spectral response acceleration parameters,

$$S_{MS} = F_a S_S = 1.0(1.289) = 1.289$$
$$S_{M1} = F_v S_1 = 1.302(0.498) = 0.649$$

Using Equations 11.4-3 and 11.4-4 to determine the design earthquake spectral response acceleration parameters,

$$S_{DS} = \frac{2}{3} S_{MS} = \frac{2}{3}(1.289) = 0.859$$
$$S_{D1} = \frac{2}{3} S_{M1} = \frac{2}{3}(0.649) = 0.433$$

Given the site location read ASCE 7-10 Figure 22-12 for the long-period transition period, $T_L = 6$ seconds.

The procedure specified in ASCE 7-10 produces seismic design ground motion parameters that are identical to those produced using the 2009 *Provisions*—but in fewer steps.

3.2.4 Horizontal Response Spectra

The design spectrum is constructed in accordance with *Provisions* Section 11.4.5 using *Provisions* Figure 11.4-1 and *Provisions* Equations 11.4-9, 11.4-10 and 11.4-11. The design spectral response acceleration ordinates, S_a, may be divided into four regions based on period, T, as described below.

From $T = 0$ to $T_0 = 0.2\frac{S_{D1}}{S_{DS}} = 0.2\left(\frac{0.433}{0.859}\right) = 0.101$ seconds, S_a varies linearly from $0.4S_{DS}$ to S_{DS}.

From T_0 to $T_S = \frac{S_{D1}}{S_{DS}} = \frac{0.433}{0.859} = 0.504$ seconds, S_a is constant at S_{DS}.

From T_S to T_L, S_a is inversely proportional to T, being anchored to S_{D1} at $T = 1$ second.

At periods greater than T_L, S_a is inversely proportional to the square of T, being anchored to $\frac{S_{D1}}{T_L}$ at T_L.

As prescribed in *Provisions* Section 11.4.6, the MCE$_R$ response spectrum is determined by multiplying the design response spectrum ordinates by 1.5. Figure 3-1 shows the design and MCE$_R$ response spectra determined using the ground motion parameters computed in Section 3.2.3.

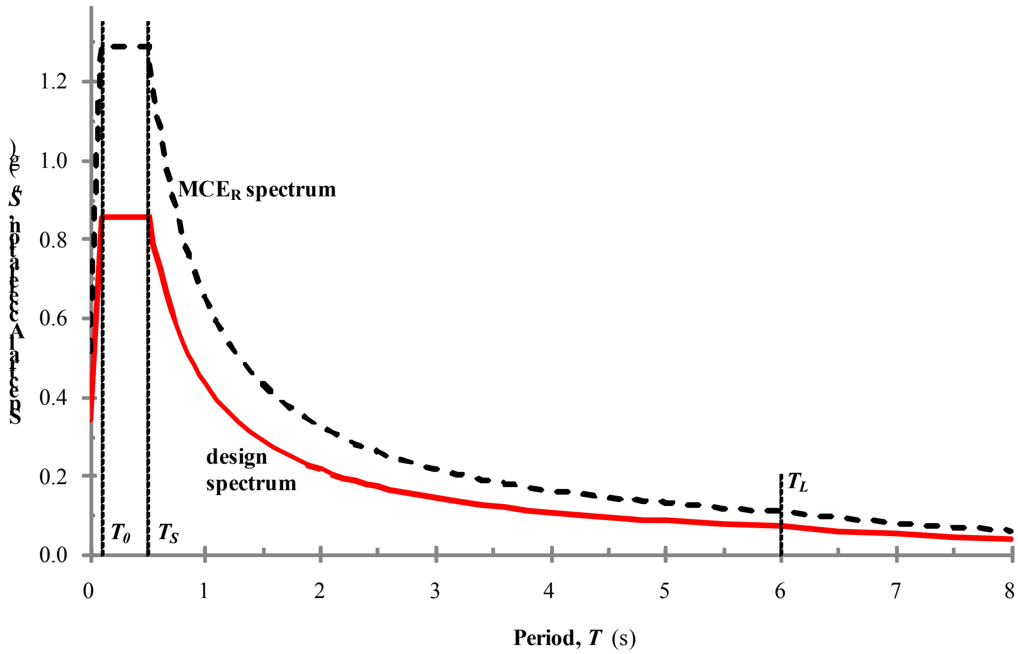

Figure 3-1 Horizontal Response Spectra for Design and MCE$_R$ Ground Motions

3.2.5 Vertical Response Spectra

Part 1 of the 2009 *Provisions* adds a new chapter (Chapter 23) to ASCE 7-05 to define vertical ground motions for seismic design. The design vertical response spectrum is constructed in accordance with *Provisions* Section 23.1 using *Provisions* Equations 23.1-1, 23.1-2, 23.1-3 and 23.1-4. Vertical ground motion values are related to horizontal ground motion values by a vertical coefficient, C_v, which is determined as a function of site class and the MCE$_R$ spectral response parameter at short periods, S_S. The design vertical spectral response acceleration ordinates, S_{av}, may be divided into four regions based on vertical period, T_v, as described below.

Using *Provisions* Table 23.1-1, read $C_v = 1.3$ for $S_S \geq 2.0$ and $C_v = 1.1$ for $S_S = 1.0$ for Site Class C. Using linear interpolation for $S_S = 1.289$,

$$C_v = 1.1 + \frac{1.289 - 1}{2 - 1}(1.3 - 1.1) = 1.158$$

From $T_v = 0$ to 0.025 seconds, S_{av} is constant at $0.3C_vS_{DS} = 0.3(1.158)(0.859) = 0.298$. From $T_v = 0.025$ to 0.05 seconds, S_{av} varies linearly from $0.3C_vS_{DS} = 0.298$ to $0.8C_vS_{DS} = 0.8(1.158)(0.859) = 0.796$. From $T_v = 0.05$ to 0.15 seconds, S_{av} is constant at $0.8C_vS_{DS} = 0.796$. From $T_v = 0.15$ to 2.0 seconds, S_{av} is inversely proportional to $T_v^{0.75}$, being anchored to $0.8C_vS_{DS} = 0.796$ at $T_v = 0.15$ seconds. For vertical periods greater than 2.0 seconds, the vertical response spectral acceleration must be determined using site-specific procedures.

As prescribed in *Provisions* Section 23.2, the MCE$_R$ vertical response spectrum is determined by multiplying the design vertical response spectrum ordinates by 1.5. Figure 3-2 shows the design and MCE$_R$ vertical response spectra determined using the ground motion parameters computed in Section 3.2.3.

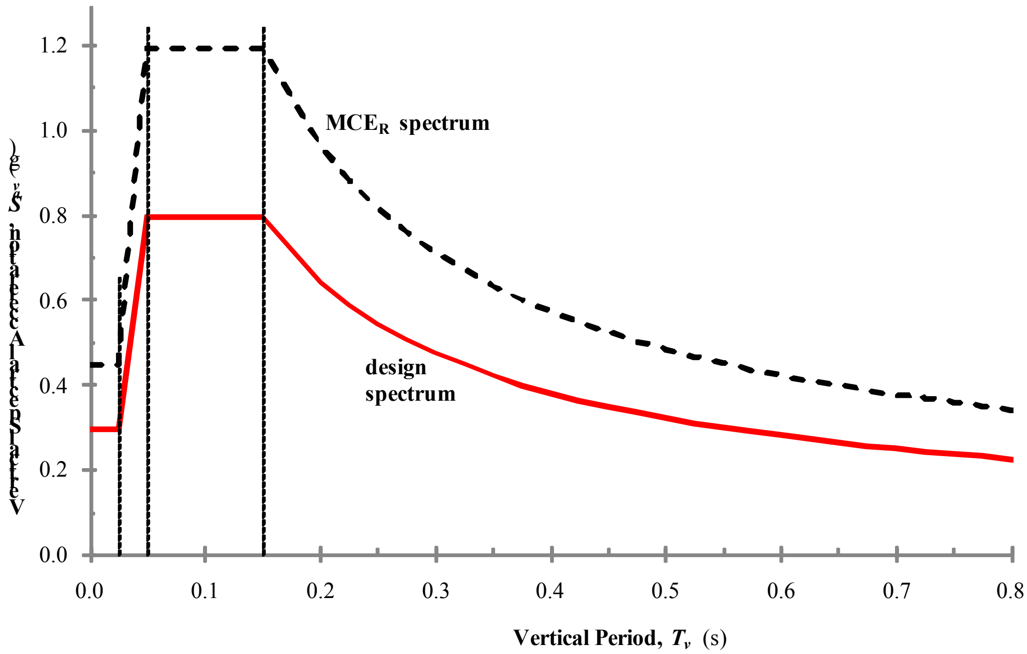

Figure 3-2 Vertical Response Spectra for Design and MCE$_R$ Ground Motions

3.2.6 Peak Ground Accelerations

Part 1 of the 2009 *Provisions* modifies Section 11.8.3 of the ASCE 7-05 to update the calculation of peak ground accelerations used for assessment of the potential for liquefaction and soil strength loss and for determination of lateral earth pressures for design of basement and retaining walls. Given the site location, the following value of maximum considered earthquake geometric mean peak ground acceleration may be determined using the online application (or read from *Provisions* Figure 22-8).

$PGA = 0.521$ g

Using this mapped peak ground acceleration value and the site class, site coefficient F_{PGA} is determined in accordance with Section 11.8.3 using Table 11.8-1. Using Table 11.8-1, for $PGA = 0.521 > 0.5$, $F_{PGA} = 1.0$ for Site Class C. Using *Provisions* Equation 11.8-1 to determine the maximum considered earthquake geometric mean peak ground acceleration adjusted for site class effects,

$PGA_M = F_{PGA}\, PGA = 1.0(0.521) = 0.521$ g

This value is used directly to assess the potential for liquefaction or for soil strength loss. The design peak ground acceleration used to determine dynamic seismic lateral earth pressures for design of basement and retaining walls is computed as $\frac{2}{3} PGA_M = \frac{2}{3}(0.521) = 0.347$ g.

3.3 SELECTION AND SCALING OF GROUND MOTION RECORDS

Response history analysis (whether linear or nonlinear) consists of the step-wise application of time-varying ground accelerations to a mathematical model of the subject structure. The selection and scaling of appropriate horizontal ground motion acceleration time histories is essential to produce meaningful

results. For two-dimensional or three-dimensional structural analysis, single-component or two-component records are used, respectively. The sections that follow discuss the approach to selection and scaling of ground motion records as prescribed in the *Provisions* (and ASCE 7), illustrate the selection and scaling of two-component ground motions for the structure analyzed in Design Example 6.3 located at the site considered in Section 3.2 and discuss differences in the process for single-component ground motions.

3.3.1 Approach to Ground Motion Selection and Scaling

In the simplest terms the goal of ground motion selection and scaling is to produce acceleration histories that are consistent with the ground shaking hazard anticipated for the subject structure at the site in question. As difficult as it is to forecast the occurrence of an earthquake, it is even more difficult to predict the precise waveform and phasing of the resulting accelerations at a given site. Instead it is necessary to approximate (somewhat crudely) what ground motions can be expected based on past observations (and, possibly, geologic modeling). *Provisions* Section 16.1.3 prescribes the most commonly applied approach to this process. While some aspects of the process are quite prescriptive, others permit considerable latitude in application.

The Pacific Earthquake Engineering Research Center makes available a database of ground motions (at http://peer.berkeley.edu/peer_ground_motion_database/) and a web application for the selection and scaling of ground motions (PEER, 2010). As useful as that data and application are, they do not provide a comprehensive solution to the challenge of ground motion selection and scaling in accordance with the *Provisions* for all U.S. sites. Pertinent limitations include the following.

- The database is limited to shallow crustal earthquakes recorded in "active tectonic regimes," like parts of the western U.S. It does not include records from subduction zone earthquakes, deep intraplate events, or events in less active tectonic regimes (such as the central and eastern U.S.).

- The web application allows use of a code design spectrum (from the *Provisions* or ASCE 7) as a target and includes powerful selection and scaling methods. However, the set of selected and scaled records produced would still require minor adjustment (scaling up) to satisfy the requirements in *Provisions* Section 16.1.3 over the period range of interest.

3.3.1.1 Number of ground motions. In recognition of the impossibility of predicting the actual ground motion history that should be expected, Section 16.1.3 requires the use of at least three ground motions in any response history analysis. Where at least seven ground motions are used, Sections 16.1.4 and 16.2.4 permit the use of average response quantities for design. The difference is not one of statistical significance; in either case mean response is approximated, but an incentive is given for the use of more records, which could identify a potential sensitivity in the response. The objective of the response history analyses is not to evaluate the response of the building for each record (since none of the records used will actually occur), but to determine the expected (average) response quantities for use in design calculations. If the analysis predicts collapse for one or more ground motions, the average cannot be computed; the structure is deemed inadequate and must be redesigned.

3.3.1.2 Recorded or synthetic ground motions. Horizontal ground motion acceleration records should be selected as single components (for two-dimensional analysis) or as orthogonal pairs (for three-dimensional analysis) from actual recorded events. Where the number of appropriate recorded ground motions is insufficient, use of "simulated" records is permitted. While generation of completely artificial records is not directly prohibited, the intent (as expressed in *Provisions* Section C16.1.3) is that such simulation is limited to modification for site distance and soil conditions.

3.3.1.3 "Appropriate" ground motions. The measure of "appropriate" applied to ground motions by the *Provisions* is consistency with the magnitude, fault distance and source mechanism that control the maximum considered earthquake. (Other characteristics of ground motion, such as duration, may influence response, but are not addressed by the *Provisions*.) While it is good practice to select ground motions with these characteristics in mind, the available data are quite limited. And even where the available records are very carefully binned and match the target characteristics quite closely, they are far from homogeneous.

As discussed in Section 3.1 the mapped ground motion parameters reflect the likelihood that a certain level of spectral acceleration will be exceeded in a selected period, considering numerous sources of earthquake ground shaking. While the mapping process does not sum accelerations from various sources it does aggregate the probabilities of occurrence from those sources. As a result, it is impossible to determine the controlling source characteristics using only the mapped acceleration parameters. In order to identify the magnitude, fault distance and source mechanism that control the maximum considered earthquake at a specific spectral period, it is necessary to "deaggregate" the hazard, which requires reviewing the underlying calculations to note the relative contribution of each source. The USGS provides tools to deaggregate hazard, providing results in three formats: a text tabulation, a graphic presentation binned by distance and magnitude and a graphic presentation projected on a map. Figure 3-3 shows the two graphic formats for the 2-second period spectral acceleration with a 2% probability of exceedance in 50 years (the maximum considered earthquake) at the site considered in Section 3.2.

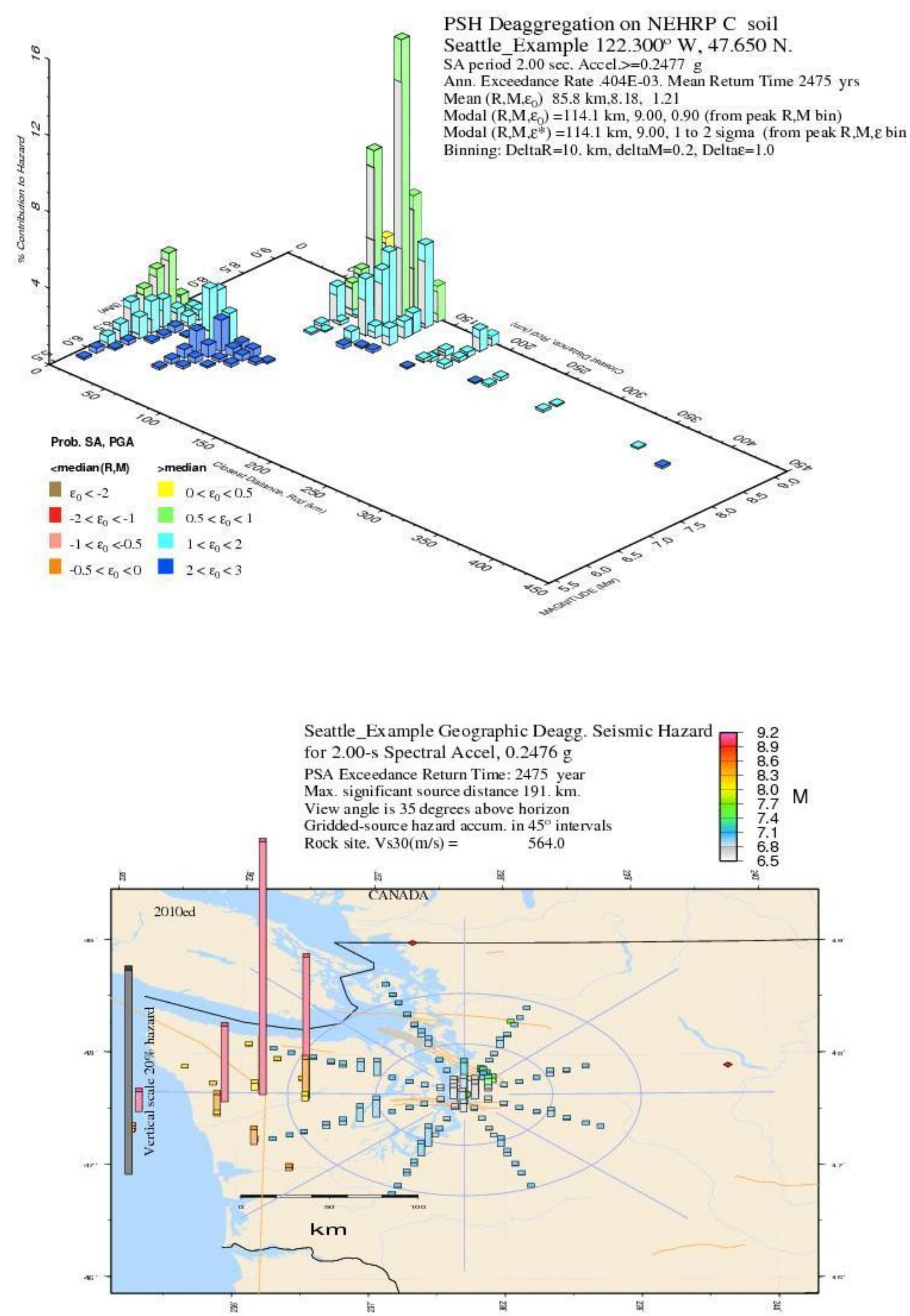

Figure 3-3 Graphic results of deaggregation

At most sites deaggregation of hazard reveals that a single source controls the maximum considered earthquake ground motions for all spectral periods. However, at some sites different sources control the maximum considered earthquake ground motions at different spectral periods. Figure 3-4 shows, for one such site, the maximum considered earthquake response spectrum generated from mapped ground motion

parameters as well as median acceleration response spectra for two of the contributing sources. Since the shape of the uniform hazard spectrum, upon which the design spectrum is based, is artificial (arising from the probabilistic seismic hazard analysis rather than the characteristics of recorded ground motions), there may be conservatisms involved in providing an aggregate match for design purposes (PEER, 2010). However, that aggregate match is exactly what the *Provisions* requires, so it is prudent to consider how that conservatism may best be balanced.

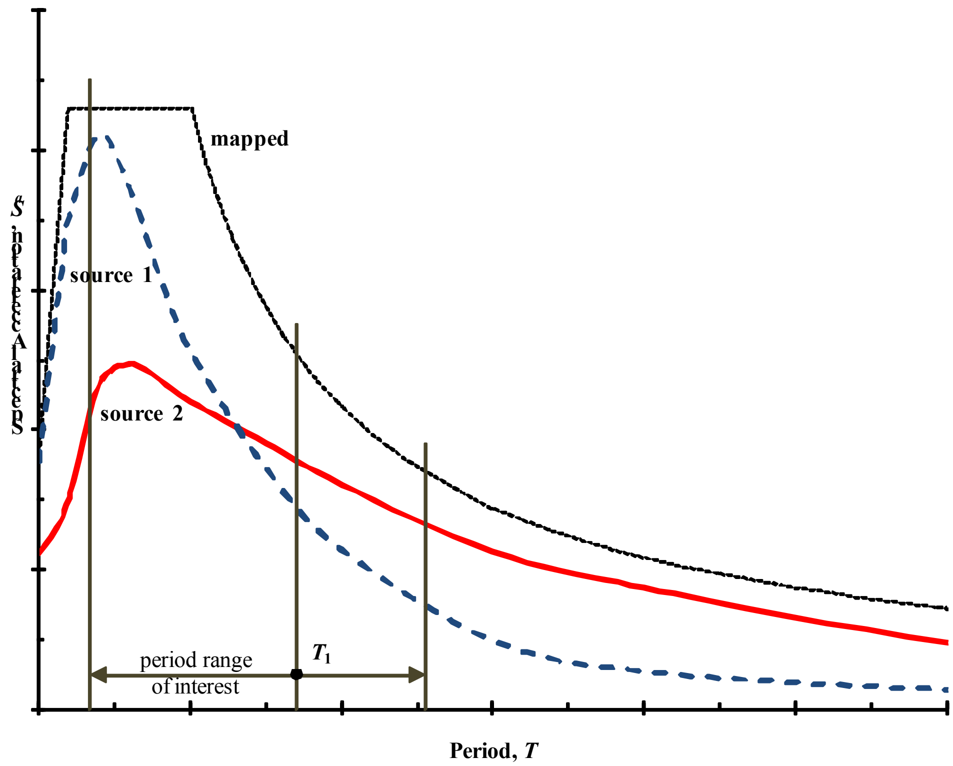

Figure 3-4 Response spectra for a site with multiple controlling sources

In this example, source 1 can generate moderate magnitude events close to the site; Source 2 can generate very large magnitude events far from the site. Due to differing source and attenuation characteristics, each source can control a portion of the MCE_R response spectrum. The response of short period structures or very long period structures will be governed by source 1 or source 2, respectively. However, the "controlling" source is less clear for a structure with a fundamental period shown as T_1 in the figure. Source 2 appears to control at period T_1, but as discussed in Section 3.3.1.5, the *Provisions* defines a wider period range of interest over which the selected ground motions must be "appropriate." As outlined below, three approaches are readily apparent.

- First (and arguably most technically correct), select two full sets of (seven or more) ground motion records conditionally—one set for each source, enveloping the MCE_R spectrum for the **portion** of the period range of interest controlled by that source. Since the corresponding portions of the actual and target spectral shapes would be similar, scale factors would be modest. In this case, an independent series of analyses would be performed for each set of ground motion records. Mean response parameters of interest could be computed for each set of analyses and the more conservative of the two mean values for each response parameter could be used for design verification. Although this approach has technical appeal, the *Provisions* do not outline such a

procedure that makes use of two sets of ground motions, instead requiring use of a single set that on average envelops the entire period range of interest of the target spectrum.

- Second, select a full set of ground motions consistent with Source 2 and then scale the set to envelop the much differently shaped MCE_R spectrum over the specified period range of interest. While permitted by the *Provisions*, this approach would require large scale factors that unrealistically exaggerate the long period response. It may seem that this set of ground motions has a desired degree of homogeneity, but that comes at the expense of a very poor fit for the average.

- Third, select a set with some ground motions for each controlling source type. Select individual scale factors so that the average of their linear elastic spectra envelops the target spectrum (as required by the *Provisions*) and is shaped similarly to the target. As a result of this process, records consistent with Source 1 will control short periods and those consistent with Source 2 will control long periods. The scale factors will be somewhat larger than those required by the first (conditional) approach, but not excessively large like those in the second approach. Although the record set is less homogeneous than that used in the second approach, the average is much closer to the target. Where used for linear response history analysis, this approach will produce average response quantities consistent with the average linear response spectrum used in the scaling process. Where used for nonlinear response history analysis, this approach (which uses scale factors that are larger than those for the conditional approach) will bias the average response quantities to be slightly more conservative and may increase the prediction of response extremes (collapse). This third method is commonly employed by seismological consultants where multiple source types may govern.

3.3.1.4 Scale factors. The most commonly employed ground motion scaling method involves multiplying all of the acceleration values of the time-acceleration pairs by a scalar value. This time-domain scaling modifies the amplitude of the accelerations (to approximate changes in source magnitude and/or distance) without affecting frequency content or phasing. Although not limited by the *Provisions*, the scale factors applied to recorded ground motions should be modest (usually falling between 1/3 and 3); if very small or very large scale factors are needed, some aspect of the event that produced the source motion likely is inconsistent with the maximum considered earthquake being modeled. An identical scale factor is applied to both components of a given ground motion to avoid unrealistically biasing one direction of response. Since the response spectra for time-domain scaled ground motions retain their natural jaggedness, the acceptance criterion compares their average to the target spectrum, without imposing limits on the scaling of individual ground motions. That means that there is no single set of scale factors that may be applied to the selected ground motions (as discussed further in *Provisions* Part 2 Section C16.1.3.2)

Another ground motion scaling method involves transforming the time-acceleration data into the frequency domain (such as by means of the fast Fourier transform), making adjustments (to match exactly the target spectrum at multiple, specific frequencies) and transforming back into the time domain. This method affects amplitude, frequency content and phasing (and tends to increase the total input energy). This method makes it possible to estimate mean response with fewer ground motions, but may obscure somewhat the potential variability of response. Use of this method is permitted by the *Provisions*, but the same number of records is required as for time-domain scaling. Given the jaggedness of individual response spectra, the process of spectral matching (which produces smoother spectra) requires scale factors that can be considerably smaller or larger than those used in time-domain scaling. Since this method applies numerous scale factors to differing frequencies of each ground motion component in order to match spectral ordinates, there is no requirement that the two components be scaled identically. As the spectral ordinates of frequency-domain scaled records may fall below the target spectrum at frequencies

other than those used for matching, a second round of (minor) scaling is needed to satisfy the *Provisions* requirements.

Where single-component records are being selected for two-dimensional analysis the design response spectrum is used as a target; and *Provisions* Section 16.1.3.1 requires that the average of the response spectra not fall below the target over the period range of interest. A different approach is needed where two-component records are being selected for three-dimensional analysis. The code writers selected the square root of the sum of the squares (SRSS) of the response spectra for the two components as a measure of the ground motion amplitude for each record. However, the SRSS of two spectra is always larger than the average (and larger than the maximum). In practical terms for ground motion, it is reasonable to expect that the SRSS is larger than the average by a factor of 1.4 to 1.5 and is larger than the maximum (resultant) by a factor of about 1.2.

The code writers decided that it is sufficiently conservative to scale two-component records such that the average of the SRSS spectra does not fall below the target over the period range of interest. Given the relationship between SRSS and average, that means that scale factors for ground motions used in three-dimensional analysis are only 2/3 of those for ground motions used in two-dimensional analysis. The rationale is that a three-dimensional analysis (using two-component ground motions) subjects the structure to the maximum (resultant) acceleration in **some** direction due to the interaction of ground motion components, while that is not possible in two-dimensional analysis. Considering other conservative criteria, such as fitting over the entire period range of interest, code writers accepted that the resultant acceleration could be about 20 percent less than the design acceleration at some periods. Note that *Provisions* Section 16.1.3.2 erroneously requires that the average of the SRSS spectra not fall below the MCE_R spectrum over the period range of interest. ASCE 7-10 corrects this error by requiring that the average of the SRSS spectra be compared to “the response spectrum used in the design” (rather than to the MCE_R response spectrum).

For the special case described in Section 3.3.1.7 below, both ASCE 7-10 and the *Provisions* require scaling so that the maximum acceleration exceeds the MCE_R response spectrum. Apparently, this is an error carried forward from the *Provisions* to ASCE 7-10. Like the rest of Section 16.1.3.2, the target spectrum used for scaling should be “the response spectrum used in the design” rather than the MCE_R response spectrum (which is 1.5 times the design response spectrum).

3.3.1.5 Period range of interest. The smooth spectral acceleration response spectrum constructed using mapped acceleration parameters (and site response coefficients) is a location-specific estimate of the ground shaking hazard. No matter how carefully recorded ground motions are selected and scaled, it is unrealistic to expect a close match to the smooth target spectrum over all periods. On the other hand, selecting and scaling ground motions to match the target spectrum at the natural period for the fundamental mode of vibration of a structure is not enough to produce reasonable estimates of response; important aspects of structural response (including collapse) are affected by both higher modes of response and period elongation due to yielding. To balance these realities, code writers have established a period range of interest (with respect to the fundamental period, T) that extends from $0.2T$ (to capture higher mode effects) to $1.5T$ (to include period elongation). Although yielding and period elongation cannot occur in linear response history analysis, for simplicity of application ground motions are selected and scaled considering the same period range of interest as for nonlinear response history analysis.

3.3.1.6 Orientation of ground motion components. Accelerometers record earthquake ground shaking along the vertical axis and two horizontal (orthogonal) instrument axes. Acceleration records can be used in the as-recorded orientation, but orientation in the directions normal to and parallel to the strike of the causative fault (termed the fault-normal and fault-parallel directions, respectively) by means of a simple trigonometric transformation permits greater seismological insights, since some ground motions recorded

very close to the causative fault contain rupture directivity effects. The differences may be meaningful for selection and scaling, application in analysis, or both. Since the orientation of instrument axes is arbitrary and reorientation along the fault-normal and fault-parallel directions can provide additional insight, it has become common (but not universal) to reorient all horizontal ground motion records in that manner.

In the very common condition where a site is not within several miles of the controlling source, the orientation of ground shaking is inconsequential, so the *Provisions* contain no general requirement to consider orientation. As discussed in Section 3.3.1.7 below, there is a selection and scaling orientation requirement (but no application orientation requirement) for sites close to active controlling faults.

Figure 3-5 shows the time series of two components of ground acceleration. Component 1 is fault-normal; component 2 is fault-parallel. What is not apparent in such traces is the interaction of the components. Figure 3-6 shows an orbit plot of ground acceleration pairs (effectively zero-period response) for the same recording. The maximum resultant acceleration occurs along a diagonal direction.

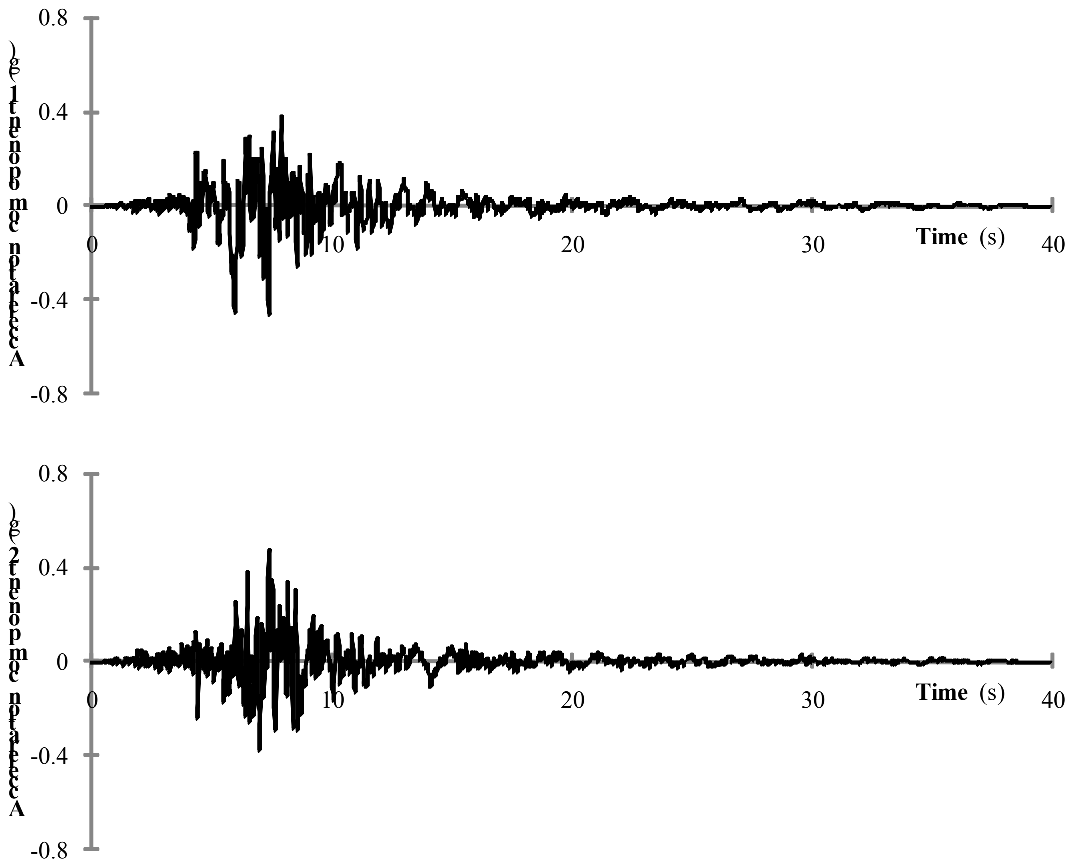

Figure 3-5 Horizontal acceleration components for the 1989 Loma Prieta earthquake (Saratoga – Aloha Avenue recording station)

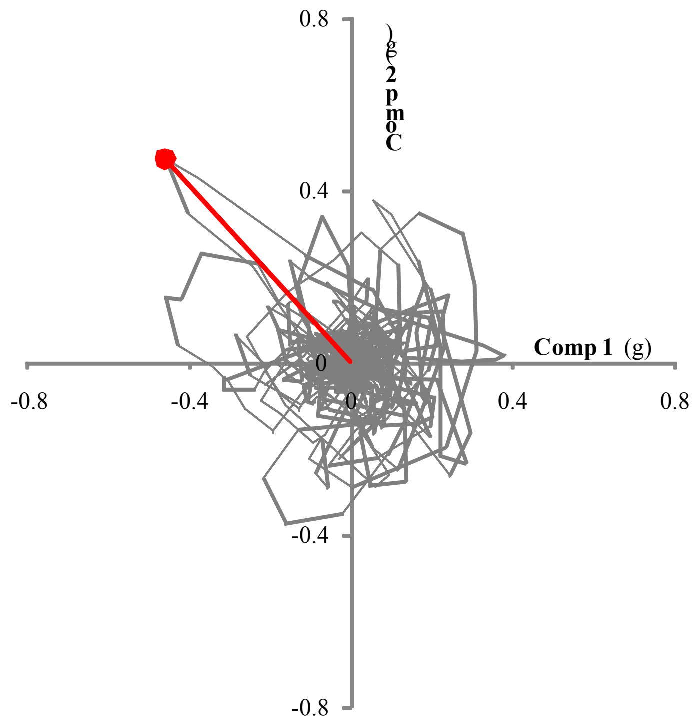

Figure 3-6 Horizontal acceleration orbit plot for the 1989 Loma Prieta earthquake (Saratoga – Aloha Avenue recording station)

Unfortunately, the direction of maximum ground acceleration may or may not correspond to the direction of maximum acceleration response at any other period and the direction of maximum response generally differs at various periods. If bilinear oscillators with various fundamental periods are subjected to the two-component acceleration record, response spectra like those in Figure 3-7 result. The uniaxial response spectra in that figure are identified by component. The "resultant" response spectrum indicates the maximum acceleration along any direction. The SRSS response spectrum is obtained by taking the square root of the sum of the squares of the corresponding component response spectrum ordinates. The case illustrated reflects a possible near-source condition: for long periods, the fault-normal component (component 1) is much larger than the fault-parallel component and is very close to the maximum (resultant) response.

The *Provisions* do not require application of ground motions in multiple possible orientations. Whether using three, seven, or more pairs, it is acceptable to consider a single, arbitrary orientation of a given two-component pair. For example, analysis can be performed with "Component 1" applied in the +X direction without considering the implications of applying that component in the -X, +Y, -Y, or other directions. Since the objective of the analyses is to estimate "average" response quantities, it may be advisable (but is not required) to consider whether there is an unwanted directional bias in the selected and scaled ground motions. For instance, in the common case where the controlling source should not produce strongly directional response, records could be oriented when applied so that the average of the component 1 spectra is similar to the average of the component 2 spectra. The much-less-common case, where strongly directional response is expected, is discussed in Section 3.3.1.7. Section 12.4.4 of these *Design Examples* outlines a more involved approach that is recommended for seismically isolated structures.

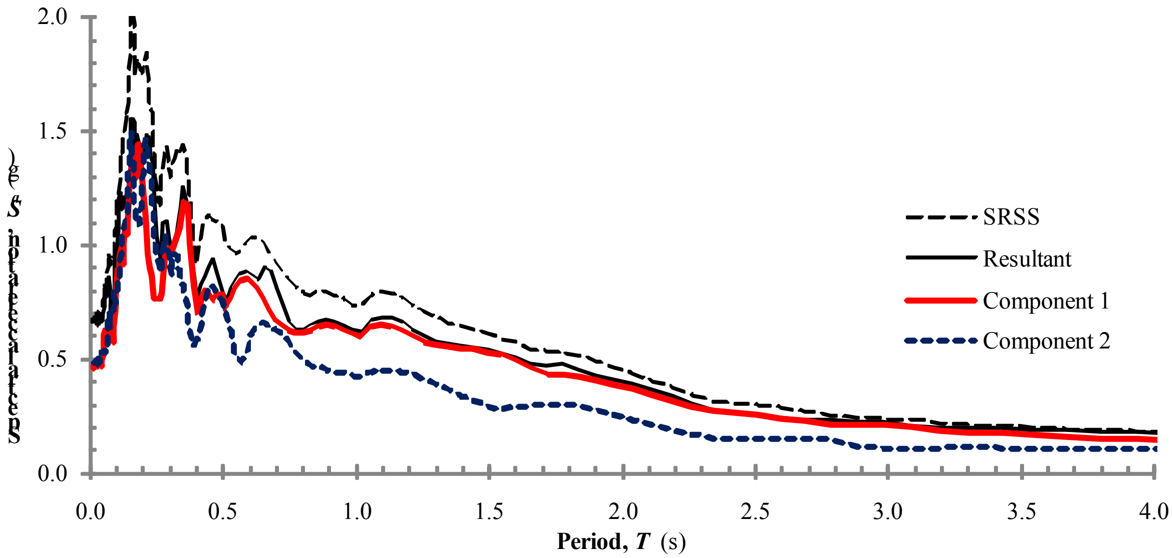

Figure 3-7 Horizontal acceleration response spectra for the 1989 Loma Prieta earthquake (Saratoga – Aloha Avenue recording station)

3.3.1.7 Sites close to controlling active faults. Ground motions at sites close to a causative fault can be strongly directional. At such sites, the maximum long period ground motion often occurs in the fault-normal direction. The last paragraph of *Provisions* Section 16.1.3.2 addresses this case, where code writers have judged that scaling should be more conservative than that achieved using the SRSS-based method. Although this requirement is well intentioned, the specific language provides a degree of additional conservatism that can vary greatly. The intent is that the maximum spectral acceleration for the scaled motions exceeds the target response spectrum.

While it is often true that the fault-normal component is dominant at long periods, some near-field ground motions show no directional bias and some are dominant in the fault-parallel direction. For instance, of the 3182 records in the PEER Ground Motion Database (for shallow crustal earthquakes), only 109 have pulse-like directional effects. Of those, 60 have pulses only in the fault-normal direction, 19 have pulses only in the fault-parallel direction, and 30 have pulses in both directions. As discussed above, it is acceptable to reorient all horizontal ground motion records to the fault-normal and fault-parallel directions. However, that does not assure that the fault-normal component will coincide with the maximum. Figure 3-8 shows response spectra for a ground motion where the fault-parallel direction (component 2) dominates for long periods. Scaling such that the fault-normal component exceeds the target response spectrum, as required in the last paragraph of Section 16.1.3.2, would force the maximum well above the target response spectrum. To obtain the intended result, ground motions should "be scaled so that the average of the ~~fault-normal~~ dominant components is not less than the ~~MCE_R~~ response spectrum used in the design for the period range from $0.2T$ to $1.5T$." (Section 3.3.1.4 above explains why all of Section 16.1.3.2 should refer to the response spectrum used in the design rather than to the MCE_R response spectrum.)

While the *Provisions* set forth orientation requirements for the selection and scaling of ground motions at sites close to controlling active faults, the orientation of ground motion components as applied in analysis is not prescribed. After going to the effort of orienting records in the fault-normal and fault-parallel directions and applying special rules for scaling in recognition of near-source effects, it would be prudent

(but not required) to apply the records in the analyses consistent with the fault-normal and fault-parallel directions at the actual site.

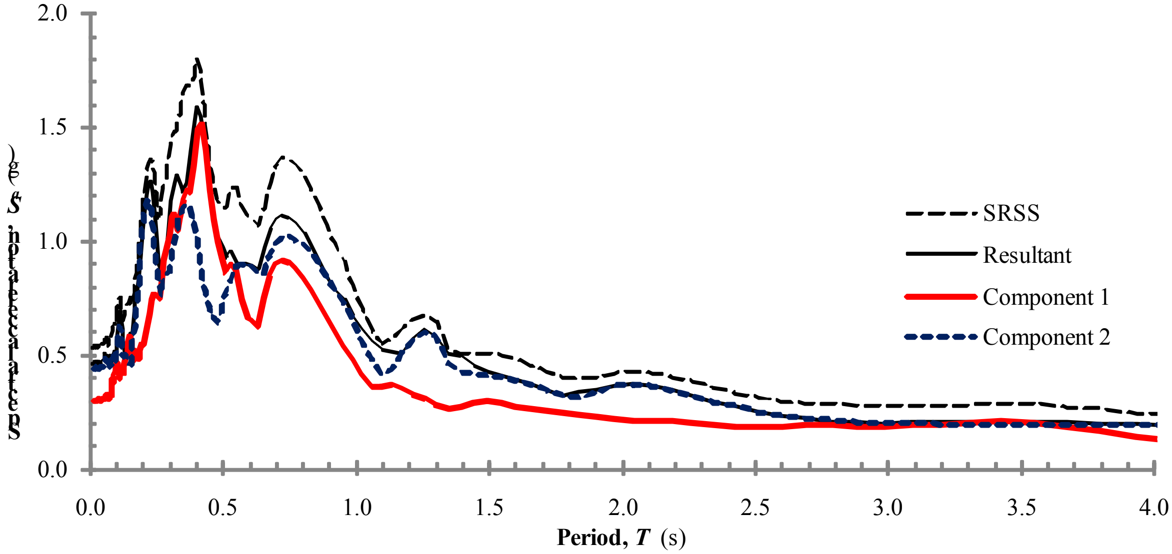

Figure 3-8 Horizontal acceleration response spectra for 1999 Duzce, Turkey earthquake (Duzce recording station)

3.3.2 Two-Component Records for Three Dimensional Analysis

Design Example 6.3 is a buckling restrained braced frame structure located at the Seattle, Washington site considered in Section 3.2. Some aspects of the design are based on results from three-dimensional nonlinear response history analysis performed in accordance with *Provisions* Section 16.2. This section illustrates application of the procedures described in Section 3.3.1 for the selection and scaling of two-component ground motion records. Pertinent information from Sections 3.2 and 6.3.6.1 is summarized as follows.

- Location: 47.65ºN, 122.3ºW
- Site Class C
- S_{MS} = 1.289
- S_{M1} = 0.649
- T_L = 6 seconds
- T_x = T_y = 2.3 seconds

The period range of interest is from 0.2 × 2.3 = 0.46 seconds to 1.5 × 2.3 = 3.45 seconds. If the two fundamental translational periods differed, the period range of interest would extend from 0.2 times the shorter period to 1.5 times the longer period.

The next step is to deaggregate the hazard, as discussed in Section 3.3.1.3, over the period range of interest. Figure 3-9 shows the MCE_R (target) response spectrum and the relative contributions of three important sources to spectral acceleration at periods between 0 and 4 seconds. For periods greater than about 1.5 seconds, ground shaking hazard is controlled by very large, but distant, subduction zone events. At shorter periods, hazard is controlled by deep intraplate events, with substantial contributions from shallow crustal events. It is necessary to identify not only the magnitude of the controlling event, but also

the distance and source type. Short and intermediate period response may be more important than long period response (depending on the period of the structure).

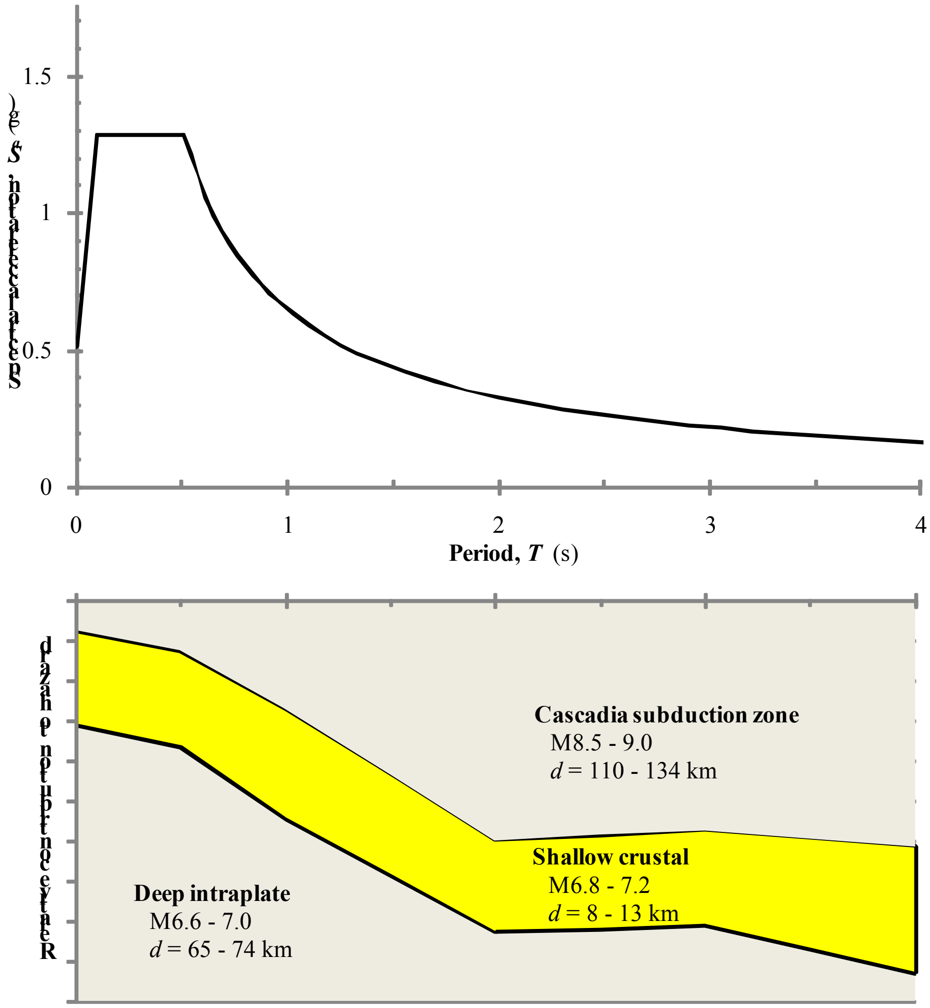

Figure 3-9 MCE_R response spectrum and corresponding hazard contributions

Since the MCE_R response spectrum over the period range of interest is controlled by multiple sources with substantially different spectral shapes, the procedure recommended in Section 3.3.1.3 is used. Table 3-1 provides key information for the selected ground motion records. Few large magnitude subduction zone records are available. Records 1, 2 and 3 are for slightly smaller events than those that control the long period hazard, but at closer distances. These differences are partially offsetting so the required scale factors are acceptable. Record 4 is nearly a perfect match for the hazard that controls short period response; and it is from a past occurrence of a similar event in the same region. Records 5, 6 and 7 are from shallow crustal events with magnitude and distance appropriate for this site. Two of those records include near-source velocity pulses. In a manner similar to that illustrated in Figure 3-4, the actual spectra for the selected ground motion records control different periods of response. Figure 3-10 shows the SRSS spectra for Records 1 and 4, along with the target (MCE_R) spectrum. The subduction zone event (Record No. 1) dominates long period response; the deep intraplate event (Record No. 4) dominates short period response.

Table 3-1 Selected and Scaled Ground Motions for Example Site

Record No.	Year	Earthquake name	M	Source type	Recording station	Distance (km)	Scale factor
1	2003	Tokachi-oki, Japan	8.3	Subduction zone	HKA 094	67	2.99
2	2003	Tokachi-oki, Japan	8.3	Subduction zone	HKD 092	46	0.96
3	1968	Tokachi-oki, Japan	8.2	Subduction zone	Hachinohe (S-252)	71	1.28
4	1949	Western Washington	7.1	Deep intraplate	Olympia	75	1.92
5	1989	Loma Prieta	6.9	Shallow crustal	Saratoga -- Aloha Ave	9	1.28
6	1999	Duzce, Turkey	7.1	Shallow crustal	Duzce	7	0.85
7	1995	Kobe, Japan	6.9	Shallow crustal	Nishi-Akashi	7	1.18

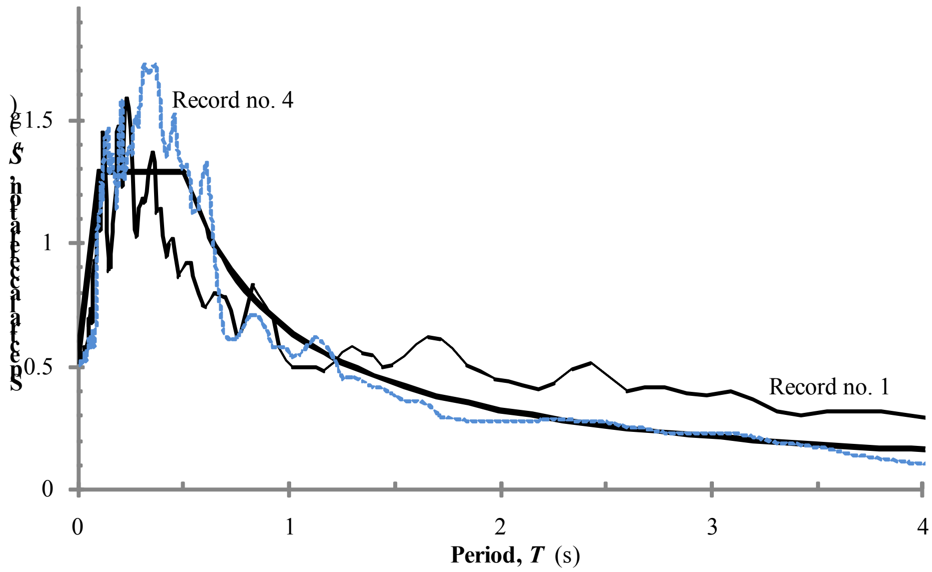

Figure 3-10 SRSS response spectra from different source types

Figure 3-11 compares the average of the SRSS spectra for the selected ground motions with the target (MCE_R) response spectrum. It also shows the period range of interest for ground motion selection for this structure. In an average sense the suite of ground motions provides a very good fit to the target. Since seven records are used, average response quantities may be used in design. This suite so well matches the target spectrum that it could be used with no modification for periods from 0.18 to 4.95 seconds, a range much wider than the period range of interest defined in *Provisions* Section 16.1.3.2. Since this suite of ground motions has been selected and scaled to match the MCE_R response spectrum, an additional scale factor of 2/3 must be applied when the records are used in an analysis to represent design-level conditions.

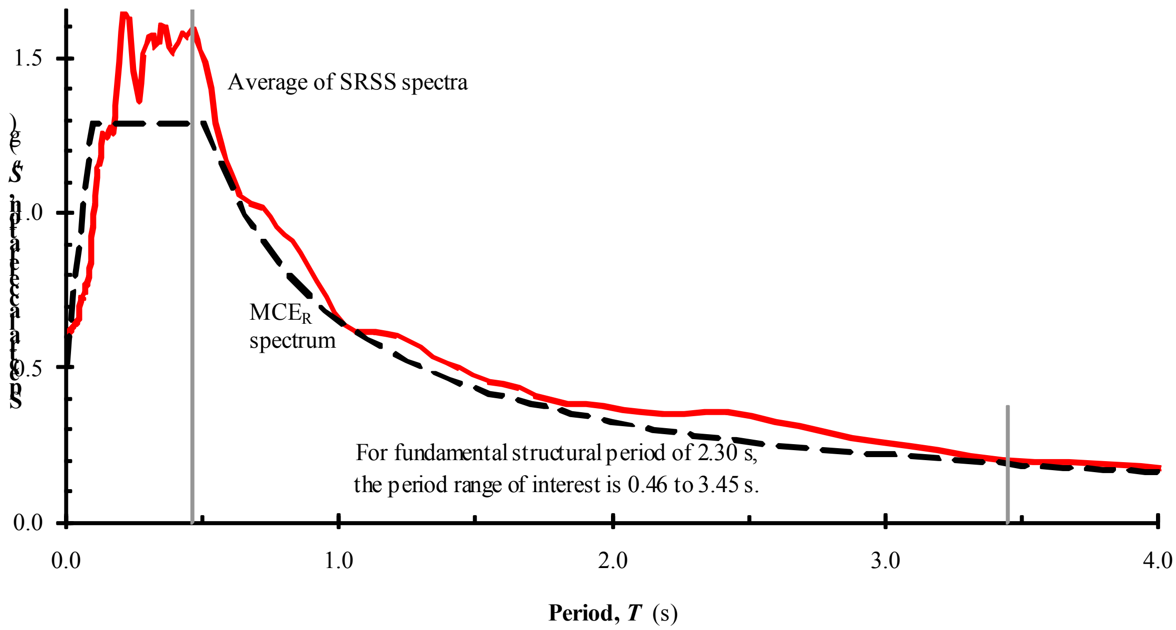

Figure 3-11 Fit of the selected suite of ground motion records to the target spectrum (for three-dimensional analysis)

3.3.3 One-Component Records for Two-Dimensional Analysis

As discussed in Section 3.3.1.4, one-component records (for use in two-dimensional analysis) are selected and scaled such that their **average** fits the design response spectrum, which is two-thirds of the MCE$_R$ response spectrum. Figure 3-12 compares the average of the 14 component spectra (for the records selected and scaled in Section 3.3.2) to the design response spectrum. These records provide an excellent fit to the target spectrum. The suite of 14 records could be used without modification. If a subset of seven records were selected, some minor adjustment to scale factors might be required. Figure 3-12 also shows the average of the SRSS spectra for those 14 scaled records. As observed in Section 3.3.1.4, the average of the SRSS spectra is about 1.5 times the average of the component spectra. Therefore, if the same suite of records was used for three-dimensional analysis, the scale factors required would be about 2/3 of those required for two-dimensional analysis, due to the difference between average and SRSS spectra (and not due to the purely coincidental 2/3 relationship between design and MCE$_R$ response spectra).

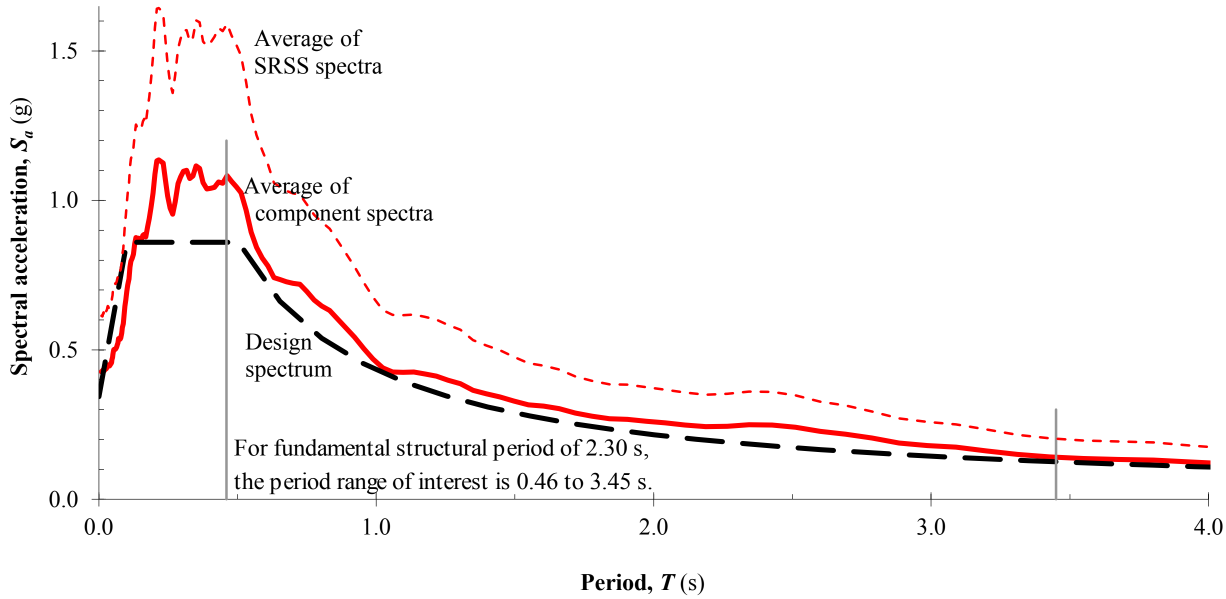

Figure 3-12 Fit of the selected suite of ground motion records to the target spectrum (for two-dimensional analysis)

3.3.4 References

PEER. 2010. *Technical Report for the PEER Ground Motion Database Web Application*, Pacific Earthquake Engineering Research Center, Berkeley, California.