Advances in Geotechnical Performance-Based Seismic Design for Tall Buildings

PBD III
VANCOUVER
Earthquake Geotechnical Engineering

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ABSTRACT

Many of the advances in performance-based seismic design (PBSD) originated in Seattle, where a community of structural and geotechnical engineers specialize in tall building design and code development. Seattle features more tall buildings designed using PBSD than any other city in North America. This paper presents the history and practice of the geotechnical engineer's role in performance-based seismic design of tall buildings in Seattle, including the characterization of the seismic hazard in the Puget Sound region and development of ground motions that are used in nonlinear dynamic structural models. The standard of practice for geotechnical seismic design continues to evolve with changes to codes and increased understanding of the seismic hazard and geologic conditions in the Puget Sound region.

Seismicity in Seattle and the Puget Sound region is dominated by the Cascadia Subduction Zone, which is associated with three types of earthquakes: crustal, intraslab (deep) subduction, and interface (M_w8.0 to 9.2) subduction earthquakes. Downtown Seattle is located in a deep sedimentary basin, within 3 miles of the northern splay of the Seattle Fault Zone, and about 15 miles southwest of the Southern Whidbey Island fault system. This paper provides an overview of the conditions under which PBSD is used and the evolution of building codes (from FEMA 356 through ASCE 7-16) used in practice. A technical overview is presented regarding the seismic setting in the Seattle area (including near-source effects of the Seattle Fault and basin amplification effects). Discussion of some of the technical aspects of PBSD, such as the development of site-specific spectra (uniform hazard, uniform risk, and conditional mean spectra), and the selection, scaling, and use of ground motion records for nonlinear response history analysis is included as well.

1 INTRODUCTION

Since the late 1990s, there has been a significant increase in the rate of tall building construction in the Puget Sound region. With it have come equally rapid advances in the methods and techniques used by geotechnical and structural engineers to design such buildings to withstand seismic loads, within a framework known as performance-based seismic design (PBSD). The benefits to using PBSD for such projects include improved constructability, floor-to-ceiling views, increased building value, and better understanding of seismic performance in the region being studied (Lindquist et al., 2016).

This paper presents a discussion of the geotechnical aspects of PBSD for tall buildings, and how they have been advanced in the Pacific Northwest over the past two decades. An overview of the seismic setting in Seattle is presented. Methods for seismic hazard characterization are discussed, as well as techniques and advances in selecting and modifying ground motion records for use in structural analysis. A summary is presented on the current state of practice in PBSD, as well as remarks on potential areas of future advancement.

2 EVOLUTION OF BUILDING CODES

Structural engineers first began use PBSD in the late 1990s and early 2000s, largely for existing structures whose seismic stability could not be reliably assessed under the existing prescriptive code framework. Early PBSD was generally performed using many of the provisions outlined in FEMA 356 – Prestandard and Commentary for the Seismic Rehabilitation of Buildings (FEMA 2000). Many key provisions outlined in FEMA 356 continue to be in use today in one form or another, including using the 2,475-year Maximum Considered Earthquake (MCE) as the basis of design, guidelines for selecting ground motions for nonlinear dynamic analyses, and guidelines regarding the determination of the period range of interest of a structure for dynamic analysis.

The adoption of ASCE 7-05 into the 2006 International Building Code (IBC) resulted in a number of changes to the techniques used in PBSD, including increasing the minimum number of ground motions used in dynamic analyses from three to seven. The adoption of ASC 7-10 introduced several major changes to the development of ground motion pairs, including adjusting the basis of ground motion scaling from the geometric mean spectrum of the ground motion pair to the maximum component spectrum. ASCE 7-10 also saw the introduction of criteria and provisions to account for near-fault effects on ground motions at sites near significant seismic sources. The basis of design was also revised from a 2% probability of exceedance in 50 years to a 1% risk of *collapse* in 50 years. This involved altering the MCE, which is a uniform hazard spectrum (UHS), to a uniform risk spectrum (URS), known as the risk-adjusted maximum considered earthquake (MCE$_R$), and also included factors for altering spectral accelerations from geometric mean to maximum component.

A current typical PBSD framework follows the provisions outlined in ASCE 7-16, which was released in early 2017. While use of the MCE_R as the basis of design remains largely unchanged for the design of tall buildings, procedures for selecting ground motions for dynamic analyses have been revised substantially. These include increasing the number of ground motion pairs from seven to 11, incorporating the conditional mean spectrum approach for developing target spectra, and introducing revised criteria for near-fault sites.

3 SEISMIC SETTING IN THE PUGET SOUND REGION

Western Washington sits at the contact between two large crustal tectonic plates. The Juan de Fuca plate forms the floor of the Pacific Ocean off the coast of the northwestern United States, and moves northeastward from its spreading ridge boundary with the Pacific plate at an average rate of about 1.5 inches per year. As it converges with continental North America, the Juan de Fuca dips (or "subducts") beneath the North American plate, forming a shallow, eastward-dipping contact interface. This boundary is known as the Cascadia Subduction Zone (CSZ), and is responsible for the seismicity in the Western Washington region, producing earthquakes associated with three types of source zones: subduction interface, subduction intraslab, and crustal (Figure 1).

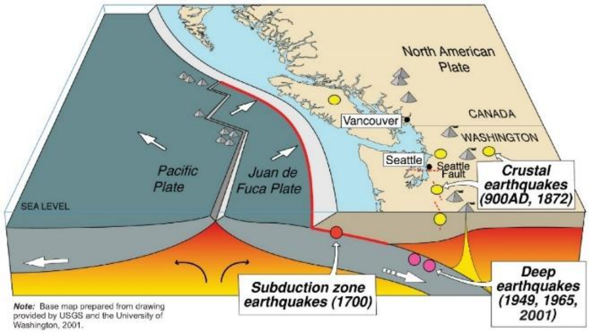

Figure 1. Cascadia Subduction Zone Earthquake Sources (not to scale) (USGS).

3.1 Subduction Interface Sources

The relative displacement between the Juan de Fuca and North American plates does not manifest as slip between the Juan de Fuca and North American plates; rather, it is absorbed by compression of the North American plate at the interface at relatively shallow depths. This compression, based on geologic and historical evidence, is released every 400-600 years in the form of M_w8 to $M_w9.2$ earthquakes, the last such event occurring in 1700. Characteristics of this type of earthquake may include very large ground accelerations, shaking durations in excess of two minutes, and particularly strong long-period ground motions, which may affect many tall buildings in the greater Seattle area.

3.2 Subduction Intraslab Sources

A deeper zone of seismicity is associated with a steeper bending of the Juan de Fuca plate, and the breaking of the plate under its own weight below the Puget Sound region. This region, termed the Benioff Zone, produces intraslab earthquakes at depths of 40 to 70 kilometers below ground surface. Such past events in Western Washington include the 1949 Olympia ($M_w6.7$), 1965 Puget Sound ($M_w6.5$), and 2001 Nisqually ($M_w6.8$) earthquakes. Deep, intraslab earthquakes tend to be felt over larger areas than shallower interface events, and generally lack significant aftershocks.

Based on the 2014 USGS National Seismic Hazard Maps, the return period for $M_w7.2$–7.5 Benioff zone events in western Washington is 1,562 years, and the return period for events with $M_w7.2$–8.0 is 1,010 years.

3.3 Crustal Sources

Fault trenching and seismic records in the Puget Sound area clearly indicate a distinct shallow zone of crustal seismicity. The primary area of interest is the Seattle fault zone, which forms the southern boundary of the Seattle basin, and consists of an approximately 50- to 75-km-long southern-dipping thrust fault system that extends about 20 km deep. This fault zone is capable of producing earthquakes of up to $M_w7.5$, with a recurrence interval of approximately 1,000 years for earthquakes of $M_w6.5$ or larger (Petersen et al. 2014).

3.4 Overall Seismic Hazard in Western Washington

The extent to which each of the seismic sources discussed in this section contribute to the overall hazard in western Washington depends on two key factors: the hazard level (or return period) being considered, and the relevant spectral period of the site or building of interest.

This can be illustrated using a probabilistic seismic hazard analysis framework (PSHA), with the hazard deaggregated into bins of magnitude and distance according to their percent contribution to the overall hazard. Figure 2 shows the deaggregated hazard from a site in downtown Seattle, for a 224-year return period at peak ground acceleration (PGA). The percent contributions to the overall hazard from crustal, intraslab, and interface sources are 53%, 30%, and 17%, respectively. If the same hazard level is evaluated, but at a longer spectral period of four seconds (Figure 3), the contribution from CSZ interface sources increases dramatically to 36%. If longer return periods are instead considered at the 4-second period, such as the MCE, (2,475-year return period) (Figure 4), the CSZ interface source becomes the dominant contributor to the overall hazard at over 50%.

Generally, for sites in the Seattle area, the trends in the deaggregated data suggest that at shorter spectral periods and shorter return intervals, the seismic hazard tends to be controlled by shallow crustal and/or deep intraplate sources. At longer spectral periods and return intervals, which are more pertinent to the design of taller buildings, the seismic hazard tends to be controlled more by the Cascadia subduction interface sources.

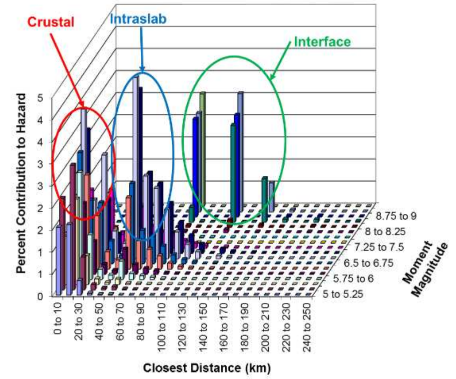

Figure 2. PSHA deaggregation for a downtown Seattle site, for a 224-year return period, at PGA

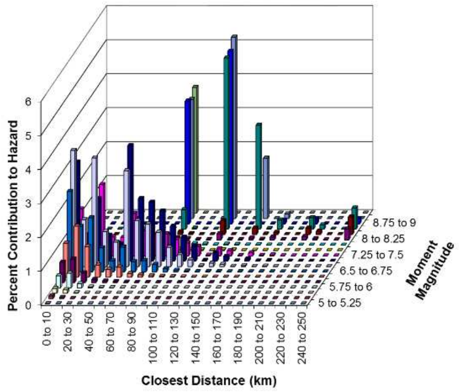

Figure 3. PSHA deaggregation for a downtown Seattle site, for a 224-year return period, at 4.0 seconds

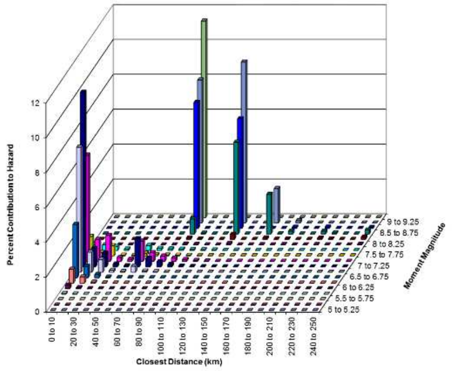

Figure 4. PSHA deaggregation for a downtown Seattle site, for a 2,475-year return period, at 4.0 seconds

4 EFFECTS OF THE SEATTLE BASIN ON GROUND MOTION AMPLITUDES

The Seattle Basin is an approximately 30-by-60-kilometer depression in a volcanic and igneous rock basement, filled with up to 8km of lower density sedimentary rock and sediment deposits.

The Seattle Basin is bounded in the south by the Seattle Fault Zone, and east-west trending thrust fault separating the thick sediment within the basin from the shallow bedrock to the south. The basin is bounded to the west by the Olympic Mountains and approximately to the east by the foothills of the Cascade Mountain range.

During an earthquake, basin edges nearest to the earthquake source tend to convert body waves propagating at shallow angles to surface waves, thus trapping a greater amount of energy within the sedimentary basin compared to ground motions caused by waves that largely propagate vertically. This results in ground motions with increased spectral amplitudes at intermediate and long periods, and longer durations compared to motions outside the basin on bedrock (Kramer 1996).

Some of the largest cities in the Puget Sound region, such as Seattle, Kirkland, Bellevue, and Redmond are located within the Seattle Basin. Thus, a critical component to developing a site-specific response spectrum in this region is characterizing the potential effects of sediment basins on ground motions.

Currently, the effects of sedimentary basins on ground motion response have been characterized using two methodologies. Ground motion models (GMMs, also referred to as attenuation relationships and ground motion prediction equations) have been used to characterize the effects for crustal ground motions, while amplification in subduction motions has been characterized through the analysis of actual ground motion data and ground motion simulations.

4.1 GMM-Based Evaluation of Basin Effects

For the prediction of ground motion amplitudes in crustal environments, the standard of practice has been to use four GMMs released by NGA–West2 in 2014, including the models from Abrahamson et al. (ASK14), Boore et al. (BSSA14), Campbell and Bozorgnia (CB14), and Chiou and Youngs (CY14). Each of these GMMs incorporate basin terms using a variable related to the depth of bedrock. For CB14, this term is $Z_{2.5}$, which denotes the depth to the 2,500 m/s shear wave velocity (V_s) horizon. The remaining three GMMs use $Z_{1.0}$, which is the depth to the 1,000 m/s horizon.

An initial PSHA is performed for the site and measured V_{s30} (the weighted average shear wave velocity, V_s, in the upper 30m of the site profile), using the default values of $Z_{2.5}$ and $Z_{1.0}$, to produce an initial uniform hazard spectrum (UHS). Site-specific amplification factors can then be obtained by taking the ratio of the GMM-based UHS for a deterministic crustal event using default Z-values calculated for the site V_{s30} with a UHS for the site-specific Z-values. In the Puget Sound area, these Z-values can be based on the Stephenson (2007) or Delorey and Vidale

(2011) models. The ratios of response spectra for basin amplification (RRS_{ba}) are then derived for a given GMM via:

$$RRS_{ba}(T) = \frac{S_{a,site}(T)}{S_{a,def}(T)} \qquad [1]$$

where $S_{a,site}$ and $S_{a,def}$ are the spectral accelerations predicted using the site-specific and default basin depth terms, respectively. The project basin amplification factors that are applied to the PSHA-generated UHS can be determined using a weighted average of the four GMMs (Figure 5). In the Pacific Northwest, more weight should be given to the *RRS* values obtained from CB14, due to its use of $Z_{2.5}$ instead of $Z_{1.0}$. $Z_{1.0}$ is generally considered a less reliable estimator of basin depth in the Pacific Northwest, particularly because of the existence of glacially overridden deposits, resulting in V_s inversions of shallow soil units exceeding V_s of 1,000 m/s with deeper units below 1,000 m/s (Chang et al. 2014).

Figure 5 illustrates the variability of basin amplification factors for a site in Seattle using the four NGA–West2 GMMs. Currently, GMMs for subduction events do not include terms for basin amplification.

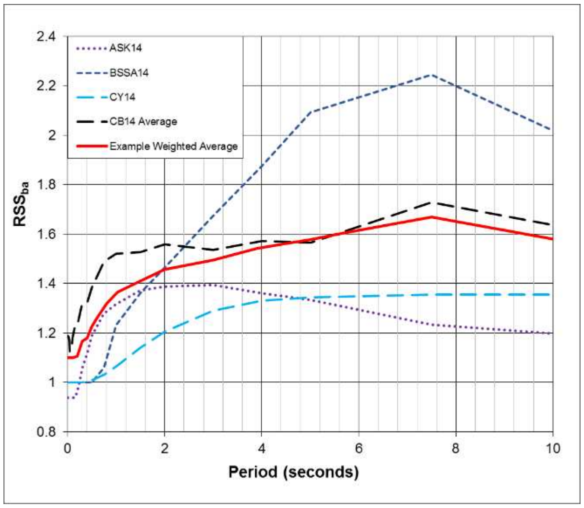

Figure 5. GMM-based basin amplification factors, derived for a M_w7.2 Seattle Fault event at a downtown Seattle site.

4.2 Basin Effects for Large Subduction Earthquakes

Two recent studies from Marafi et al. (in review) and Frankel et al. (2009) have shed light on how sedimentary basins amplify ground motions in subduction events. The Marafi et al. study was based on observations from several earthquakes in Japan, and the Frankel et al. study on three-dimensional ground motion simulations of subduction events in the Seattle Basin. The analysis of the Japan data was based on comparing ground motion spectra from four sedimentary basins with corresponding motions recorded outside the sedimentary basins from six subduction events (M_w6.7 to M_w9.0). After controlling for source-site distance and local site effects, Marafi et al. found that spectral amplification ratios due to basin sites ranged from 2 to 4 at periods longer than about 2.0 seconds, and generally increased with spectral period and basin depth. The one exception to these trends was the Kanto basin from the Tohoku earthquake, which may be attributed to the sharp azimuthal angle between the basin and the earthquake source. These factors were largely independent of earthquake magnitude.

These results are consistent with the amplification factors presented by Frankel et al. from 3D simulations of five subduction earthquakes in the Seattle area, including the 2001 Nisqually earthquake, which was presented as validation. The results of these simulations also suggest amplification factors of 2 to 4 between periods of about 1 to 10 seconds. The results of these two studies suggest that using crustal, GMM-based methods for applying basin amplification factors may be unconservative for the design of tall buildings in Seattle, where subduction events contribute significantly to the overall hazard.

5 SITE-SPECIFIC SPECTRA FOR GROUND MOTION SELECTION

An essential component of performance-based design of tall buildings is the evaluation of the seismic response of the building in the time domain. This requires the selection of a suite of ground motion pairs that appropriately represents the range of ground motion characteristics expected to be seen at the hazard level of interest. One of the most important criteria for the selection of ground motion pairs is their compatibility with the target response spectrum for the given hazard level. Current practice is to scale ground motion pairs to either the MCE_R or to two conditional mean spectra.

5.1 Risk-Adjusted Maximum Considered Earthquake

Per ASCE 7-16, the seismic basis of design for collapse prevention performance is the MCE_R. Development of the MCE_R spectrum is initially based on characterizing the seismic hazard level associated with the MCE (2,475-year return period). The initial MCE uniform hazard spectrum is obtained by performing a PSHA at the site, which consists of characterizing the site's earthquake sources and their magnitude-frequency relationships, the distribution of source-to-site distances, and the expected shaking intensities for all source-magnitude-distance combinations using GMMs.

The information obtained from these calculations provides probability distributions of ground shaking intensity versus annual rate of exceedance (Baker, 2008). For a given annual rate of exceedance (e.g., the MCE), the shaking intensities (in this case characterized as spectral amplitudes) can be extracted at a series of spectral periods, thus producing a UHS.

The UHS is then adjusted to a risk-targeted spectrum, using an algorithm developed by Luco et al. (2007). The algorithm combines fragility curves for collapse capacity of a generic structure with the ground motion hazard curves to obtain spectral accelerations that coincide with a 1%

probability of collapse in 50 years, or the MCE_R. The risk coefficient generally has the effect of lowering the overall hazard from the MCE by roughly 5 to 10% at most periods.

5.2 The Conditional Mean Spectrum

The uniform hazard spectrum developed from probabilistic seismic hazard analyses is calculated as the sum of the hazard curves from all earthquake sources near a given site. While this may be a useful spectrum for the initial design of the seismic force-resisting system (which are designed using lower hazard levels than the MCE), this UHS may be unsuitable for use as a target spectrum for selection of ground motions in time-history analysis procedures.

Selecting and scaling ground motions to a target UHS implies that a ground motion from a single earthquake source should be scaled to the UHS developed from all earthquake sources. For sites in regions with multiple earthquake sources, this assumption maybe overly conservative (Baker, 2011). For instance, the MCE in the Seattle area is controlled by the Seattle Fault at shorter periods and by the Cascadia subduction zone at longer periods. Crustal and subduction motions tend to have generally different shapes from each other and from a UHS. This may result in selecting motions according to a target spectrum with a significantly different shape, thus potentially requiring overconservative scaling factors to meet code provisions.

The conditional mean spectrum (CMS) is an alternative method for generating target spectrum. The CMS is defined as the "*expected response spectrum,*" conditional on a given spectral acceleration at a specified period of interest, and tends to be a more physically realizable target spectrum for ground motion selection than its corresponding UHS (Baker 2011) (Figure 6). The selection of the period of interest, known as the *conditioning period*, is a critically important step to developing CMS for ground motion selection. The conditioning period is generally based on the fundamental period of the structure. However, this may not sufficiently account for the full structural period range of interest, and thus a CMS can be developed by enveloping multiple CMS conditioned at different periods (e.g., the first and second modes of vibration of the building). The CMS approach has been adopted into ASCE 7-16, with the requirement that the CMS is at least 75% of the MCE_R from which it is conditioned within the period range of interest.

For a given hazard level, conditioning period, and spectral amplitude, the CMS can be obtained using the deaggregated PSHA data, and is the weighted average of the conditional mean spectra from all considered earthquake sources. Thus, for situations where ground motion suites are to be comprised of records from multiple source types (e.g. crustal, interface, and intraslab), it is possible to select and scale crustal ground motions according to a target CMS comprised of only crustal sources, interface motions from a CMS of interface sources, and so on (Figure 7). This has the effect of selecting ground motions according to target CMS spectrum with an even more consistent shape than the CMS spectrum based on multiple different source types.

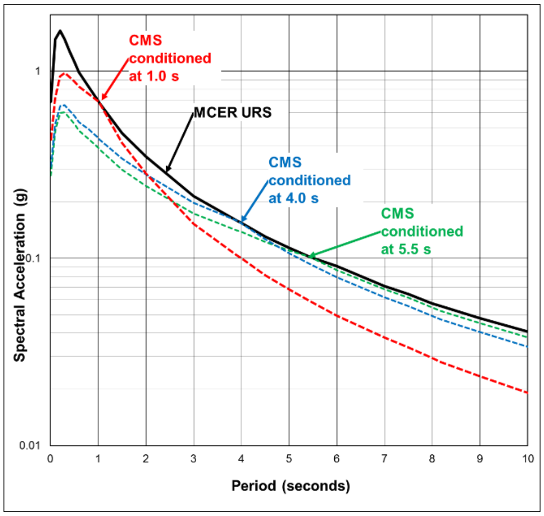

Figure 6. MCE_R uniform spectrum, plotted with conditional mean spectra for three different conditioning periods

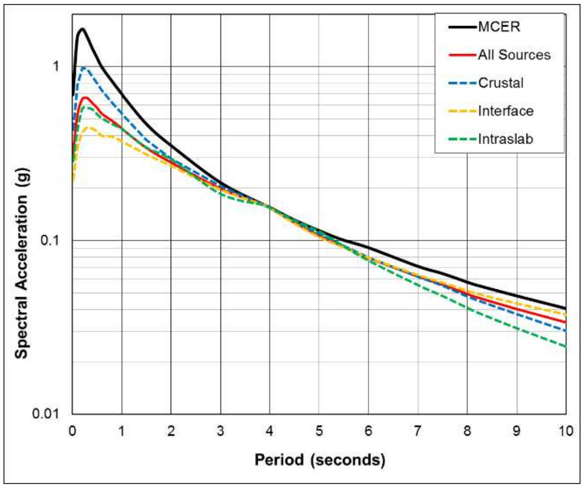

Figure 7. Comparison of MCE_R with conditional mean spectra from all earthquake sources, crustal sources only, intraslab sources only, and interface sources only.

5.3 Additional Target Spectrum Modifications

Another key spectral modification stems from the fact that the spectral accelerations obtained from the USGS hazard maps (and GMMs) are geometric mean values. Using peak directional spectral accelerations, which are independent of orientation, are considered more suitable for structural design (Ghosh 2014). The geometric mean MCE spectrum is then modified using period-dependent peak directional amplification factors to reflect this, per Supplement 1 of ASCE 7-10. The factors provided in Supplement 1 are to be used unless other factors are found to more closely approximate the maximum response, with similar language presented in ASCE 7-16. Shahi and Baker (2013) presented peak directional factors based on a database of recorded ground motions, which show that the factors in the ASCE 7-10 supplement are very conservative at long periods (Figure 8).

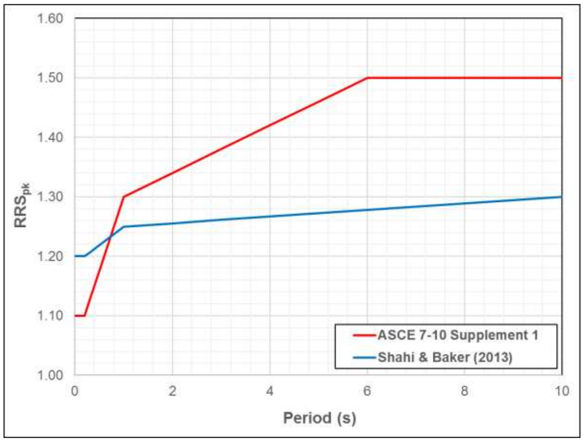

Figure 8. Comparison of peak directional factors from ASCE 7-10 and Shahi and Baker (2013)

A final, optional modification can be made to the target MCE, to account for the effects of the interaction between structural foundation elements and their surrounding soil. These effects come from base-slab averaging and foundation embedment, which reduce ground motion amplitudes at short periods (less than one second) by up to 20%. Such short period reductions are generally on the low end of the period range of interest for tall building designs, however, and are not required in tall building PBSD frameworks.

6 SELECTION OF GROUND MOTION PAIRS FOR NONLINEAR DYNAMIC STRUCUTRAL ANALYSIS

As discussed previously, it is necessary for the design of tall buildings to perform three-dimensional nonlinear dynamic analyses in the time domain for the MCE_R risk level. This requires the selection of ground motion pairs, which, in addition to being spectrally compatible with the target URS or CMS, also must meet certain criteria relating to their source, site, and time history characteristics. Much of these criteria can be determined from the PSHA deaggregation; others require knowledge of the site of interest, as well as the metadata from the ground motion records being considered.

6.1 Source Characteristics

The first step in selecting ground motion pairs is determining the distribution of crustal, interface, and intraslab records that should be represented in the suite of motions. This can be achieved by examining the PSHA deaggregation at one or more periods of interest, and determining how the overall hazard is broken down by source. An example of this is provided for a site in Seattle in Table 1. Based on the percentage contributions to the overall hazard from each source, for a suite of 11 ground motions, the distribution by source would be four crustal records, one intraslab record, and six interface records.

Table 1. Example source deaggregation for a 2,475-year return period at 3.0 seconds, for a site in downtown Seattle

Source Type	Source	Modal Values			
		% Contr.	M_w	R (km)	ε
Shallow Crustal	Seattle Fault Zone	22	7.1	5	0.62
Shallow Crustal	S. Whidbey Island Fault System	2	7.4	25	1.77
Shallow Crustal	Nonextensional Shallow Gridded	15	7.4	5	1.21
Intraslab	PNW Deep Gridded	6	7.1	55	1.51
Interface	Cascadia Interface	55	9.1	85	1.03

Once the distribution of source types is determined, each record should be selected such that its earthquake magnitude and source-to-site distance are consistent with the modal magnitudes and distances obtained from the PSHA deaggregation. Referring back to Table 1, for example, the modal magnitudes and distances of the more significant crustal sources (Seattle Fault and background gridded) are approximately 7.0 to 7.5 and 5 km, respectively. Thus, the four selected crustal records should approximately have source magnitudes of about 6.5 to 7.8, and source-site distances of roughly 0 to 15 km.

6.2 Near-Fault Ground Motions

Sites located close to known earthquake sources, known as *near-fault* or *near-field* sites, tend to experience certain ground motions characteristics that are typically not seen at distal sites. Such characteristics must be accounted for in the selection of ground motions if a nearby earthquake source contributes significantly to the overall hazard.

A significant manifestation of near-fault effects occurs in time domain, in the form of long-period pulses in the velocity time history, which may significantly affect the dynamic response of the structure. Ground motions featuring such characteristics are known as *pulse-like motions*, and are generally limited to sites in shallow, crustal environments. When selecting crustal ground motion pairs, a certain proportion of motions should have pulse-like characteristics, depending on the modal distance and *epsilon* (i.e., the difference between a given S_a and the GMM-predicted mean S_a for the same magnitude-distance combination) values associated with the crustal sources of interest.

Another consideration for ground motions in the near field is the significant dependence of ground motion amplitudes on azimuthal orientation. Typically, the greatest disparity in amplitudes between orthogonal components occurs when the fault-normal and fault-parallel components of a ground motion are considered, with the greater amplitudes experienced in the fault normal direction. Such azimuthal disparities are largely masked when selecting ground motion pairs based on their maximum-component spectra.

As such, when selecting ground motions for sites in the near field of one or more earthquake sources, a number of ground motion pairs proportional to the percent contribution of those sources to the overall hazard should be selected and rotated from their as-recorded components into fault-normal and fault-parallel components.

7 GROUND MOTION RECORD MODIFICATION FOR SPECTRAL COMPATIBILITY

For a given target spectrum, there exist prohibitively few ground motion records that require no modification to be spectrally compatible. Candidate records are thus typically selected based on the consistency of their relative spectral shape with the target spectrum, and then modified in certain ways to achieve similar spectral amplitudes. The provisions in ASCE 7-16 require that ground motions are selected and modified such that the average spectrum of the suite meet or exceed 90% of the target spectrum in the period range of interest. Three strategies for record modification are discussed in this section: amplitude scaling, tight spectral matching, and mean spectral matching.

7.1 Amplitude Scaling

The simplest approach to modifying ground motions is to apply a uniform scaling factor to the pair, generally such that the mean-squared error (MSE) between the scaled spectrum and the target spectrum is minimized in the period range of interest. Once a suite of ground motions is selected and scaled based on MSE, the suite average is then checked against the target spectrum, and an additional suite scaling factor is applied to all records (if necessary) to ensure that the suite average spectrum is above 90% of the target. In the design of tall buildings, this period range can be quite wide, often on the order of 0.5 to 8 seconds or so, and may require excessive suite scaling factors to be applied to ensure that the conditions are met throughout the entire period range (Figure 9).

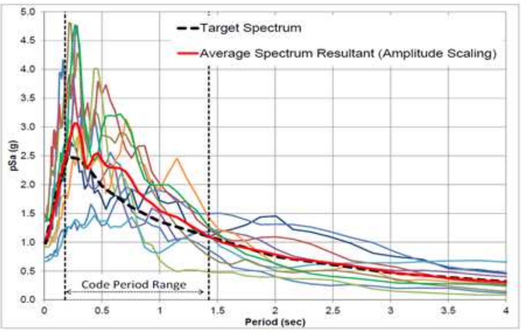

Figure 9. Suite of amplitude-scaled ground motions (Mazzoni et al., 2012)

7.2 Tight Spectral Matching

An alternative to amplitude scaling is to iteratively alter the ground motion in the time domain using wavelet analysis (Al Atik & Abrahamson, 2010) such that the modified spectrum has nearly the exact shape as the target spectrum (Figure 10). This method, while producing more consistently compatible spectra, has two drawbacks. One is that the modified records no longer have physically realizable response spectra, since the target spectrum to which they have been matched is based on smoothed GMM-based spectra. The other is that all 11 motions are modified to have the exact same spectrum, thus neglecting real record-to-record variability in the dynamic analysis. This is reflected in ASCE 7-16, which requires tight spectrally matched ground motions to be scaled up by a factor of 1.1.

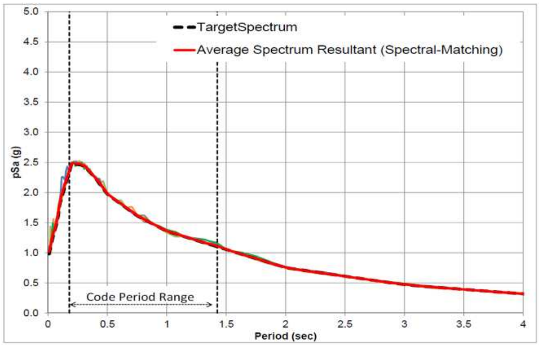

Figure 10. Suite of tight spectrally-matched ground motions (Mazzoni et al., 2012)

7.3 Mean Spectral Matching

An alternative time-domain method that preserves record-to-record variability, while still producing a tight spectral match on average is known as mean spectral matching (Mazzoni et al. 2012) (Figure 11). Mean spectral matching uses the same wavelet methods as tight spectral matching to alter ground motions in the time domain, but the iterative nature of it is based on assessing the compatibility of the average spectrum, rather than every single ground motion spectrum, with the target. Mean spectral matching can also be performed for a specified standard deviation of spectral amplitudes to achieve a desired record-to-record variability.

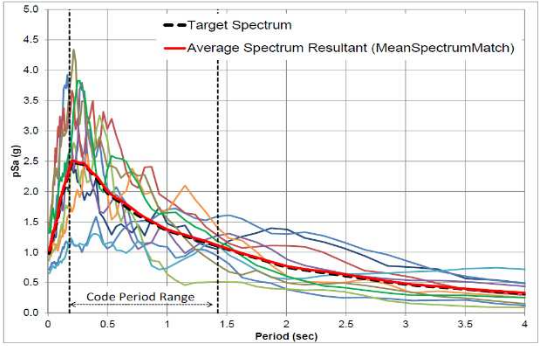

Figure 11. A suite of mean spectrally matched ground motions (Mazzoni et al. 2012)

Washington. US Geological Survey, Open-File Report 2014-1196.

8 SUMMARY AND CONCLUSIONS

Performance-based seismic design has advanced dramatically since the late 1990s, due in large part to the efforts of a dedicated group of researchers and practitioners. Significant progress has been made in seismic hazard characterization, basis of design determination, development of response spectra for structural design, and the selection of ground motions for structural analysis.

There are still several areas in PBSD that are likely to see further development in the coming years. Chief among them is the characterization of basin effects, particularly the establishment of a specific framework for incorporating the potentially higher amplification factors seen in subduction zone ground motions. Other developments may be seen in the modification of ground motion records, namely the increased use of mean spectral matching, and specific provisions regarding its use in design codes. The process of selecting subduction ground motions is also expected to improve in the near future, with the introduction of an NGA subduction ground motion database, making subduction motions more widely available to researchers and practitioners. PBSD will continue to be a useful and valuable framework to incorporate such developments in the coming years.

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