6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Updated ground motion spectral matching requirements in the 2015 NEHRP Recommended Seismic Provisions

Jack W. Baker[1], Curt B. Haselton[2], Nicolas Luco[3], Jonathan P. Stewart[4], Reid B. Zimmerman[5]

ABSTRACT

The Building Seismic Safety Council (BSSC) recently completed a multi-year effort to rewrite Chapter 16 of the ASCE/SEI 7-10 Standard (2010), which governs ground motion selection and modification for new building projects in the United States. A committee of 23 experts from research and practice was convened to review our current understanding of issues related to seismic hazard, ground motions, response history analysis, and soil-structure interaction effects on ground motions, and to develop an updated standard to reflect the significant advances in our knowledge of these areas that has been achieved in the past few decades. This paper provides an overview of some changes made to the Standard, with a particular focus on new language regarding the use of spectral matching. Example results are shown to illustrate the reasoning behind the implications of the spectral matching language, and to demonstrate the relative differences in response estimates obtained from scaled versus spectrally matched motions. These revisions should significantly advance the practice of ground motion selection and modification in the United States and elsewhere, by aligning practice with research outcomes.

Introduction

The ASCE/SEI 7-10 Standard (2010) provisions for ground motion selection and modification essentially date from 1997, when the language was first introduced to the National Earthquake Hazard Reduction Program (NEHRP) Recommended Seismic Provisions. Nearly two decades of experience with the procedure and research on ground motion selection and modification had led to significant advances in our understanding of ground motion characterization (NIST 2011), and so the BSSC formed the "Issue Team #4" committee to formulate new requirements for response history analysis that incorporate this current knowledge into the standard. General background on the overall effort and motivations for these changes are provided by Haselton et al. (2015), whereas this paper focuses on providing additional background regarding new guidance on ground motion spectral matching.

ASCE/SEI 7-10 and prior versions of the document provided no text indicating whether spectral matching was allowable, or how it should be utilized, when developing ground motions for dynamic analysis. This led to variation in its use depending upon the makeup of a project's peer-review panel, which was seen as undesirable by BSSC. BSSC tasked the group with providing some consistent guidance on the use of matching. The topic of spectral matching was a

[1] Associate Professor, Civil & Environmental Eng., Stanford University, USA, bakerjw@stanford.edu
[2] Professor and Chair, Civil Eng., California State Univ. Chico, USA, chaselton@csuchico.edu
[3] Research Structural Engineer, Geologic Hazards Science Center, United States Geological Survey, Golden, Colorado, USA, nluco@usgs.gov
[4] Professor and Chair, Civil & Environmental Eng, UCLA, Los Angeles, USA, jstewart@seas.ucla.edu
[5] Structural Design Engineer, KPFF Consulting Engineers, Portland, USA, reid.zimmerman@kpff.com

challenging one, as some members of the committee felt that the process was inherently unable to produce informative structural response estimates, and so wanted the updated guidance to explicitly prohibit matching. Others felt that it was a useful and valuable procedure and felt strongly that it should be allowed. There was much discussion of literature indicating that spectrum compatibilized motions produced smaller demands on structures than comparable amplitude-scaled motions (Bazzurro and Luco 2006; Carballo 2000; Iervolino and De Luca 2010; Huang et al. 2011; Seifried 2013), and literature indicating no such systematic difference in demands (Hancock et al. 2008; Heo et al. 2010; Huang et al. 2011; Grant and Diaferia, 2013).

Another important factor in the development of requirements is that two horizontal components of ground motions must be developed, and the target response spectrum quantifies the maximum response spectrum observed in any horizontal direction—the so-called *RotD100* spectrum (Boore 2010; Stewart et al. 2011). The ASCE/SEI 7-10 provisions adopted ground motion design maps that quantified target *RotD100* spectra, and so the BSSC committee determined that the selected ground motions should have *RotD100* spectra equivalent to that target, for internal consistency (Baker and Cornell 2006; Beyer and Bommer 2007). For scaled ground motions it was quickly determined that the two horizontal components of a ground motion should be scaled by the same factor in order to produce a ground motion with a *RotD100* spectrum consistent with the target. The case of spectral matching is more complicated, however, as individual components of a ground motion are typically manipulated separately, and so there is no unique way to produce a ground motion with the target *RotD100* spectrum.

In the end, the BSSC committee produced spectral matching requirements that were relatively simple, addressed the complication of having a *RotD100* spectral target, and provided a small level of conservatism in the spectra of matched motions in order to compensate for potential unconservatism in the structural response estimates produced by matched motions. In the end, it was hoped that the new procedures would be straightforward to implement, more consistently applied from project to project, and produce similar structural designs whether scaling or spectral matching of ground motions is used.

Requirements regarding spectral matching

The relevant proposed language regarding scaling or spectral matching of horizontal ground motions is quoted below (BSSC, 2015):

> [If ground motion scaling is used] Each ground motion shall be scaled, with an identical scale factor applied to both horizontal components, such that the average of the maximum-direction spectra from all ground motions generally matches or exceeds the target MCE_R response spectrum over the period range defined in Section 16.2.3.1. The average of the maximum-direction spectra from all the ground motions shall not fall below 90% of the target response spectrum for any period within the same period range.
>
> [If spectral matching is used] Each ground motion component shall be spectrally matched such that the average of the spectra from all ground motion components, in a given horizontal direction, shall not be less than the target MCE_R response spectrum, over the period range defined in Section 16.2.3.1.
>
> For sites identified as near-fault in Section 16.2.3.3, spectral matching shall not be utilized unless the pulse characteristics of the ground motions are retained after the matching process has been completed.

The language regarding scaling of ground motions is similar in intent to the ASCE/SEI 7-10 language, though some procedural changes have been made to ensure consistency with the maximum direction target spectrum. The language regarding spectral matching is new. Note that only single-component checks are required in the spectral matching requirements. This does not preclude simultaneously matching both-components (e.g., Grant 2010), or iteratively matching the ground motion in arbitrary orientations, but such steps are not required.

Example analysis

To illustrate the implications and potential impact of these requirements, example results are shown here. The structure considered consists of two torsionally irregular L-shaped 5-story towers with buckling restrained braced frames, sitting atop a two-story podium supported by reinforced concrete walls. The building is located in San Francisco, and was originally designed using the response spectrum procedure supplemented by limited linear response history analysis under the 1997 Uniform Building Code (1997); the design was re-evaluated as part of the BSSC effort, to see if it would be acceptable under the newly proposed criteria. Additional details regarding the building and resulting analysis are provided in Zimmerman et al. (2015). Eleven ground motions[1] were selected and scaled from the NGA West database (Chiou et al. 2008), based on their having scaled response spectra similar to the target MCE_R spectrum, having been recorded on site conditions consistent with the target site, and having associated magnitudes and distances reasonably consistent with the site hazard. All of the ground motions were additionally spectrally matched using the RSPMatch2005 software (Hancock et al. 2006). The two horizontal as-recorded components were individually matched using the software. Matching was performed only over the period range from 0.4 to 2.92 seconds—the period range specified by the procedure. The scaled and matched ground motions were then compared (in terms of both their properties and the demands they placed on the structure) in order to evaluate the implications of this procedure.

Figure 1 shows response spectra of the 11 selected and scaled ground motions, as well as the target spectrum for the site. Max direction (i.e., $Sa_{RotD100}$) spectra are shown. Figure 2a shows individual-component spectra as well as the $Sa_{RotD100}$ spectrum for one of the 11 ground motions. Figure 2b shows the same component spectra and $Sa_{RotD100}$ spectrum for that ground motion, after spectral matching was performed. Figure 3 shows time series of one component of this motion before and after matching, and indicates that the characteristics of the time series were not dramatically altered by the spectral matching (checks of this type were performed for each record). Note in Figure 2b that the individual component spectra now match the target spectrum exactly (in order to satisfy the code language above). At some periods the *RotD100* spectrum exceeds this target spectrum, indicating that there is some other orientation at which an elastic oscillator subjected to this motion would have a larger response than required by the target spectrum. It can be shown that the *RotD100* spectrum of a matched ground motion will be at least as large as the target (because the matched components have spectra that large) and can be as large as the square root of two times the target (in the case that both components have their maximum oscillator response simultaneously).

[1] The new BSSC procedure requires the use of 11 ground motions.

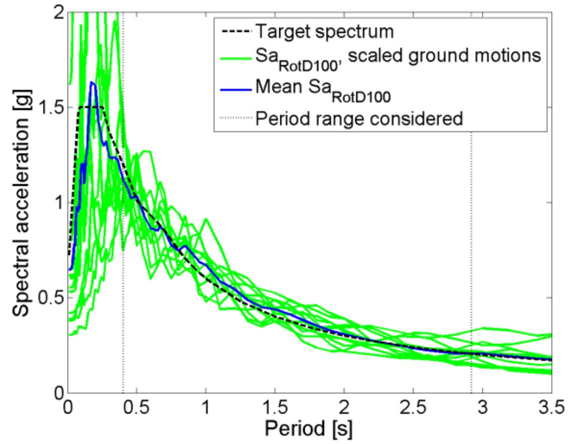
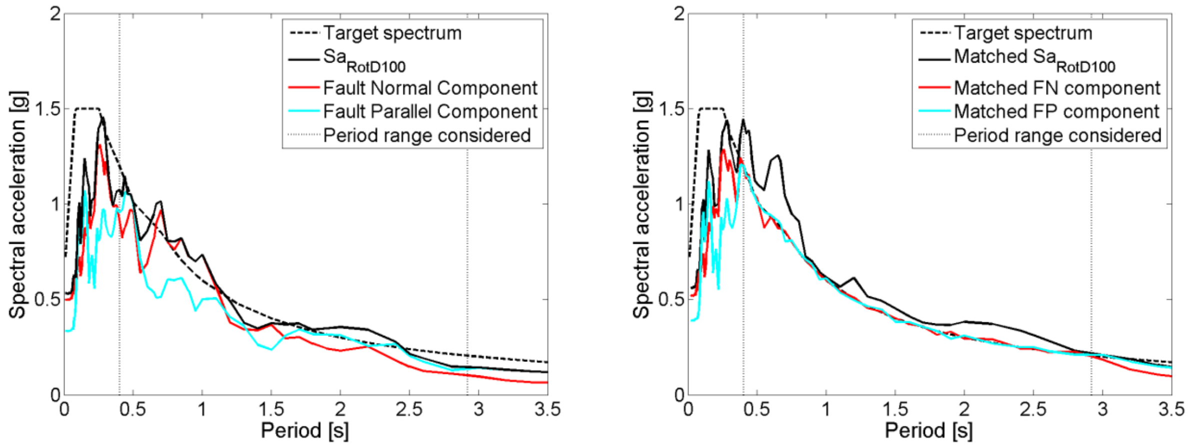
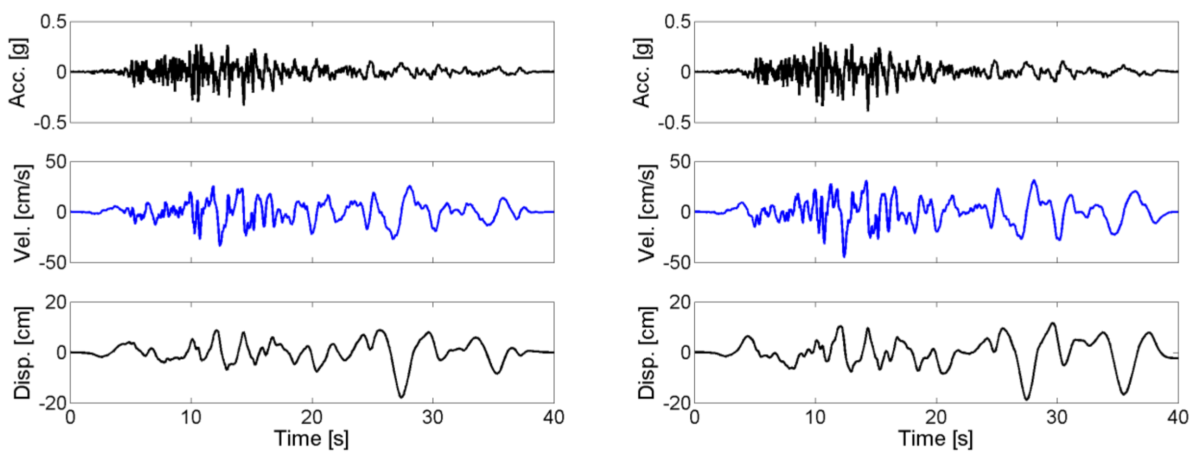


Figure 1: Response spectra of selected and scaled motions for example analysis.



a) b)

Figure 2: Response spectra of a single ground motion, (a) before and (b) after spectral matching. The ground motion is the West 15th Street recording from the 1994 Northridge earthquake.



a) b)

Figure 3: The Fault Normal component of the West 15th Street recording from the 1994 Northridge earthquake, (a) before and (b) after spectral matching.

Figure 4a shows all 22 individual-component response spectra for the 11 matched motions, indicating the close match to the target spectrum over the period range of interest. Figure 4b shows the 11 *RotD100* spectra for these same motions, along with their average, indicating that on average the $Sa_{RotD100}$ of motions processed in this manner are 10-15% larger than the target spectrum.

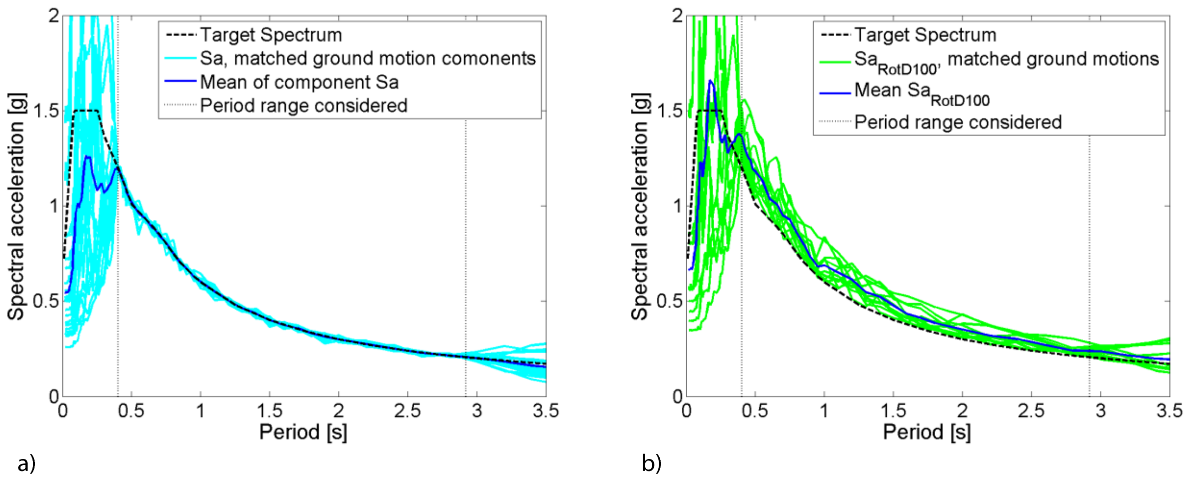


Figure 4: (a) Individual-component response spectra of spectrally matched ground motions. (b) *RotD100* spectra of spectrally matched ground motions.

The scaled and matched spectra were then used for response history analysis of the example structure. The average story drifts[2] in "Tower A" of the building are shown in Figure 5a. Results are shown for both the scaled ground motions and spectrally matched ground motions. In this case, the spectrally matched ground motions produced 2% to 13% larger drift displacements than the scaled ground motions, depending upon the story. Figure 5b and Figure 5c show story drifts from two other test case buildings subjected to scaled and spectrally matched ground motions obtained using the same procedure; in those cases, at a number of floors the spectrally matched motions produced lower average story drifts than the scaled motions. Figure 5d shows a histogram of 208 ratios of response estimates obtained from matched versus scaled motions (story drift ratios in each of two directions for four buildings, plus peak material strains in two directions for one building). While this is by no means a random or representative sample of all buildings, it does show that the matched records do not universally produce larger demands on the structure (a concern of some regarding these requirements). The mean value of these 208 ratios is 1.02, with a standard deviation of 0.11. In 108 cases the matched motions produced a larger response, and in 100 the scaled motions produced a larger response. Zimmerman et al. (2015) perform additional checks of individual member forces and also found no substantial systematic overestimation of response quantities for spectrally matched versus scaled ground motions, in spite of the on-average larger *RotD100* spectra of the matched motions.

Given the uncertainty associated with estimating average response parameters from 11 dynamic analyses, the above anecdotal statistics do not suggest that the spectrally matched motions

[2] This quantity will govern the acceptability of some building designs, so obtaining equivalent results from scaled or spectrally matched motions is one indicator that the two approaches will produce comparable building designs.

produce significantly larger demands on the structure. Given the apparently small difference in average responses produce by the scaled and matched motions, we anticipate that the proposed criteria will produce structural designs that are effectively comparable regardless of whether scaled or matched motions are used.

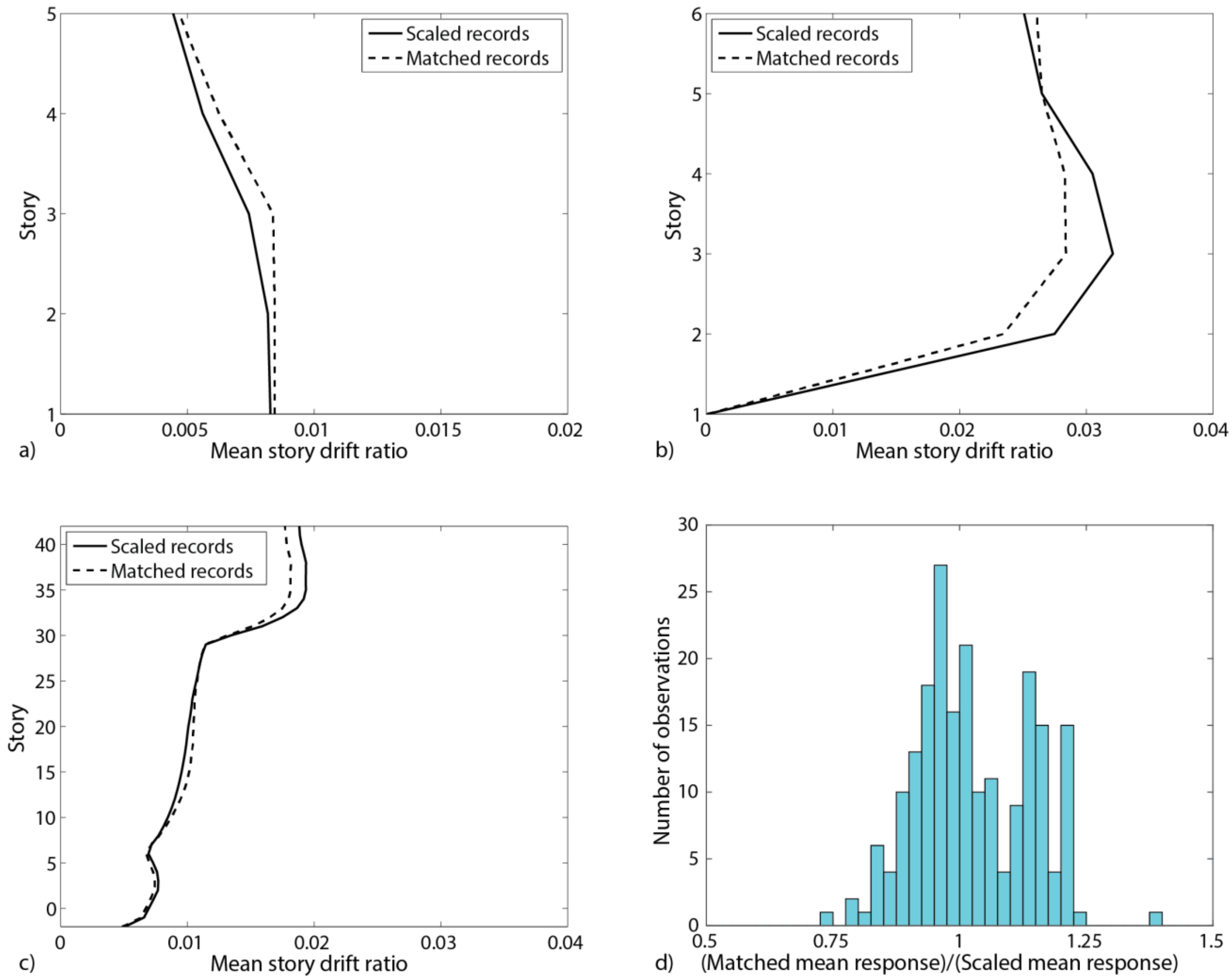


Figure 5: Mean story drift ratios for (a) the example building in San Francisco, CA, (b) a separate six-story steel moment frame building located in Berkeley, CA, and (c) a 42-story reinforced concrete core wall building located in Seattle, WA. (d) Ratio of responses from eight analysis cases (adapted from Zimmerman et al. 2015).

Discussion

As seen in the example above, the spectral matching requirements will often produce motions with max direction spectra larger than the corresponding target spectrum. Results such as those in Figure 4 indicated that the spectrally matched motions have *RotD100* spectra that are 10-15% larger than the target spectrum[3] when RSPMatch2005 is used with moderate-magnitude crustal

[3] The ASCE 7-16 provisions have modified the BSSC proposal discussed in this paper. Rather than checking that individual ground motion components match the *RotD100* spectral target, ASCE 7-16 will require that the spectrally matched ground motions exceed the *RotD100* target by 10%. These results suggest that the BSSC proposal to match individual components to the *RotD100* target should also work to satisfy the ASCE 7-16 requirement.

ground motions. This difference was noted as coincidentally being comparable in size to the approximately 10% underestimation of structural demands that some researchers have reported when using spectrally matched ground motions instead of scaled ground motions (e.g., Carballo 2000; Seifried 2013). Additionally, while the spectrally matched motions using this procedure typically have an average *RotD100* spectrum above the target, amplitude-scaled motions sometimes do as well because scaled spectra are bumpy, and at some periods a peak of an average scaled spectrum will be significantly above the target in order to ensure that the valleys at other periods are not too low (below 90% of the target).

The objective of the requirements is to ensure that evaluations of a building design's acceptability are comparable whether scaled or spectrally matched motions are used. The BSSC committee judged that the above requirements were preferable to other practical alternatives for achieving this goal. The potential for the spectral matching requirements to produce ground motions with maximum-direction response spectra slightly larger than the target was judged an acceptable compensation for the potential, in the view of some Issue Team #4 committee members, for spectrally matched ground motions to produce lower demands on average than scaled motions with comparable spectra. This line of thinking was especially persuasive, given example results such as those shown above, given the preference of some committee members to disallow spectral matching completely.

Conclusions

This paper provides background for some of the new ground motion selection and modification requirements adopted for the 2015 NEHRP Recommended Seismic Provisions. The new language regarding spectral matching has been exercised on a number of actual buildings analyzed by practicing structural engineers. The example analyses using a plausible spectral matching procedure produced ground motions with max-direction spectra that were on average 10-15% larger than comparable scaled ground motions. For three example analysis cases, the demands placed on the buildings by these spectrally matched motions were not substantially different than the demands produced by amplitude scaled motions (i.e., the building designs would be essentially identical whether scaled or spectrally matched motions were used to perform the analyses).

The language regarding requirements for spectral matching in particular has been a source of some disagreement, and so additional information regarding the new language has been the focus of this paper. Additional testing of the language will certainly lead to further insights regarding the impacts of this language and the relative impacts of using scaled or spectrally matched motions. For this reason, future refinement of these procedures may occur. Additional documentation of these results are currently in review in the peer-reviewed journal papers cited above. Collectively, the documentation produced from this project is intended to be a resource for other international groups interested in adopting or further improving this set of requirements for ground motion selection and modification and response history analysis.

Acknowledgements

The authors thank the members of the BSSC Issue Team #4 committee for enlightening discussions that led to the recommended criteria referenced throughout this document. The interpretation and commentary provided in this document is the work of the authors only and not officially endorsed by the BSSC or Issue Team #4.

References

American Society of Civil Engineers. (2010). *Minimum Design Loads for Buildings and Other Structures, ASCE 7-10*. American Society of Civil Engineers/Structural Engineering Institute.

Baker, J. W., and Cornell, C. A. (2006). "Which spectral acceleration are you using?" *Earthquake Spectra*, 22(2), 293–312.

Bazzurro, P., and Luco, N. (2006). "Do scaled and spectrum-matched near-source records produce biased nonlinear structural responses?" *Proceedings, 8th National Conference on Earthquake Engineering*, San Francisco, California, 10.

Beyer, K., and Bommer, J. J. (2007). "Selection and Scaling of Real Accelerograms for Bi-Directional Loading: A Review of Current Practice and Code Provisions." *Journal of Earthquake Engineering*, 11, 13–45.

Boore, D. M. (2010). "Orientation-Independent, Nongeometric-Mean Measures of Seismic Intensity from Two Horizontal Components of Motion." *Bulletin of the Seismological Society of America*, 100(4), 1830–1835.

Building Seismic Safety Council. (2015). *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, FEMA P-1050*. Federal Emergency Management Agency.

Carballo, J. E. (2000). *Probabilistic seismic demand analysis: spectrum matching and design*. Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA.

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

Grant, D. N. (2010). "RSPMATCHBI: A program for spectral matching two-component ground motions." *SECED - Society for Earthquake and Civil Engineering Dynamics Young Engineers Conference*, 8.

Grant, D. N., and Diaferia, R. (2013). "Assessing adequacy of spectrum-matched ground motions for response history analysis." *Earthquake Engineering & Structural Dynamics*, 42(9), 1265–1280.

Hancock, J., Bommer, J. J., and Stafford, P. J. (2008). "Numbers of scaled and matched accelerograms required for inelastic dynamic analyses." *Earthquake Engineering & Structural Dynamics*, 37(14), 1585–1607.

Hancock, J., Watson-Lamprey, J., Abrahamson, N. A., Bommer, J. J., Markatis, A., McCoy, E., and Mendis, R. (2006). "An improved method of matching response spectra of recorded earthquake ground motion using wavelets." *Journal of earthquake engineering*, 10, 67–89.

Haselton, Curt B., Baker, Jack W, Stewart, Jonathan P., Whittaker, Andrew W., Luco, Nicolas, Fry, Andy, Hamburger, Ronald O., and Zimmerman, Reid B. (2015). "Response-History Analysis for the Design of New Buildings in the NEHRP Provisions and ASCE/SEI 7 Standard: Part I - Overview and Specification of Ground Motions." *Earthquake Spectra*, (in review).

Heo, Y., Kunnath, S. K., and Abrahamson, N. (2010). "Amplitude-scaled versus spectrum-matched ground motions for seismic performance assessment." *Journal of Structural Engineering*, 137(3), 278–288.

Huang, Y., Whittaker, A., Luco, N., and Hamburger, R. (2011). "Scaling Earthquake Ground Motions for Performance-Based Assessment of Buildings." *Journal of Structural Engineering*, 137(3), 311–321.

Iervolino, I., and De Luca, F. (2010). "Spectral shape-based assessment of nonlinear response to real, adjusted and artificial accelerograms." *Engineering Structures*, 32(9), 2776–2792.

International Council of Building Officials. (1997). *Uniform Building Code*. Whittier, CA.

NIST. (2011). *Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses*. NIST GCR 11-917-15, Prepared by the NEHRP Consultants Joint Venture for the National Institute of Standards and Technology, Gaithersburg, Maryland.

Seifried, A. (2013). *Response spectrum compatibilization and its impact on structural response assessment*. PhD Thesis, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA.

Stewart, J. P., Abrahamson, N. A., Atkinson, G. M., Baker, J. W., Boore, D. M., Bozorgnia, Y., Campbell, K. W., Comartin, C. D., Idriss, I. M., Lew, M., Mehrain, M., Moehle, J. P., Naeim, F., and Sabol, T. A. (2011). "Representation of Bi-Directional Ground Motions for Design Spectra in Building Codes." *Earthquake Spectra*, 27(3), 927–937.

Zimmerman, R., Baker, J. W., Hooper, J. D., Bono, S., Haselton, C. B., Engel, A., Hamburger, R. O., Celikbas, A., and Jalalian, A. (2015). "Response History Analysis for the Design of New Buildings in the NEHRP Provisions and ASCE/SEI 7 Standard: Part III - Example Applications Illustrating the Recommended Methodology." *Earthquake Spectra*, (in review).