Use of Conditional Mean Spectra with Minimum Magnitude less than 5 in Seismic Hazard Analysis

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The 2019 ANCOLD seismic guidelines state that "A hazard assessment should be conducted for earthquake magnitudes Mw 5 and above. However, under certain circumstances, smaller magnitude earthquakes may form the lower limit. With masonry dams, slab and buttress dams, older concrete dams, and structural concrete components of dams, Mw 4 earthquake magnitudes should form the lower limit." However, when using probabilistic Uniform Hazard Spectra (UHS) with M_{min} less than 5.0 per the 2019 ANCOLD Guidelines, the hazard will be overestimated unless Conditional Mean Spectra (CMS) are used to represent the ground motions. As described by Somerville et al. (2015), use of the UHS can significantly overestimate the seismic hazard levels presented by individual earthquake scenarios because the UHS envelopes the ground motions from multiple earthquake scenarios in one spectrum. This overestimation is especially true of the ground motions from small magnitude earthquake scenarios. The probabilistic UHS may have large short period ground motions with contributions from a range of scenario earthquakes, but if the UHS is used as the design spectrum, these ground motions will often be represented by earthquake scenarios having inappropriately large magnitudes, long durations, and high long period ground motion levels. As a result, these design ground motions have the potential to overestimate the response of the structure under consideration. By using CMS spectra and time histories, the large probabilistic peak accelerations, predominantly from small earthquakes, are better represented by earthquakes having appropriately small magnitudes, durations, and lower long period ground motion levels, yielding more realistic estimates of the response of the structure.

Keywords: *Minimum magnitude, liquefaction, conditional mean spectrum*

Introduction

Liquefaction can be triggered by relatively low peak accelerations (10% to 15%g), so it is important to carefully consider the potential of small earthquakes to trigger liquefaction. Small earthquakes occur much more frequently than large earthquakes and can locally generate peak accelerations that are quite large, although their durations and long period ground motions may be sufficiently low to render their liquefaction potential negligible. Hence including small earthquakes in the PSHA could cause a positive bias in the PGA hazard and hence the liquefaction hazard.

ANCOLD 2019 Guidelines on Minimum Magnitude M_{min}

The 2019 ANCOLD guidelines, Section 2.5. Requirements of a Seismic Hazard Assessment, Paragraph 8, state that:

Minimum magnitude earthquake: A hazard assessment should be conducted for earthquake magnitudes Mw 5 and above. However, under certain circumstances, smaller magnitude earthquakes may form the lower limit. With masonry dams, slab and buttress dams, older concrete dams, and structural concrete components of dams, Mw 4 earthquake magnitudes should form the lower limit.

The 2019 ANCOLD guidelines evidently allow the use of a minimum magnitude (M_{min}) of M 5 for analysis of embankments. This is consistent with the conclusion that the ground motions of smaller earthquakes have insignificant damage potential (e.g. Bommer and Crowley 2017). Inclusion of these smaller events elevates the hazard level, especially at short periods, in a way that is difficult to accommodate in a realistic way in response analyses. Green and Bommer (2018) conclude that liquefaction potential is negligible for earthquakes with magnitude less than 5.0. Specifically, they conclude that in probabilistic liquefaction hazard analysis, earthquakes of magnitude smaller than M 5 do not need to be considered in the hazard integrations.

Revision of Australian Earthquake Magnitudes in NSHA18: Implications for M_{min}

As a result of revision of Australian earthquake magnitudes (Allen et al., 2018) in the Geoscience Australia National Seismic Hazard Assessment of 2018 (NSHA18) by Allen et al., 2019), it is now clear that earthquakes considered to be magnitude 5 at the time of writing of the 2019 ANCOLD Guidelines are actually magnitude 4.7 on average. Hence the perception in those guidelines that earthquakes of magnitude less than 5 do not pose significant liquefaction potential now applies to magnitudes less than about 4.7, suggesting that magnitudes less than 5.0 should be considered in the analysis of embankments.

Use of the Conditional Mean Spectrum to Offset Hazard Bias from Small M_{min}

As described above, including small earthquakes in probabilistic seismic hazard analysis may cause a positive bias in the PGA hazard and hence the liquefaction hazard. This paper describes a rigorous and advantageous method for accounting for small earthquakes in seismic hazard analysis using the Conditional Mean Spectrum (CMS), which is recommended in the 2019 ANCOLD Guidelines and more generally has been adopted in ASCE 7-16 (2016). The advantage stems from avoiding the overconservatism entailed in using a probabilistic Uniform Hazard Spectrum (UHS) to represent individual scenario earthquakes.

Until recently, it has been almost universal practice to use the probabilistic UHS as the design spectrum. However, the structure will only be subjected to one earthquake at a time, and no single earthquake ground motion has a response spectrum identical to the UHS. For example, the ground motions from a small nearby earthquake may match the UHS at short periods but be much lower than the UHS at long periods. Conversely, the ground motions from a large distant earthquake may match the UHS at long periods but be much lower than the UHS at short periods. The UHS is thus too "broadband" (strong across too broad a period range) to realistically represent the ground motions of scenario earthquakes. For this reason, using the UHS is generally an inaccurate and overconservative representation of the hazard.

The specific nature of the overconservatism in the case of analysis of the liquefaction potential of embankments is described in Green and Bommer (2017). The stress reduction factor tends to decrease as magnitude decreases (i.e., the soil column responds less rigidly as magnitude decreases), mainly due to the decrease in the energy of long period motions in smaller magnitude events. This implies that the cyclic stresses imposed in a stratum at depth in a soil profile are less demanding as the magnitude of the earthquake decreases, separate from the additional magnitude dependencies of PGA and duration of shaking. This overconservatism can be ameliorated using the Conditional Mean Spectrum (Baker and Cornell, 2006; Baker, 2011) in place of the UHS, as described by Somerville and Thio (2015).

Baker (2011) showed that the UHS should be represented by CMS for a set of 3 or 4 central ground motion periods (Figure 1). The CMS are for scenario earthquakes (combinations of magnitude and distance) which are identified through deaggregation of the UHS (Figure 2). The response spectra of ground motion recordings typically contain peaks and troughs (left side of Figure 1), and the peaks have high severity levels, i.e. they have high epsilon values; the recordings whose response spectra are shown on the left side of Figure 1 represent a magnitude 7 earthquake at a closest distance of 12 km. Epsilon is the number of standard deviations by which the median spectrum for a given earthquake scenario for a given magnitude and distance must be scaled to match the UHS at a specified period. It is these high epsilon values that control all of the ground motion periods that compose the UHS, but statistically, no single recording has high epsilon values at all periods, as demonstrated on the left side of Figure 1.

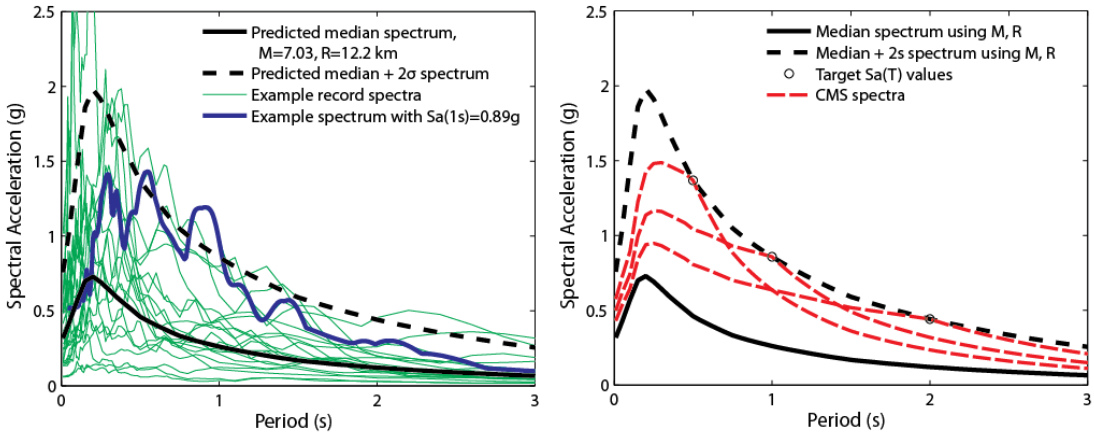

Figure 1. Left: response spectra of a large set of strong motion recordings compared with a median scenario spectrum and the corresponding spectrum that is two standard deviations above the median. Right: Three CMS representing the median + 2 standard deviations spectrum.

Source: Baker (2011)

The CMS for a given central ground motion period accounts for this by representing the response spectrum that, averaged over all of the recordings available in the strong motion data base, is most likely to accompany the high epsilon value that is associated with that central period. The right side of Figure 1 shows the development of the CMS for a set of three central ground motion periods. A suite of CMS having different central periods can collectively represent the UHS.

Demonstration in Practice

We have examined the sensitivity of seismic hazard calculations to the selection of M_{min} and use of CMS spectra. The deaggregation of the hazard for PGA (top) and 1 sec Sa (bottom) for M_{min} 5.0 (left) and M_{min} 4.5 (right) are compared in Figure 2. There are more small earthquakes in the deaggregation for M_{min} 4.5 than for M_{min} 5.0, but the deaggregation for 1 sec Sa is similar, indicating that the inclusion of earthquakes with magnitudes between 4.5 and 5.0 mainly affects the short period ground motions. UHS spectra for M_{min} 5.0 and 4.5 are compared in Figure 3. The PGA and short period spectral acceleration for M_{min} 4.5 is larger than for M_{min} 5.0, but this difference becomes negligible for periods longer than about 0.5 seconds, consistent with the response spectral shape of small earthquakes.

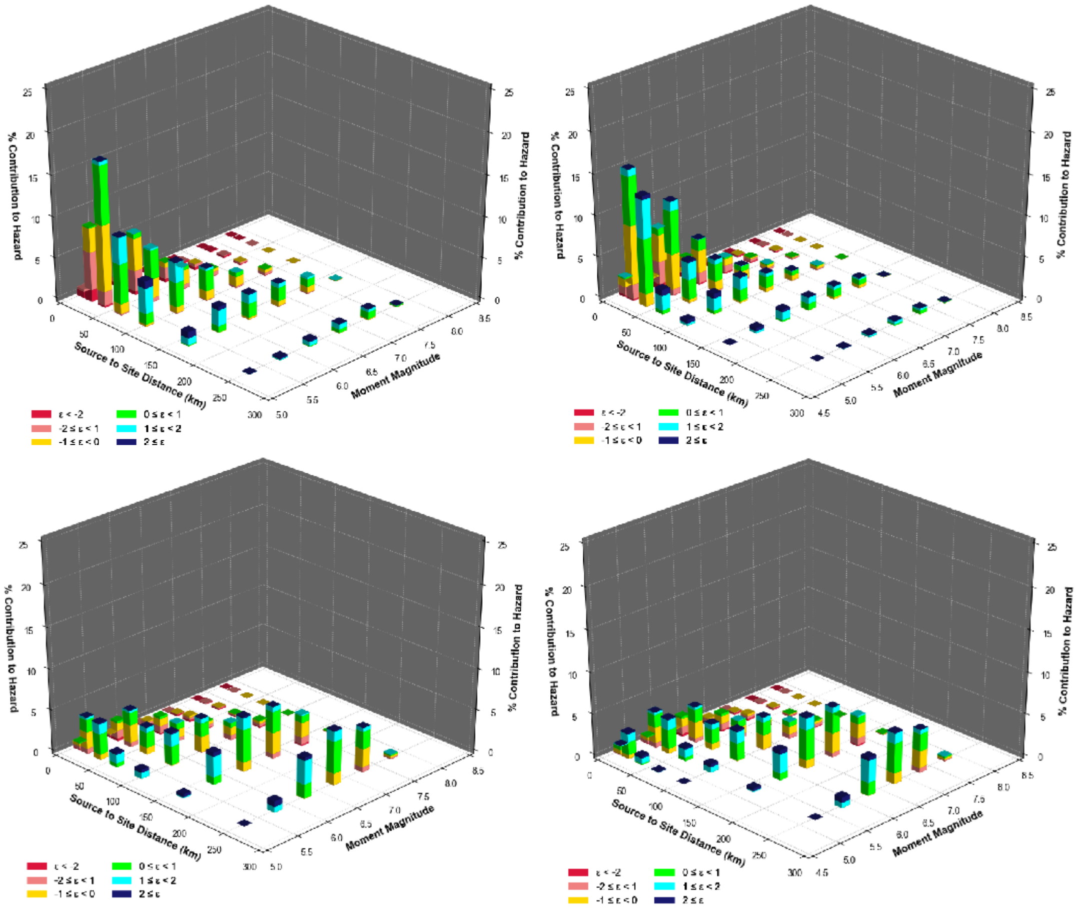

Figure 2. Deaggregation of PGA (top) and 1 sec Sa (bottom) for M_{min} 5.0 (left) and M_{min} 4.5 (right).

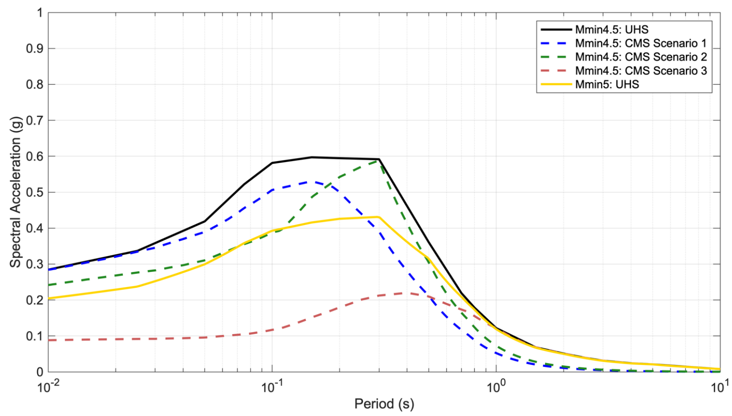

Figure 3. Probabilistic UHS response spectra for M_{min} 5.0 (yellow) and M_{min} 4.5 (black). Three CMS spectra for M_{min} 4.5, representing central periods of 0 (PGA), 0.3, and 1 second are also shown with the blue, green and red dashed lines respectively.

The response spectrum for M_{min} 4.5 in Figure 3 is a more accurate representation of the true hazard level at short periods; the problem lies in how to appropriately represent this hazard in ground motion time histories. This problem is addressed by representing the M_{min} 4.5 UHS response spectrum in Figure 3 not by that UHS spectrum but by the set of three CMS spectra shown in Figure 3.

Figure 4 shows time histories spectrally matched to the UHS spectrum for M_{min} 5.0 (top) and for CMS spectra for M_{min} 4.5 for central periods of 0 sec (bottom left) and 1 sec (bottom right). In the bottom left panel of Figure 4, the CMS (M_{min} 4.5) spectrum for a central period of 0 sec has a larger PGA than the UHS M_{min} 5.0 spectrum because it includes smaller magnitude earthquakes that have relatively high short period ground motions (Figure 3). However, the CMS M_{min} 4.5 spectrum is dominated by smaller magnitude earthquakes having short duration and low damage potential, which is reflected in the fact that it is lower than the UHS M_{min} 5.0 spectrum for periods longer than 0.3 sec. The CMS M_{min} 4.5 spectrum for a central period of 1.0 sec is almost the same as the UHS M_{min} 5.0 spectrum at 1 second period, because the inclusion of smaller earthquakes in the CMS M_{min} 4.5 spectrum does not increase the hazard very much at 1 sec Sa. But the CMS M_{min} 4.5 spectrum at a central period of 1 sec is much lower than the UHS M_{min} 5.0 spectrum at periods shorter that 1 sec. These features are reflected in the spectrally matched time histories shown in Figure 4.

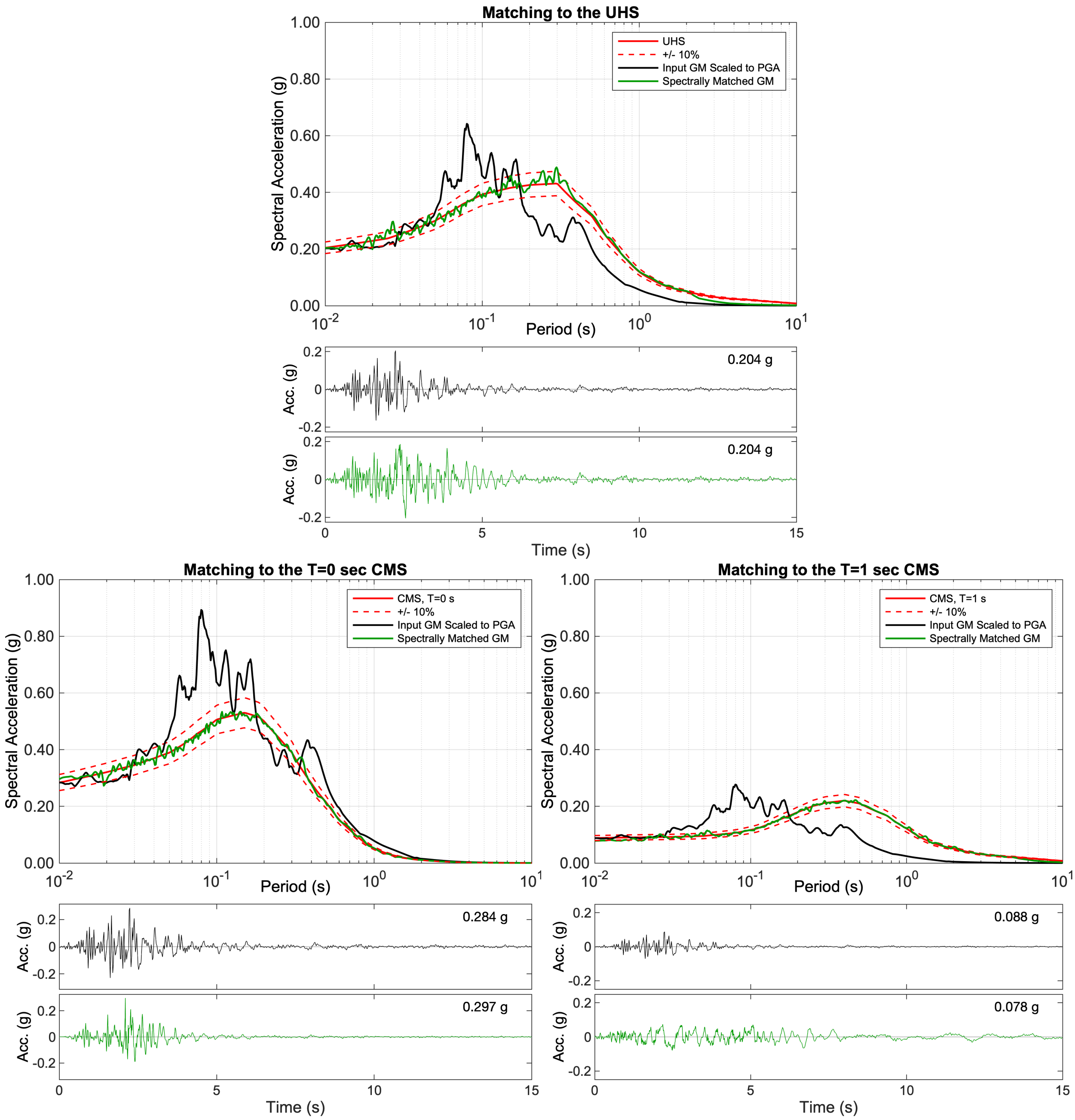

Figure 4. Time histories for UHS spectrum (top) for M_{min} 5.0, and CMS spectra for M_{min} 4.5 for central periods of 0 sec (bottom left) and 1 sec (bottom right).

The 2019 ANCOLD Guidelines recommend the use of at least four or five three-component time histories for the analysis of an embankment. If three CMS response spectra are used, then at least four or five three-component time histories would be used for each of these three CMS response spectra, yielding a total of 12 or 15 time history sets for analysis. As demonstrated above in Figure 4, the response spectrum for 1 second central CMS period is much lower at short periods, reducing its impact. Although the CMS spectrum for PGA is larger than the UHS, this larger probabilistic peak acceleration, predominantly from small earthquakes, is represented by earthquakes having appropriately small magnitudes, durations, and lower long period ground motion levels, reducing its impact and yielding more realistic estimates of the response of the structure.

Conclusions

The 2019 ANCOLD seismic guidelines prescribe consideration of earthquakes smaller than magnitude 5 for certain brittle concrete structures but not for embankments. Small earthquakes occur much more frequently than large earthquakes, and can generate peak accelerations that are quite large, although their durations and long period ground motions may be low. Liquefaction can be triggered by relatively low peak accelerations (10% to 15%g), so it is important to carefully consider the potential of small earthquakes to trigger liquefaction. As a result of revision of Australian earthquake magnitudes in the Geoscience Australia National Seismic Hazard Assessment of 2018 (NSHA18), it is now clear that earthquakes considered to be magnitude 5 at the time of writing of the Guidelines are actually magnitude 4.7 on average, suggesting that earthquakes with magnitudes less than 5.0 may be important for the analysis of embankments.

However, use of the UHS including small earthquakes can significantly overestimate the seismic hazard levels presented by individual earthquake scenarios because the UHS envelopes the ground motions from multiple earthquake scenarios in one spectrum. We show how the use of CMS spectra to represent UHS spectra including magnitudes down to 4.5 avoids this shortcoming of using the UHS, providing a more accurate representation of the hazard and resulting in reduction of the impact of the hazard as represented in CMS response spectra and ground motion time histories.

It is possible that use of M_{min} of 5.0 with the UHS spectrum, ignoring the contributions of earthquakes smaller than 5.0, would yield results that are comparable with the more rigorous treatment using CMS with M_{min} of 4.5, avoiding the need to perform many more analyses of the embankment using suites of time histories for multiple CMS spectra. This would bring practice into conformance with ANCOLD (2019) and Green and Bommer (2018), but would first need to be demonstrated in practice.

References

Allen, T., J. Griffin, M. Leonard, D. Clark and H. Ghasemi (2019). The 2018 National Seismic Hazard Assessment: Model overview. Record 2018/27. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2018.027

Allen, T. I., Leonard, M., Ghasemi, H, Gibson, G. 2018. The 2018 National Seismic Hazard Assessment for Australia – earthquake epicentre catalogue. Record 2018/30. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2018.030

ANCOLD (2019). ANCOLD guidelines for design of dams and appurtenant structures for earthquake.

ASCE/SEI (2016). 7-16 Minimum Design Loads and Associated Criteria for Buildings and Other Structures.

Baker, J. W. (2011). "Conditional Mean Spectrum: Tool for ground motion selection." Journal of Structural Engineering,137(3), 322-331. http://dx.doi.org/10.1061/(ASCE)ST.1943-541X.0000215

Baker, J.W. & Cornell, C.A. (2006). Spectral shape, epsilon and record selection. Earthquake engineering and structural dynamics, 35, 1077-1095.

Baker, J.W. & Jayaram, N. (2008). Correlation of spectral acceleration values from NGA ground motion models. Earthquake Spectra 24, 299-317.

Bommer, J.J. and H. Crowley (2017). The purpose and definition of the minimum magnitude limit in PSHA calculations. Seismological Research Letters 88, 1097-1106.

Green, R. and J. Bommer (2018). What is the Smallest Earthquake Magnitude that Needs to be Considered in Assessing Liquefaction Hazard? Earthquake Spectra 35(3):1441-1464.

Somerville, P., A. Skarlatoudis, and H.K. Thio (2015). Development of Ground Motion Time Histories for Seismic Design. Proceedings of the Annual ANCOLD Conference, 201