Ground Motion Modelling and Response Spectra for Australian Earthquakes

Ryan D. Hoult[1], Elisa Lumantarna[2], Helen M. Goldsworthy[3]

1. Corresponding Author. PhD Candidate, Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia. Email: rhoult@student.unimelb.edu.au
2. Lecturer, Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia. Email: elu@unimelb.edu.au
3. Associate Professor, Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia. Email: helenmg@unimelb.edu.au

Abstract

Due to the relatively low frequency of large earthquake events in Australia, and the inadequacy of recorded data, engineering seismologists commonly adapt ground motion prediction equations (GMPEs) developed from other regions with similar conditions to the Australian continent for the calculation of acceleration and displacement response. Recent improvements using high quality recorded data have given rise to Next Generation Attenuation (NGA) ground motion models. However, these NGA ground motion models show significant discrepancies with other ground motion prediction equations that have been developed and used in Australia, and these include the models that have helped establish the new Australian Earthquake Hazard Map. This paper presents a study which looks at the possibility of a very rare earthquake occurring at close proximity to the Sydney CBD. The suitability of use in Australia of the various available ground motion models is discussed, and some of these models are used to calculate the acceleration and displacement response spectra. There is a large discrepancy observed between the western North American derived NGAs and some of the other Australian GMPEs. The SHAKE2000 computer program was used to illustrate amplification of response at a soil site relative to that at a rock site. An NGA-West 2 model, that will be available in 2013, is also shown to illustrate improvements to the original 2008 NGA models.

Keywords: Australian earthquakes, intra-plate, Next generation attenuation, NGA-West 2, ground motion prediction equations, SHAKE2000

1. Introduction

The number of high-quality ground motion recorders in Australia is limited, which has made it difficult to develop an accurate attenuation model for Australian conditions (Burbridge, 2012), and hence to construct suitable GMPEs.

Although the catalogue of recorded earthquakes in Australia is small, Somerville *et al.* (2009a) and (2009b) have been able to use earthquake source scaling relations in Australia and broadband simulation of accelerograms using regional crustal velocity models to derive a GMPE that simulates strong-motion for both Non-Cratonic and Cratonic regions of Australia. Most recently, another Australian based GMPE was derived by Allen (2012) in conjunction with Geoscience Australia and the release of the 2012 Australian Earthquake Hazard Map (Burbidge, 2012). Both of these Australian derived GMPEs were used in the final weightings of the 2012 Australian Earthquake Hazard Map (Burbidge, 2012), along with other equations derived internationally. The resulting map predicts a peak ground acceleration (PGA) value of just 0.05g for Sydney for a 500 year return period. This is lower than the PGA, or 'Hazard Factor', that is stipulated by the current earthquake loading standard AS 1170.4 (Standards Australia, 2007) for most capital cities in Australia. For example, Sydney has a hazard factor of 0.08g for a return period of 500 years (Lam & Wilson, 2008).

The lack of strong motion data for Australia has also forced seismologists and earthquake engineers to look at adopting GMPE models from other regions. Ground motion models developed in California are said to be more appropriate to adopt for eastern Australia (Non-Cratonic) than models developed in other stable, intra-plate regions like eastern North America (Brown & Gibson, 2004). This is because the geology of Australia east of the Tasman Line is mostly Palaeozoic in age, a considerably younger crust than the western parts of Australia, and is more comparable to the Californian region (Gibson & Dimas, 2009). Consequently, the attenuation functions derived in western North America more appropriately represent ground motion excitations that may occur in these regions (Brown & Gibson, 2004). It is important to note that the Atkinson and Boore (2006) function was specifically developed for the eastern North American region and has been used in the final weightings for ground motion response in the 2012 Australian Earthquake Hazard Maps (Burbidge, 2012) for all regions of Australia, including the Eastern and Extended Crust regions.

The Next Generation Attenuation (NGA-West) project was a multidisciplinary research project that was undertaken to develop new ground-motion prediction relations based on high-quality recordings of earthquake events in western North America. The NGA-West models were found to provide much better results at 'the extremes of small and large earthquakes, near and far earthquakes, and short and long periods of ground motion' (Gibson & Dimas, 2009). Some of the requirements of the NGA project in 2008 include the ability to accurately predict ground motions for shallow crustal earthquakes in the western North America with a moment magnitude ranging from 5 to 8 for reverse fault earthquakes (Power *et al.*, 2008). Some characteristics of the earthquakes that are common in Australia include reverse fault mechanisms and ruptures that occur at a shallow depth within the top 20 km layer. These earthquakes also tend to cluster in space and time, and have stress drops that are above average (Brown & Gibson, 2004).

2. Earthquake Risk in Sydney

Sydney's Central Business District (CBD) is located within the Sydney Basin, an area comprised of Quaternary alluvial deposits (site class D) and softer materials associated with artificial fill, intertidal and alluvial deposits (site class DE and E), similar to the deposits found in Newcastle (McPherson & Hall, 2013). A strong correlation between the areas of maximum damage around Newcastle from the earthquake in 1989 and the geographical extent of Quaternary sediments has been reported previously (Jones *et al.*, 1996). Although the seismic hazard associated with Sydney is not as great as some other cities in Australia such as Adelaide (Goldsworthy & Gibson, 2012), the international insurance industry has recognised the potential for a damaging earthquake event close to the CBD. This is partly due to the seismic vulnerability of many types of structures that are present in Sydney, particularly the older structures. In fact, the reinsurance companies rate an earthquake event occurring in Sydney within their 20 top risk exposures worldwide (Wilson *et al.*, 2008).

3. Sydney CBD Case Study

In this paper, the aim is to model a very rare (2500-year return period) earthquake event occurring within a short distance from the Sydney CBD area. The earthquake will have similar characteristics to those seen in previous Australian earthquakes, such as Newcastle.

The latest two Australian GMPEs from Somerville *et al.* (2009b) (Non-Cratonic) and Allen (2012) will be used to determine the acceleration and displacement spectra due to an earthquake of a given magnitude and at a given distance. These will be compared with similar spectra determined using NGA-West models. The Boore and Atkinson (2008) NGA-West model will not be used with the assumption that the earthquake event is likely to have a high stress drop. According to Goldsworthy and Gibson (2012) this model was unsuitable for use in the case study for the Adelaide region, since the database selected as the basis for the model contained mainly earthquake generated on faults with low stress drops. In contrast, the NGA models by Chiou and Youngs (2008) and Abrahamson and Silva (2008) were selected as they are able to represent earthquakes with higher stress drops (Gibson & Dimas, 2009).

The shear-wave velocity of the top 30 m below the ground surface (V_{S30}) of 760 m/s was adopted as an approximated average value for Australian sites classified as rock (site class B). This value was obtained as the average site V_{S30} value for Australian conditions determined by several different studies (Burbidge, 2012).

The site responses with horizontally layered soil deposits were simulated using SHAKE2000 (Ordonez, 2013b). The site responses will be used for comparisons with the NGA model by Chiou and Youngs (2008). "Average Sand" (Seed & Idriss, 1970) has been used to represent the material properties for soil class D, and values taken from EPRI (1993) were used for rock.

Three different soil profiles will be investigated (illustrated in Figure 1):

(i) Profile 1 (Fig. 1a): Constant V_{S30} (760 m/s) for 30 m depth to bedrock, to compare with the NGA model results for the same shear wave velocity.

(ii) Profile 2 (Fig. 1b): Constant V_{S30} (284 m/s) for 30 m depth to bedrock, to compare with the NGA model results for the same shear wave velocity. The V_{S30} value of 284 m/s is the median calculations for Holocene units (site class D) from 214 sites in the Greater Sydney area (McPherson & Hall, 2013).

(iii)Profile 3 (Fig. 1c): A median V_{S30} profile for a depth of 30m deep will also be used for Holocene units (fine/medium sands) in the Botany Bay area as defined in McPherson and Hall (2013).

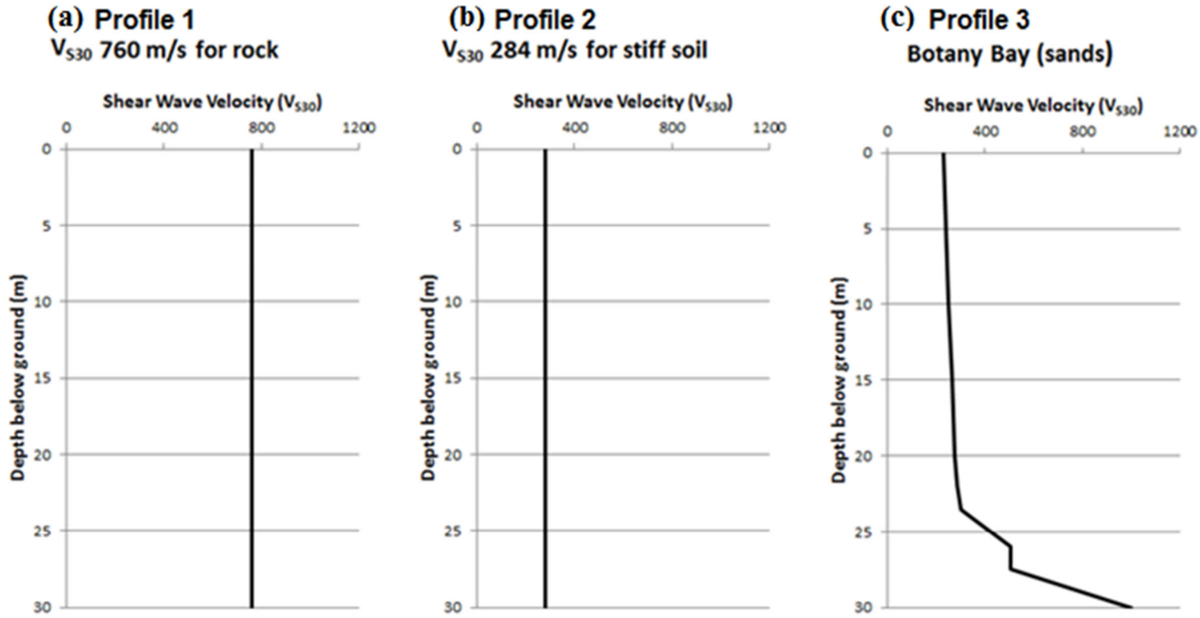

Figure 1 Soil profiles that will be used in SHAKE2000

The earthquake magnitude-distance (M-R) scenarios considered for this study were adopted from Lam *et al.* (2003) and would produce a PGA of 0.144g on rock (site class B). These combinations include **M 6 R 23** km, **M 6.5 R 30** km and **M 7 R 35** km.

It is noted that this approach is not based on recurrence intervals of ruptures on faults or on the proximity of a site in Sydney to active faults. It is consistent with the existing AS 1170.4 (Standards Australia, 2007) predictions of PGA and PGV for a return period of 2500 years, but has very little statistical basis. As shown in Goldsworthy and Gibson (2012) the actual response spectra derived using the well-known Cornell method, which does take active fault zones into account, may result in much higher predications for the 2500 return period event, in that case for a site in Adelaide.

In order to calculate the acceleration and displacement response spectrum using the NGA-West models and GMPEs, the following assumptions for the earthquake characteristics were made:

- Z_{TOR}, the depth to the co-seismic rupture, is 5 km
- W, fault rupture width, is 2.5 km
- δ, the average dip angle of rupture plane, is 60º
- Reverse faulting mechanism, hanging-wall site
- Site (Sydney CBD) on down-dip side of top of rupture

4. Results and Discussion

4.1 Rock Site (Site Class B, V_{S30} = 760 m/s)

The results from the scenario of a magnitude 6.5 earthquake at a distance of 30 km on a rock site in Sydney are shown in Figures 2 and 3. These graphs represent an estimation of the accelerations and displacements respectively of the ground motions of this 2500-year return period event using the selected GMPEs and NGAs. Due to space limitations the results are shown for only one of the magnitude-distance (M-R) scenarios, M 6.5 R 30, but the following observations are also relevant for the other M-R combinations that have been given.

The GMPE by Allen (2012) generally has the lowest accelerations and displacements of all of the M-R combinations. In contrast, results from Somerville *et al.* (2009b) give highest prediction for acceleration and displacement for all of the M-R combinations. The higher the magnitude and distance, the larger the discrepancy between the displacement response between the Somerville *et al.* (2009b) model and the others, especially towards the higher period range (T > 3s). In the short period range this GMPE is reasonably consistent with the predictions from the NGA models.

Although there are still some discrepancies between the NGA-West models for displacement response at the higher period range, both models by Chiou and Youngs (2008) and Abrahamson and Silva (2008) show comparable predicted values for both acceleration and displacement. Their predictions generally fit in between the two extremes from Allen (2012) and Somerville *et al.* (2009b).

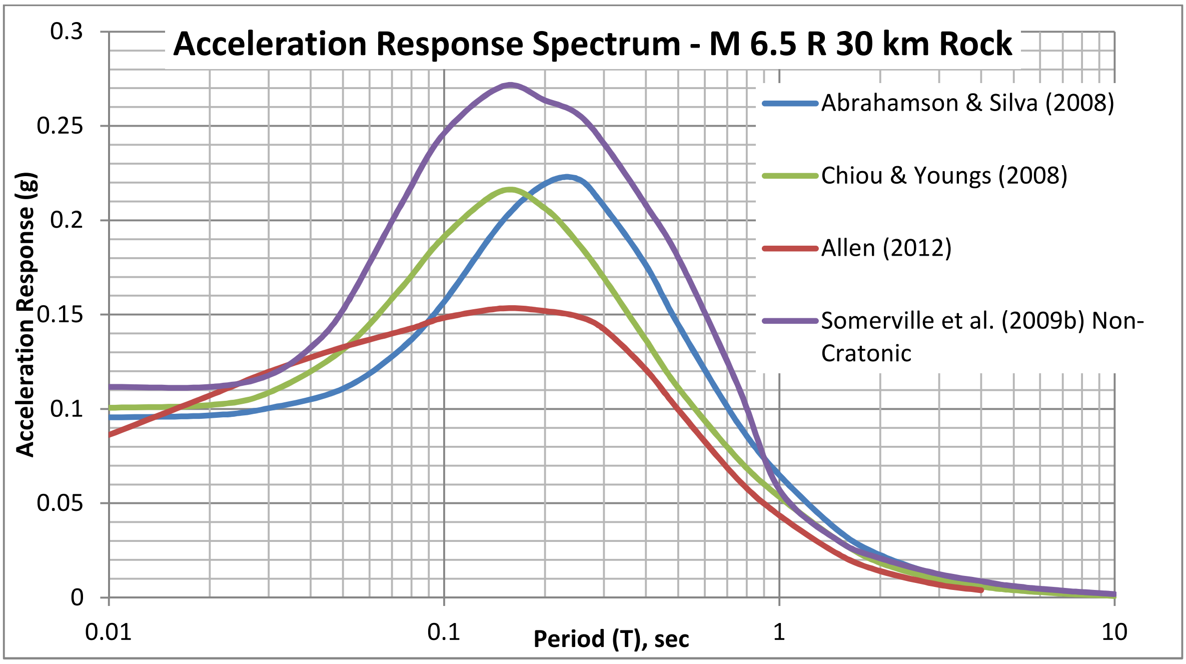

Figure 2 – Acceleration Response Spectrum (5% Damping) for Magnitude 6.5 at 30 km rock site

4.2 Soil Site (Site Class D, V_{S30} = 284 m/s)

Multiple acceleration time-histories (accelerograms) were obtained from the PEER ground motion database that were from a similar tectonic environment, reverse fault type and within a magnitude and distance that was close to magnitude 7 at 35 km distance (one of the M-R combinations for the 2500-year return period event). These time-histories were then adjusted using the program RspMatchEDT (Ordonez, 2013a) targeted to match closely to the acceleration response spectrum of Chiou and Youngs (2008) NGA results for a magnitude 7 at a distance of 35 km. This approach produced seven adjusted acceleration time-histories that were used as input to SHAKE2000 for ground motions in order to observe and obtain results for site response. Seven artificial accelerograms were also generated using a program SeismoArtif (SeismoSoft, 2013) based on the ground motion model by Chiou and Youngs (2008). The adjusted and artificial accelerograms were used as input accelerations in SHAKE2000 to simulate acceleration and displacement response on soil. The ground motions were assigned as outcrop motion, which assumes that the rock motion was recorded on a rock outcrop. The median of the seven adjusted or artificial accelerogram responses after running the analysis for the different soil profiles will be used for the results of SHAKE2000.

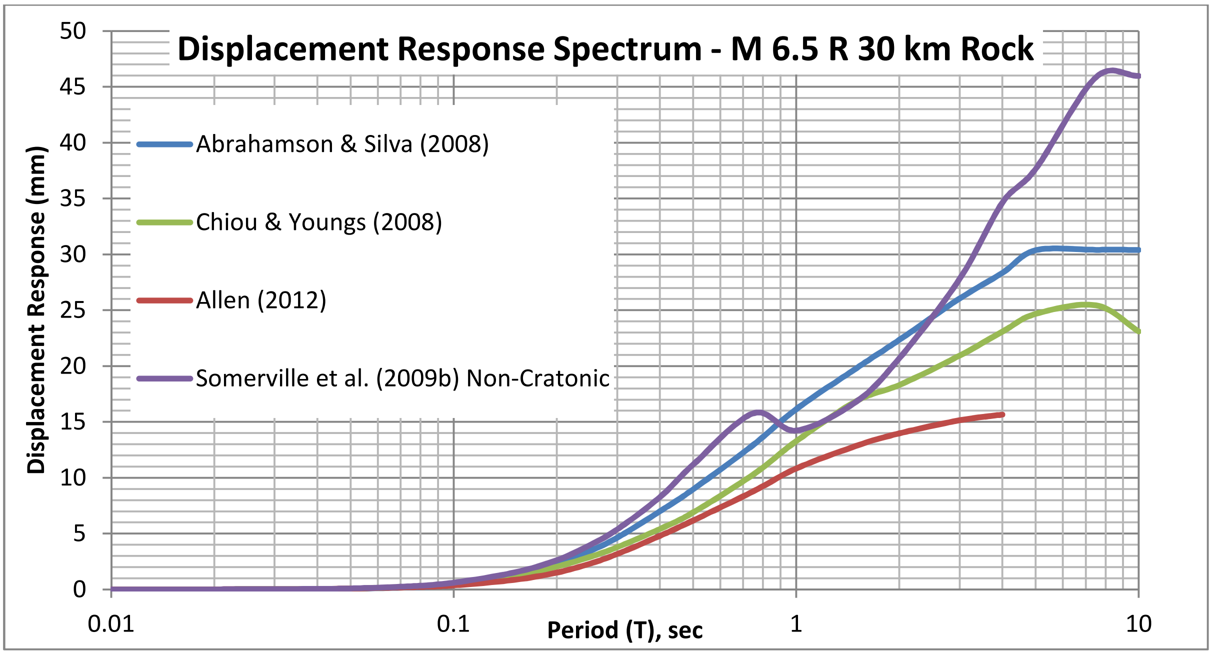

Figure 3 – Displacement Response Spectrum (5% Damping) for Magnitude 6.5 at 30 km rock site

Figures 4 and 5 show the results from SHAKE2000 for a magnitude 7 earthquake at a distance of 35 km from a site in the Sydney CBD. The site acceleration response from SHAKE2000 using adjusted motions and profile 2 differs from Chiou and Youngs (2008) results for profile 2. The two peaks of acceleration response at short periods (T < 1 sec) are higher than what the Chiou and Youngs (2008) model has predicted. Analyses using the V_{S30} profile (profile 3) for the Botany Bay area (McPherson & Hall, 2013) results in similar response, but high acceleration. Using this profile and applying the artificial accelerograms in SHAKE2000 also gives similar results. In general, the acceleration and displacement response predictions from the SHAKE2000 results using profiles 2 and 3 exceed the Chiou and Youngs (2008) predictions for profile 2 in the period range from 0.1 to 0.7 seconds. At periods greater than 1 second the SHAKE2000 results reveal little site amplification of acceleration or displacement response relative to a rock site for the particular soil site conditions (profile 2 and 3) that have been investigated here.

The NGA-West 2 project followed on from the original NGA project and is expected to result in improved predictions due to the better quality of the ground motion recordings in the new database, particularly for high periods. The Chiou and Youngs (2013) NGA-West 2 spectra are obtained for the same M-R combination and profile 2. The model results in a significant increase in acceleration and displacement response relative to the 2008 Chiou and Youngs model in the 0.3 to 0.5 second range.

The displacement spectra in Figure 5 shows higher predicted values of displacement from the 2013 NGA model compared to its 2008 predecessor, but these values are not that significant. The 2013 NGA model envelopes the displacement values at the natural period of the soil profiles 2 and 3, which can be illustrated in Figures 4 and 5 at around 0.4s, which demonstrates the improvements of the NGA-West 2 project in predicting soil amplification. The displacement predictions from site response using SHAKE2000 are much lower than the predicted NGA models, which are a result of the lower acceleration values in the periods higher than 1 second. This could be attributed by both of Chiou and Youngs models accounting for sites with much deeper soils.

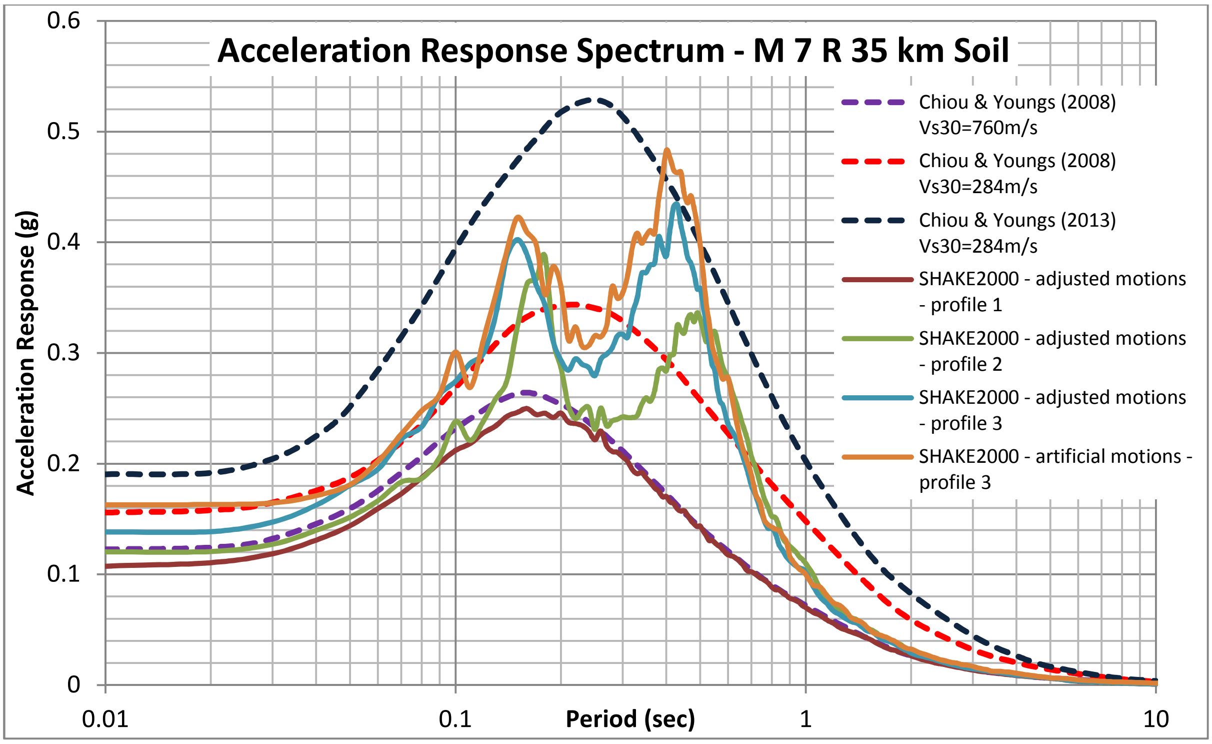

Figure 4 – Acceleration Response Spectrum (5% Damping) for Magnitude 7 at 35 km for soil site (class D)

5. Conclusion

In this paper various GMPEs have been investigated for use in defining a very rare earthquake event for sites in the Sydney CBD with either rock or soil conditions. The M-R combinations used are consistent with the definition of a 2500 year return period event in AS1170.4, although it is recognised that this has little statistical basis in that knowledge of slip rates in active fault zones are not explicitly taken into account when determining these M-R combinations. Large discrepancies have been illustrated between the two Australian GMPEs from Allen (2012) and Somerville *et al.* (2009b) that have been investigated in this paper, especially with larger magnitude events, which are the events of most concern to engineers. The NGA-West models can provide the most consistent predictions of ground motions to date, due to its extensive dataset of well recorded events and range of mechanisms for different conditions that seem to be eligible for some regions of Australia. However, the GMPEs investigated in this paper cannot be chosen to represent the ground motions for earthquake events in Australia with a high degree of confidence until they can be properly validated against well recorded moderate and large events that rarely occur in Australia. One of the only possible ways of achieving this is by increasing the density of high-quality recorders in regions that are known to be active ("hot spots").

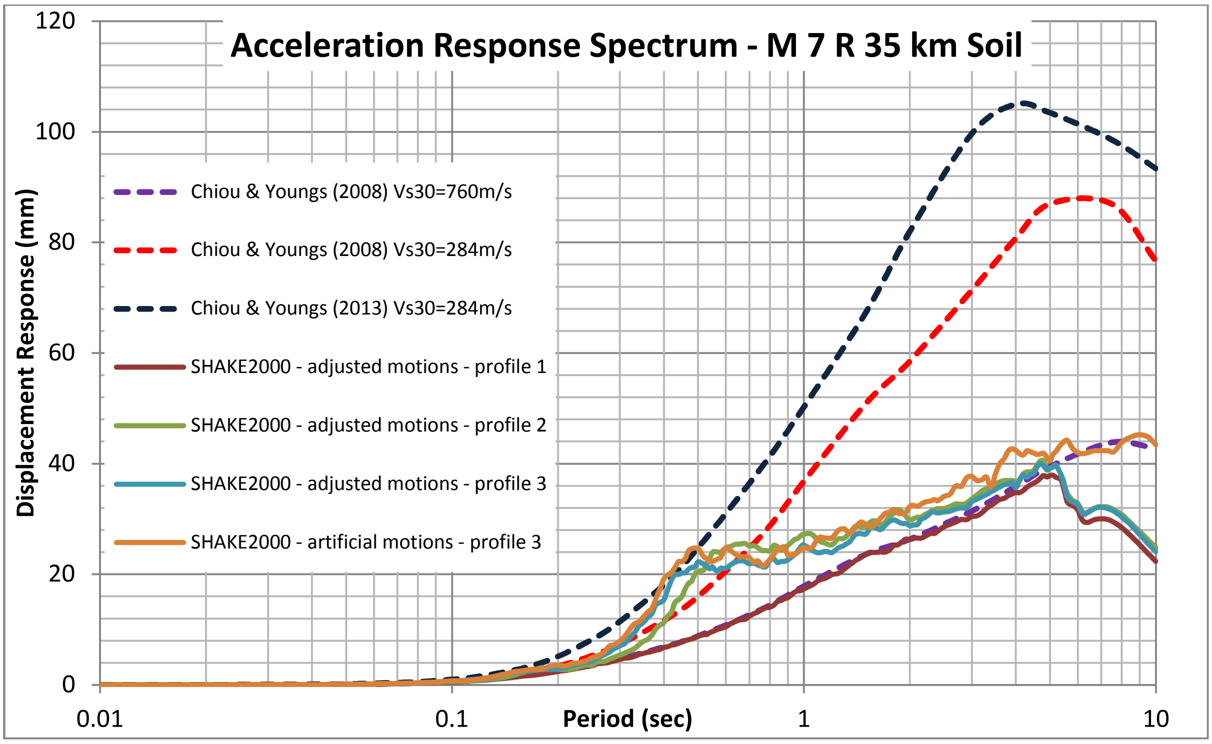

Figure 5 – Displacement Response Spectrum (5% Damping) for Magnitude 7 at 35 km for soil site (class D)

The results from SHAKE2000 highlight the importance of site response and amplification of the ground motions. It is clear that the alluvial soils, that are present around the Sydney CBD area and other capital cities in Australia, have the ability to amplify the acceleration and displacement response. It is recommended that more research is investigated into these amplification effects with varying soil depths and the integration of basin effects.

1. References

Abrahamson, N., & Silva, W. (2008). Summary of the Abrahamson & Silva MGA Ground-Motion Relations. *Earthquake Spectra, 24*(1), 67-97. doi: 10.1193/1.2894832

Allen, T. I. (2012). Stochastic ground-motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters. *Record 2012/69. Geoscience Australia: Canberra.*

Atkinson, G. M., & Boore, D. M. (2006). Earthquake Ground-Motion Prediction Equations for Eastern North America. *Bulletin of the Seismological Society of America, 96*(6), 2181-2205. doi: 10.1785/0120050245

Boore, D. M., & Atkinson, G. M. (2008). *Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at spectral periods between 0.01 s and 10.0 s*.

Brown, A., & Gibson, G. (2004). A multi-tiered earthquake hazard model for Australia. *Tectonophysics, 390*(1–4), 25-43. doi: http://dx.doi.org/10.1016/j.tecto.2004.03.019

Burbidge, D. R. e. (2012). The 2012 Australian Earthquake Hazard Map *Record 2012/71*: Geoscience Australia: Canberra.

Burbridge, D. R. e. (2012). The 2012 Australian Earthquake Hazard Map. *Record 2012/71. Geoscience Australia: Canberra.*

Chiou, B.-J., & Youngs, R. R. (2008). An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthquake Spectra, 24*(1), 173-215. doi: 10.1193/1.2894832

Chiou, B. J., & Youngs, R. R. (2013). Update of the Chiou and Youngs NGA Ground Motion Model for Average Horizontal Component of Peak Ground Motion and Response Spectra: PEER 2013/07.

EPRI, E. P. R. I. (1993). Guidlines for Site Specific Ground Motions: Palo Alto, California, Electric Power Research Institue, Novemeber, TR-102293.

Gibson, G., & Dimas, V. (2009). *Earthquake Hazard at Newcastle*. Paper presented at the Australian Earthquake Engineering Society 2009 Conference, Newcastle, New South Wales.

Goldsworthy, H. M., & Gibson, G. (2012). *Changes in Seismic Design Philosophy for RC Structures in Areas of Low to Moderate Seismicity Following the Christchurch Earthquake*. Paper presented at the Proceedings of the 15th World Conference in Earthquake Engineering.

Jones, T. D., Neville, M. J., Scott, G., & Sinadinovski, C. (1996). *Earthquake Microzonation and the Developement of the Australian Earthquake Loading Standard*. Paper presented at the Paper presented at the Proceedings of the 1996 Australian earthquake Engineering Society Conference, Adelaide.

Lam, N., Sinadinovski, C., Koo, R., Wilson, J. L., & Doherty, K. (2003). Peak ground velocity modelling for Australian intraplate earthquakes.

Lam, N. T. K., & Wilson, J. L. (2008). The new response spectrum model for Australia.

McPherson, A., & Hall, L. (2013). Site Classification for Earthquake Hazard and Risk Assessment in Australia. *Bulletin of the Seismological Society of America, 103*(2A), 1085-1102. doi: 10.1785/0120120142

Ordonez, G. A. (2013a). RspMatchEDT (Version 9.99.2 - July 2013). Retrieved from http://www.geomotions.com

Ordonez, G. A. (2013b). SHAKE2000 (Version 9.99.2 - July 2013). Retrieved from http://www.geomotions.com

Power, M., Chiou, B., Abrahamson, N., Bozorgnia, Y., Shantz, T., & Roblee, C. (2008). An Overview of the NGA Project. *Earthquake Spectra, 24*(1), 3-21. doi: citeulike-article-id:5410272

Seed, H. B., & Idriss, I. M. (1970). Soil moduli and damping factors for dynamic response analyses (Vol. Report No. EERC 70-10): University of California, Berkekley, December.

SeismoSoft. (2013). SeismoArtif (Version 2.1.0 Build: 200, June 2013). Retrieved from www.seismosoft.com

Somerville, P. G., Graves, R. W., Collins, N. F., Song, S. G., & Ni, S. (2009a). Ground motion models for Australian earthquakes. *Report to Geoscience Australia, 29 June 2009*.

Somerville, P. G., Graves, R. W., Collins, N. F., Song, S. G., Ni, S., & Cummins, P. (2009b). *Source and ground motion models for Australian earthquakes*. Paper presented at the Proceedings of the 2009 Australian Earthquake Engineering Society Conference, Newcastle.

Standards Australia. (2007). AS 1170.4-2007: Structural design actions, Part 4: Earthquake actions in Australia.

Wilson, J. L., Lam, N. T. K., & Pham, L. (2008). Development of the new Australian earthquake loading standard: EJSE International Ltd 2008.