



NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
**2019 Pacific Conference on
Earthquake Engineering**
TURNING HAZARD AWARENESS INTO RISK MITIGATION
4 – 6 April | SkyCity, Auckland | New Zealand



Site and event specific response spectra and accelerograms for low to moderate seismicity regions

N. Lam & E. Lumantarna

Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Australia

H.-H. Tsang

Swinburne University of Technology, Melbourne, Australia

D. Looi & J. Wilson

Swinburne University of Technology, Sarawak Campus, Kuching, Sarawak, Malaysia

ABSTRACT

The design of an important structure on a site with onerous conditions of the underlying soil sediments may require the use of response spectra that specifically represent the subsoil conditions and at the same time compatible to code stipulated seismic actions. Such requirements apply to countries in regions of lower seismicity like Australia as much as in regions of higher seismicity. Many computer programs are available on the market to perform soil dynamic analyses in accomplishing the stated task. In performing the analyses it is required to select, or generate, suitable accelerograms representing bedrock excitations (as well as specifying properties of the subsoil) for input into the analyses. The conditional mean spectrum (CMS) has been introduced as a technique to select earthquake accelerograms based on specific earthquake events that are compatible to the code stipulated actions. This article first presents an outline of the probabilistic seismic hazard analysis based on a generic activity model which fits with the minimum hazard design factor (being $Z = 0.08$) in the Australian Standard (which applies to most parts of Australia). With the use of the CMS technique event specific response spectra have been derived for generating spectrally compatible accelerograms for rock conditions. Example site and event specific response spectra are then presented for use in engineering design.

1 INTRODUCTION

Time-history analyses of a structure requiring the use of accelerograms are seldom undertaken in practice, and more so in regions of low-to-moderate seismicity like Australia. However, there are occasions when the development of (site specific) response spectra which accurately represent the subsoil conditions of the building are justified because of exceptionally onerous subsoil conditions coupled with the importance of the built infrastructure that is found on the site. The assessment of the seismic performance of an unconventional form of construction at the limit state of collapse in a very rare earthquake event would also necessitate the use of strong motion accelerograms.

The Australian Standard for seismic actions AS1170.4-2007 (Standards Australia 2007) provides only very brief guidance over the selection and scaling of accelerograms for use in time-history analyses. Eurocode 8 (EN1998-1 2004) provides more detailed guidance but has not been kept up to date with the development of the Conditional Mean Spectrum (CMS) methodology noting that the code clauses of the current edition of Eurocode 8 were drafted some 20 years ago. The development of CMS to be reported in this article is based on guidelines introduced in Somerville and Thio (2011) and Baker (2011).

Maps defining the value of the design seismic hazard factor (Z) forming part of AS1170.4 have been revised very recently (in 2018) to incorporate a minimum Z value of 0.08 across the whole of Australia thereby superseding maps that had been derived in a conventional manner from probabilistic seismic hazard analysis (PSHA). Identifying M-R combinations that are compatible with $Z_{\min} = 0.08$ would need to make use of data generated from a PSHA in which a uniform spatial distribution of seismic activities was assumed. The need to find a ground motion model which accurately represents regional and local conditions poses additional challenges in places like Australia where there is a paucity of strong motion data that can be sourced locally. The development of the CMS attending to all these challenges is described in this article which also presents response spectra of accelerograms representing rock conditions that have been selected and scaled in accordance with the newly derived CMS. Program SHAKE (Schnabel et al. 1972; Ordonez 2013) has also been employed for simulating response spectra on the surface of an example Class D site.

2 OUTLINE OF CONDITIONAL MEAN SPECTRUM METHODOLOGY

The Conditional Mean Spectrum (CMS) methodology as introduced in Baker (2011, 2015) and Somerville and Thio (2011) provides a more realistic (and less conservative) target response spectrum for the selection and scaling of accelerograms than a code design response spectrum or a uniform hazard spectrum. The CMS is based on the use of a selected ground motion model (or several ground motion models) that is representative of the seismological condition of the studied region to construct a response spectrum that is specific to a dominant earthquake scenario. Each of the scenario specific response spectrum is first derived considering median response spectral predictions for rock conditions. The response spectrum (the CMS) which is scaled up from the median spectrum based on Equation 1 and factors that are listed in Table 1 is to match with the target response spectrum stipulated by the current code of practice at a reference natural period (or a range of natural periods). Accelerograms are then selected and scaled to the CMS.

$$\mu_{\ln Sa(T_i) | \ln Sa(T^*)} = \mu_{\ln Sa}(M, R, T_i) + \rho(T_i, T^*) \varepsilon(T^*) \sigma_{\ln Sa}(M, T_i) \quad (1)$$

where $Sa(T^*)$ is the target Sa at period T^* , $\varepsilon(T^*)$ is the number of standard deviations by which $\ln Sa(T^*)$ differs from the mean prediction $\mu_{\ln Sa}(M, R, T^*)$. $\mu_{\ln Sa}(M, R, T_i)$ and $\sigma_{\ln Sa}(M, T_i)$ are the logarithmic mean and standard deviation of Sa at all periods T_i , respectively, and $\mu_{\ln Sa(T_i) | \ln Sa(T^*)}$ is the conditional mean Sa at other periods. $\rho(T_i, T^*)$ is the correlation coefficient between pairs of ε values (Table 1).

Table 1: Values of $\rho(T_i, T^*)$ as per recommendations by Baker (2011)

$T^* \setminus T_i$	0.2 sec	1 sec	2 sec
0.2 sec	1.0	0.44	0.26
1 sec	0.44	1.0	0.75
2 sec	0.26	1.0	1.0

In summary, the CMS procedure is divided into the following steps each of which is elaborated in the rest of the paper under separate headings:

- Identification of dominant M-R combinations from results of a suitable probabilistic seismic hazard analysis (Section 3).
- Determination of median scenario specific response spectra associated with selected M-R combinations and a representative ground motion model (Section 4).
- Construction of CMS by scaling from the median scenario specific response spectrum using the prescribed scaling factors (Section 5).
- Selection and scaling of ground motions (either uniformly or spectrally) to conform to the CMS for rock conditions at the reference range of natural periods (Section 6).
- Generation of site specific response spectra from soil dynamic analyses (using a recognised software such as program SHAKE (Ordonez 2013) based on use of accelerograms obtained from Step (iv) as the base applied excitation time-histories (Section 7).

3 A GENERIC SEISMICITY MODEL FOR LOCAL EARTHQUAKES IN INTRAPLATE REGIONS

The generic seismicity model to be introduced herein was derived from results of the survey of the rate of earthquake exceeding magnitude 5 ($M > 5$) occurring in landmass within intraplate regions around the globe (Lam et al. 2016). It was found from the survey that there were on average five $M > 5$ events occurring in a land area of 1 million square kilometres in a 50 years period. This observed rate of occurrences can be expressed in the Gutenberg-Richter (G-R) form as shown by Equation 2 taking $b = 0.9$ which was based on considerations of recommendations in the literature as cited in Lam et al. (2016).

The KD factor was introduced to allow for the rate of earthquake occurrence to be adjusted in view of the “migration” phenomenon of intraplate seismicity in view of the heterogeneous pattern of spatial, and temporal, distribution of seismic activities that can be observed in large intraplate areas like Australia. KD is set at unity (i.e., $KD = 1$) for five events occurring in an area of 1M sq km and a period of observation of 50 years; $KD = 2$ for ten events and $KD = 3$ for fifteen events, and so on. In a probabilistic seismic hazard analysis (PSHA) adopting the generic model as described, the seismic areal sources are modelled as annuli which have the “site” being their common centre (Lam et al. 2016). A uniform value of KD is taken for every location of the earthquake source surrounding the site to be consistent with the assumption of uniform distribution of seismic hazard. Accordingly, the value of parameter “ a ” in the G-R relationship (Equation 2) characterising an annular source is controlled by the area of the annulus and value of KD which is held constant in a PSHA.

$$\log_{10} N = 5.2 - 0.9M \quad (2)$$

where N is the number of events exceeding magnitude M occurring in an area of 1 million square kilometres in a 50 years period.

Observations of the annual rate of occurrence (from PSHA) reveal no distinctive M-R combinations dominating contributions to the earthquake hazard of the site in this uniform hazard model. The seismic

hazard is instead contributed by a diversity of potential earthquake scenarios. Earthquakes of magnitudes up to the maximum considered magnitude (M_{max}) can occur at all locations including the immediate vicinity of the site but the probability of occurrence is much lower than earthquakes occurring at distance of 10 km from the site. In the context of PSHA (for a return period of 2500 years) earthquakes in the lower magnitude range (M5 - M5.5) tend to have the highest contribution to seismic hazard because of their higher frequency of occurrence. Most of such local hazard comes from earthquakes occurring within the distance range of 10 - 15 km. Low rise structures found on shallow soil sites are mostly affected by these M-R combinations. Earthquakes in a higher magnitude range (M6 - M6.5) and from the distance range: 20 – 40 km is potentially more damaging because of their richness in energy contents at higher periods thereby amplifying motions more severely on deep soil sites. Although their rate of occurrence is much lower than the lower magnitude events their potential contributions to site hazards cannot be ignored and more so for structures found on deep soil sites.

4 GROUND MOTION MODELLING FOR SOUTHEASTERN AUSTRALIA

A ground motion model (GMM) provides predictions for earthquake ground motion behaviour for a given earthquake scenario (expressed in terms of M-R combination) and site conditions (along with the style of faulting in certain models). One common form of GMM is ground motion predictive expressions (GMPE) which enables response spectral accelerations across the entire natural period range of engineering interests to be calculated (by use of some simple algebra). Thus, a GMPE is convenient to be used by engineering practitioners. The biggest challenge with the development of a GMM (or GMPE) in a region of low-to-moderate seismicity like Australia is the paucity of strong motion accelerograms that can be sourced locally. In a well-studied intraplate region like Eastern North America (ENA) where strong motion data is also lacking, seismological modelling is the most commonly adopted, and most successful, approach for developing GMMs by virtue of a viable critical mass of geophysics researchers alongside the availability of high quality low intensity data that have been captured by seismological instruments from seismic tremors and distant earthquakes (not to be confused with strong motion accelerograms). Refer review report on ground motion models developed for use in ENA by the Pacific Earthquake Engineering Research Centre (2015).

It is cautioned herein that GMMs/GMPEs that are intended for use in ENA might not be suitable for use in all parts of Australia because of significant variations in crustal conditions between continents as well as within a continent. However, GMMs developed from seismological modelling are potentially powerful because of their ability to adapt to a diversity of conditions, and much of this is attributed to the viability of resolving the ground motion generation process into the source, path and site components (e.g., Boore 2016; Lam et al. 2006). Thus, GMMs that are representative of Australian conditions can be developed by combining the source model from ENA with path and site models that have been modified to be representative of local conditions. The need to repeat all of the seismological model development work for Australian applications is therefore spared but it is still essential to have reliable information of the local crustal properties for applying suitable modifications.

However, few engineering users have the skills and knowledge to decouple various components within a seismological model, apply modifications to suit local conditions and then have the results presented in the form of a GMPE. The Component Attenuation Model (CAM) which was first published in year 2000 and continuously refined by the authors of this article and co-workers over many years is precisely to accomplish this series of tasks in one model (Lam et al. 2000, 2003, 2005, 2010; Lumantarna et al. 2012; Tang et al. 2018). Presentation of the latest version of CAM by Tang et al. (2018) demonstrated that macroseismic intensity information (expressed in MMI) recorded during thirteen destructive earthquake events in Australia (dating back to 1868) matched best with that inferred from CAM than from five other well documented, and

well recognised, GMPEs. A listing of input parameter values into CAM for use in southeastern Australia is provided in the cited reference.

5 EXAMPLE CONDITIONAL MEAN SPECTRA FOR USE IN SOUTHEASTERN AUSTRALIA

Earthquake scenarios that have been selected for derivation of the CMS are:

- 1) M5, $R_{rup} = 15$ km; 2) M5.5, $R_{rup} = 15$ km; 3) M6, $R_{rup} = 20$ km; 4) M6.5, $R_{rup} = 30$ km

Scenarios (1) - (3) which are based on $T^* = 0.2$ s have relatively high frequency of occurrence (as stated in Section 3) whereas scenario (4) which is based on $T^* = 1$ s occur much less frequently but need to be considered because of their richness in energy contents in the high period range. The median spectra as presented in Figures 1a - 1d for the four selected scenarios were first constructed based on the GMPE of CAM (Section 4). The CMS were then obtained by scaling up from their respective median spectra based on Equation 1 and factors of ρ (as listed in Table 1). The value of ε was chosen to achieve matching of the individual CMS with the code target spectrum at a reference period of either 0.2 sec or 1.0 sec. In the next section one of the CMS (as presented in Fig. 1d) was chosen for spectral scaling of an ensemble of accelerograms representing rock conditions.

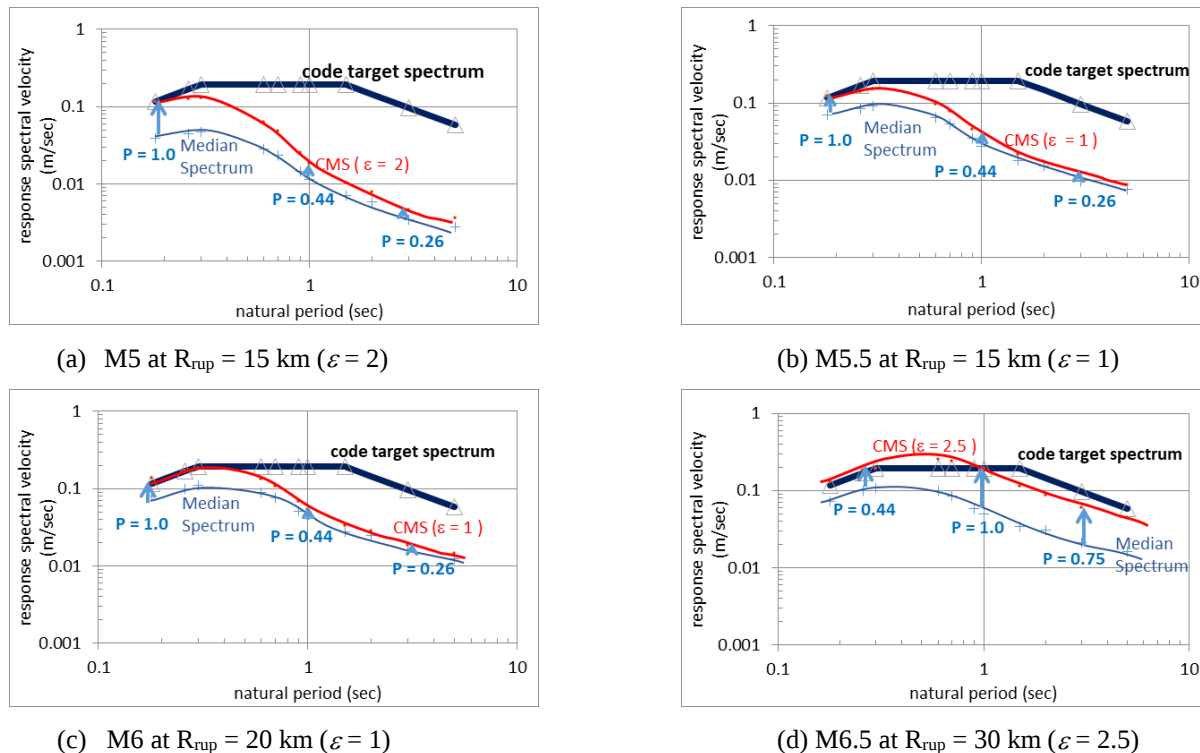


Figure 1: Code Compatible Conditional Mean Spectra (CMS)

6 ACCELEROGRAMS SELECTED AND SCALED TO MATCH WITH THE CMS

Eight pairs of rock accelerograms were selected from the PEER NGAWest2 database (<https://ngawest2.berkeley.edu/>) based on the following criteria: i) fault type: reverse/oblique; ii) magnitude: 5.5 to 7; iii) R_{rup} : 5 to 70 km; iv) $V_{S30} = 450$ to 1800 m/sec; and then scaled uniformly by amplitude to match the target spectrum (CMS based on M6.5, $R_{rup} = 30$ km as shown in Figure 1d). The scaling factors were chosen to minimise the mean squared error (MSE) of the squared-root-sum-of-the-square (SRSS) for each of the accelerogram pairs (refer Table 2 for a listing of the accelerograms alongside the scaling factors).

Response spectra of the individual accelerogram pairs overlaid on the target spectrum are presented in Figure 2, and the respective acceleration time histories are presented in Figure 3.

Table 2 Details of accelerograms selected to match the target median spectrum $M6.5 R_{rup} = 30$ km

Record No.	Earthquake	Year	Station	Magnitude	R_{rup} (km)	Scaling factor
72	"San Fernando"	1971	"Lake Hughes #4"	6.6	25	0.91
413	"Coalinga-05"	1983	"Skunk Hollow"	5.8	12	0.54
671	"Whittier Narrows-01"	1987	"Pacoima Kagel Canyon"	6.0	36	1.09
680	"Whittier Narrows-01"	1987	"Pasadena - CIT Kresge Lab"	6.0	18	1.27
954	"Northridge-01"	1994	"Big Tujunga_ Angeles Nat F"	6.7	20	0.78
1065	"Northridge-01"	1994	"Rolling Hills Est-Rancho Vista"	6.7	49	0.93
3033	"Chi-Chi_ Taiwan-05"	1999	"HWA049"	6.2	52	1.44
4227	"Niigata_ Japan"	2004	"NIGH10"	6.6	39	0.88

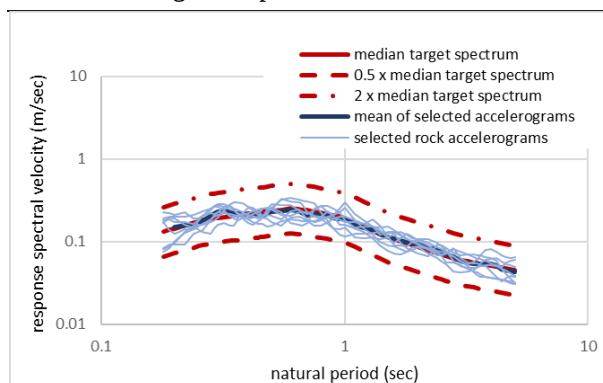
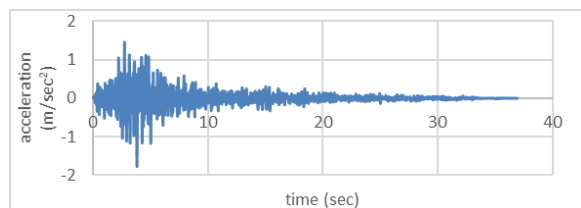
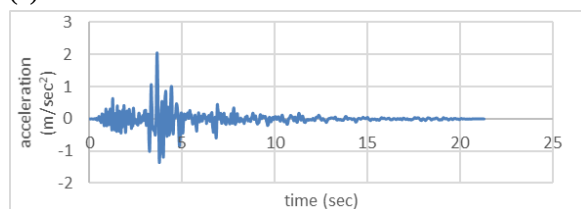


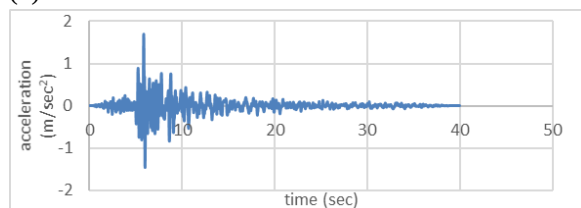
Figure 2: SRSS response spectra of the selected rock accelerograms ($M6.5 R = 30$ km)



(a) Record no. 72



(b) Record no. 413



(c) Record no. 671

Figure 3: Acceleration time histories of selected rock ground motions ($M6.5, R_{rup} = 30$ km)

7 CMS COMPATIBLE SITE-SPECIFIC RESPONSE SPECTRA AND ACCELEROGRAMS

The selected accelerogram pairs so derived were used as input into program SHAKE (Ordenez 2013) to simulate surface motions of an example class D site (as per definition by AS1170.4-2007). The purpose is to illustrate the use of the CMS methodology for simulating a site and event specific response spectrum using an example soil profile. The shear wave velocity profile (Figure 4) used for input into SHAKE was derived from information presented in a borehole log taken from a deep soil site that is located in Melbourne (Lam et al. 2005). The average SRSS response spectra of the accelerogram pairs as simulated on the soil surface is overlaid on that of the base excitations showing distinctive amplification at a site period of about 1 second (refer Figure 5). Some examples of the acceleration time histories representing motion behaviour on the soil surface are shown in Figure 6, and their respective response spectra in Figure 7. The outcome from the simulation procedure that has been outlined in this article is a site and event specific response spectrum (alongside an ensemble of compatible accelerograms) that is more representative of the projected earthquake scenario and site conditions than that derived from the current code stipulated methodologies.

8 CONCLUSIONS

The use of CMS methodology for generating site and event specific response spectrum for the low-to-moderate seismicity region of Australia is demonstrated herein based on a projected scenario of a M6.5 earthquake event occurring at a distance of 30 km. The example CMS based on a reference period of 1 sec was first constructed for scaling an ensemble of accelerograms that were sourced from the PEER database. The scaled accelerograms representing conditions on rock were then input into program SHAKE for deriving the response spectrum representing conditions of a 45 m deep soil site. The site and event specific response spectrum, and the accelerograms, so obtained is more representative of real conditions for the considered scenario than current code stipulated methodologies.

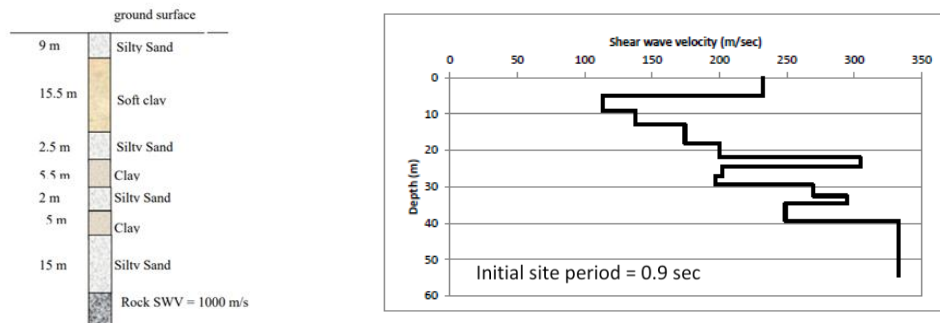


Figure 4: Class D site compatible shear wave velocity profile (Lam et al. 2005)

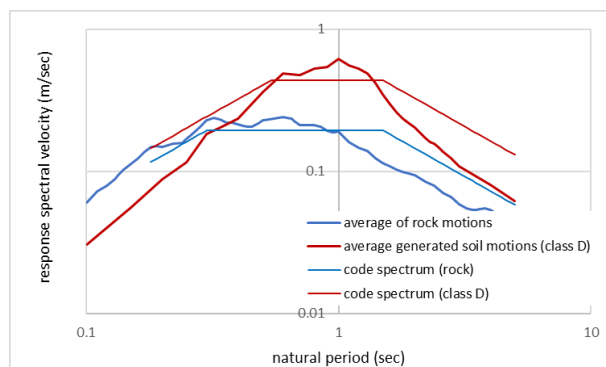
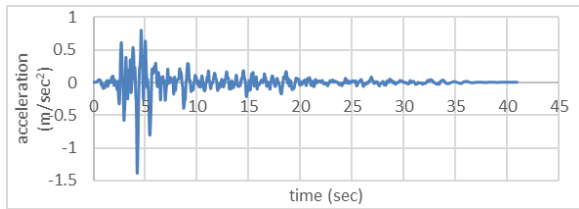
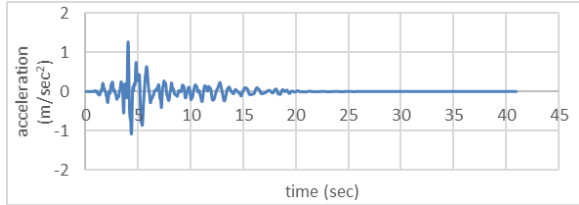


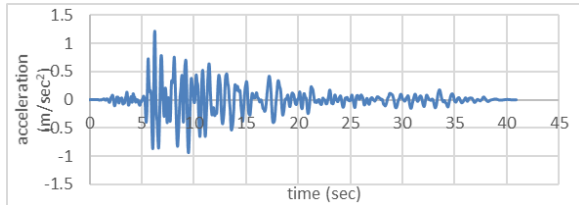
Figure 5: Average SRSS of the generated soil motions



(a) Record No. 72



(b) Record No. 413



(c) Record no. 671

Figure 6: Acceleration time histories of generated soil ground motions ($M_{6.5}$, $R_{rup} = 30$ km)

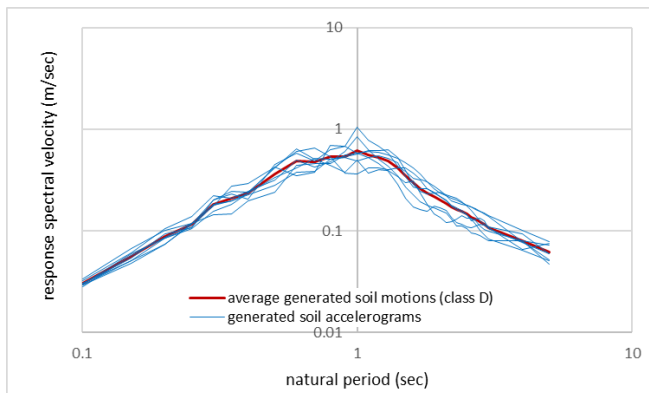


Figure 7: SRSS response spectra of the generated soil accelerograms

9 ACKNOWLEDGEMENTS

Assistances given by Dr Scott Menegon at Swinburne University of Technology and by PhD candidates Yiwei Hu and Yuxiang Tang at University of Melbourne in the preparation of the paper are gratefully acknowledged.

10 REFERENCES

- Baker, J.W. 2011. Conditional Mean Spectrum: Tool for Ground-Motion Selection, *Journal of Structural Engineering*, Vol 137(3) 322-331.
- Baker, J.W. 2015. Ground motion selection for performance-based engineering, and the Conditional Mean Spectrum as a selection tool, *Proceedings of the Tenth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Pacific*, Sydney, 6-8 November 2015.
- Boore, D.M. 2016. Determining generic velocity and density models for crustal amplification calculations, with an update of the Boore and Joyner (1997) generic site amplification for $V_s(Z) = 760$ m/s, *Bulletin of Seismological Society of America*, Vol 106(1) 316-320.
- EN 1998-1:2004. 2004. *Eurocode 8: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings*. United Kingdom: European Committee for Standardisation.

Paper 290 – Site and event specific response spectra and accelerograms in low to moderate seismicity ...

- Gaull, B.A., Michael-Leiba, M.O. & Rynn, J.M.W. 1990. Probabilistic earthquake risk maps of Australia, *Australian Journal of Earth Sciences*, Vol 37 169-187.
- Lam, N.T.K., Wilson, J.L., Chandler, A.M. & Hutchinson G. 2000. Response spectral relationship for rock sites derived from the component attenuation model, *Earthquake Engineering and Structural Dynamic*, Vol 29 1457-89.
- Lam, N.T.K., Wilson, J.L. & Hutchinson, G.L. 2000. Generation of synthetic earthquake accelerograms using seismological modelling: a review, *Journal of Earthquake Engineering*, Vol 4(3) 321-354.
- Lam, N.T.K., Sinadinovski, C., Koo, R.C.H. & Wilson, J.L. 2003. Peak Ground Velocity modelling for Australian intraplate earthquakes, *International Journal of Seismology and Earthquake Engineering. International Institute of Earthquake Engineering and Seismology*, Vol 5(2) 11-22.
- Lam, N.T.K & Chandler, A.M. 2005. Peak Displacement Demand in stable continental regions, *Journal of Earthquake Engineering and Structural Dynamics*, Vol 34 1047-1072.
- Lam, N.T.K., Wilson, J.L., & Venkatesan, S. 2005. Accelerograms for dynamic analysis under the New Australian Standard for Earthquake Actions, *Electronic Journal of Structural Engineering*, Vol 5: 10-35.
- Lam, N.T.K., Asten, M., Roberts, J., Venkatesan, S., Wilson, J.L., Chandler, A.M. & Tsang, H.H. 2006. Generic approach for modelling earthquake hazard. Invited paper, *Journal of Advances in Structural Engineering*, Vol 9(1) 67-82.
- Lam, N.T.K., Wilson, J.L. & Tsang, H.H. 2010. Modelling earthquake ground motions by stochastic methods, *Stochastic Control*, SCIYO Publisher, Chapter 23: 475 -492.
- Lumantarna, E., Wilson, J.L. & Lam, N.T.K. 2012. Bi-linear displacement response spectrum model for engineering applications in low and moderate seismicity regions, *Soil Dynamic and Earthquake Engineering*, Vol 43 85-96.
- Lam, N.T.K., Tsang, H.H., Lumantarna, E. & Wilson, J.L. 2016. Minimum loading requirements for areas of low seismicity, *Earthquakes and Structures*, Vol 11(4) 539-561. DOI 10.12989/eas.2016.11.4.539.
- Ordenez, G.A. 2013. *SHAKE2000 (Version 9.99.2 - July 2013)*. Retrieved from <http://www.geomotions.com>
- Pacific Earthquake Engineering Center. 2015. *NGA-East: median ground-motion models for the Central and Eastern North America Region*, PEER Report No. 2015/04, Pacific Earthquake Engineering Research Center. USA: University of California at Berkeley.
- Schnabel, P.B., Lysmer, J. & Seed, H.B. 1972. *SHAKE: a computer program for earthquake response analysis of horizontally layered sites*. Earthquake Engineering Research Center Report: EERC 72-12. USA: University of California at Berkeley.
- Somerville, P.G. & Thio, H.K. 2011. Development of Ground Motion Time Histories for Seismic Design, *Proceedings of the Ninth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society, Auckland, 14-16 April 2011*.
- Standards Australia. 2007. *AS 1170.4-2007: Structural design actions, Part 4: Earthquake actions in Australia*. Sydney, NSW: SAI Global.
- Tang, Y., Lam, N.T.K. & Tsang, H.H. 2018. A review of GMPEs that have been proposed for use in Southeastern Australia by Comparison with MMI data, *Proceedings of the Annual Technical Conference of the Australian Earthquake Engineering Society, Perth, 16-18 November 2018*.
- Wilson, J. & Lam, N. (ed.). 2007. *AS 1170.4-2007 Commentary. Supplement to the Australian Standard AS 1170.4 Structural Design Actions – Part 4: Earthquake Actions in Australia*, Australian Earthquake Engineering Society, Australia.