Program on Generation of Site-Specific Response Spectra in Australia

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Abstract

Designing a seismic sensitive structure to specific earthquake scenarios and site-specific conditions which control modifications of the earthquake ground shaking can be translated into significant cost savings. Site-specific response spectra can have immense economical merits but are hardly adopted by structural designers because of a lack of guidance in regulatory documents nor textbooks. To fill in this knowledge gap, the authors have developed a (free for public access) online platform called "quakeadvice.org" which hosts a suite of computer programs for facilitating the development of site-specific response spectra. This paper aims at introducing this newly established online facility for (1) selecting and scaling bedrock motion accelerograms to event-specific conditional mean spectra, (2) developing soil column models to represent the subsoil conditions of the site, and (3) undertaking equivalent linear amplification analysis of the soil column models for the construction of site-specific response spectra. A case study is presented along with the program user interface to promote the adoption of the facility.

Keywords: site-specific response spectra; seismic design in Australia; Quake Advice; soil amplification; time-history and dynamic analyses

1 Introduction

Australian continent, located within the Indo-Australian plate, is considered an intra-plate region with low to moderate seismicity. The earthquake occurrence rate in Australia is considerably lower than that in high seismicity regions such as north-western America. However rare large ground motion events that are close to populated centres, such as the 1989 Newcastle earthquake could cause devastating casualties and significant financial loss. Poorly designed buildings have been considered as one of the crucial causes for the damage which raises concerns about the current seismic design approach. Meanwhile, the role of soil sediment amplification in the 1989 Newcastle Earthquake brought questions regarding the general principle that site with deep soft soil tends to cause higher amplification and thus larger damage (Melchers, 1990). McPherson & Hall (2013) suggested that ground movements on shallow and soft soil sites were greatly amplified in the short period range, resulting in significant damage towards low-rise masonry buildings. Therefore, the determination of seismic loading needs to incorporate not only the ground motion intensity level but also specific site conditions and characteristics of the structure to be designed.

The traditional approach of seismic design in Australia commonly employs code spectrum models. In the Australian standard for earthquake actions AS1170.4 (2007), generalised response spectra are provided for five soil classes, which are categorised predominately by the average shear wave velocity and site natural period. The generalised response spectra serve the need of determining structural response without detailed site investigations or regional hazard analyses. However, there are significant limitations in adopting code response spectra because it is derived from earthquake scenarios that may not apply to the specific site, and it poorly represents the site amplification phenomenon. The spectra in AS 1170.4 is based on large earthquake intensity events from regions of high seismicity; in low-to-moderate regions, it is possible to have high amplification than what the code specifies the amplified spectra to be (Hoult et al., 2017). Moreover, shear wave velocity, soil column depth to bedrock, and ground motion intensities all contribute to site amplification (Dhakal et al., 2013). Substantial amplification is expected when the earthquake excitation, the soil column and the structure resonate. However, the averaging process in calculating the code amplification factors smear the resonance effects. As the result, the average amplification factors presented in the design code do not reflect actual soil behaviour. This problem is especially alarming in lower seismicity regions because the limited/non-ductile structures are not capable of damping the extra kinetic energy from resonance (Tsang et al., 2012).

Compared to the code response spectra, site-specific response spectra are developed based on regional seismic hazard and local site conditions and can capture realistic soil response. Despite this advantage, few engineers develop site-specific response spectra because of the workload involved and the need to provide additional information related to the site. To lighten the associated workload, this study provides a clear procedure for the generation of site response spectra with up to date information and modelling techniques. This paper is a companion to the online software that facilitates the development of site-specific response spectra, which has been made available for free public access in “quakeadvice.org”. The generation of a site-specific response spectrum involves the following procedures: (1) modelling of shear wave velocity and dynamic properties of the soil layers and bedrock to develop a soil column model; (2) selection and scaling of accelerograms for defining input motion at the bedrock level; (3) execution of dynamic analysis of the soil column model. These procedures are explained further in Section 3-6 by the use of a case study.

2 Overview of the Program and Development of a Site-Specific Response Spectrum

The online program referred to here as the ‘Quake Advice program’ is developed by the authors to automate the generation of site-specific response spectra. The procedure uses information of the soil column: depth of soil layer, SPT-N count, soil type, soil description, water content, soil age and bedrock properties: density and shear wave velocity and provide soil surface motion as an output result. A brief introduction to each of the input and output parameters and the details of the modelling and analysis techniques are illustrated in Sections 3 to 5.

3 Processing Borehole Information and Modelling Soil Properties

The program provides a neat and handy user interface (an example of which is shown in Figure 1) for entering the input parameters into the program. Before entering the borelog information, the shear wave velocity and soil material model are selected. The user has the option of selecting one shear wave velocity (SWV) model out of four empirical models: Imai and Tonouchi all soil model (Imai and Tonouchi, 1982), Ohta and Goto Model (Ohta and Goto, 1978), Imai and Tonouchi model (Imai and Tonouchi, 1982), and PEER model (Wair, DeJong and Shantz, 2012 and one material model out of three models: Hardin & Drnevich model

(1972), Vucetic & Dobry model (1991), and Darendeli model (2001). The compulsory input parameters are the depth of soil layers and SPT-N values. However, if the Ohta and Goto Model is selected then information on soil type also need to be provided. Moreover, if the PEER model and Darendeli model are selected, additional information such as water level and vertical stress from the structure is required. However, all the input parameters except depth and SPT-N values are optional and a user may automatically define these optional parameters by the press of a 'default value' button when desired. The detail about each of these methods, the expression used for calculating the SWV, dynamic material curves of damping and stiffness degradation, and bedrock density and shear wave velocity, and the default parameters are provided in Hu et al. (2021).

4 Development of the Conditional Mean Spectrum (CMS) and Selection of Bedrock Accelerograms

Bedrock ground motion accelerogram is an essential input into soil amplification analysis and it controls the intensity and frequency content of the surface ground motion. This section described an approach to select an ensemble of bedrock ground motions that are representative of Australian crustal conditions and earthquake recurrence rate. The conditional mean spectrum approach (CMS) is employed to calculate event-specific bedrock response spectrum for use in ground motion selection as the target spectrum (Baker, 2011; Baker and Cornell, 2006; Jayaram, Lin, and Baker, 2011). The conditional mean spectrum approach (CMS) considers hazard computation at one or a series of reference periods (T^*) which is generally defined by the fundamental period of the structure or the natural period of the site. In this program, CMS at four distinctive reference periods (i.e. 0.2, 0.5, 1 and 2 seconds) are generated to cover the periods of interest for low to mid-rise building structures. The controlling earthquake scenario (magnitude-distance combination) is identified through hazard disaggregation analysis based on the code response spectral value at the reference period. The next step involves computations of the medium and standard deviation of response spectral acceleration throughout the period range of engineering interest by adopting ground motion prediction expressions. In this program, the ground motion is determined as the average value of the widely recognised five ground motion prediction models: SGC09 (Somerville et al., 2009), ASK14 (Abrahamson et al., 2014), CY14 (Chiou and Youngs, 2014), A12 (Allen, 2012), and CAM (Tang, 2019). The event-specific response spectrum is then developed by rising the medium response spectral value at the reference period to the same value as the code response spectrum and applying correlation values to the spectrum at periods other than the reference period. For each of the conditional mean spectrum, ground motion records are selected and scaled to match with the spectral values in the period range between $0.2T^*$ to $2T^*$. The earthquake records are retrieved from the international Pacific Earthquake Engineering Research (PEER) NGA-West 2 strong motion database based on the criteria: reverse/oblique fault, magnitude range (half-bin width) of $\pm 0.3\,M_w$, Joyner-Boore distance range (half-bin width) of $\pm 30\ km$ centred at the distance of the controlling scenarios, and $V_{S,30}$ of 400-1800 m/s.

If either site natural period or the fundamental period of vibration of the building is within ±20% of one of the four reference periods, then six ground motion records from that reference period(s) are adopted. Likewise, at least four ground motions from each of the adjacent reference periods are selected. Moreover, two ground motions are selected from the reference periods that are far away from the site natural period or the fundamental period of the building to examine period elongation and higher mode effect. Therefore, the final bedrock ground motion ensemble consists of 12 – 16 earthquake records which in principle are from different earthquake events to achieve diversity. Artificial ground motion accelerograms are also generated to make up the ensemble where necessary (refer to Hu et al. (2021) for the procedure). The time step for each ground motion record is normalised to a pre-defined time step parameter (default is 0.005 seconds) for easier application in time history analyses. To facilitate bi-directional time history dynamic analyses, the bedrock motions are selected in orthogonal pairs, with the motions in the primary direction (i.e. stronger direction) matching with the conditional mean spectrum.

5 Generation of Soil Surface Accelerograms

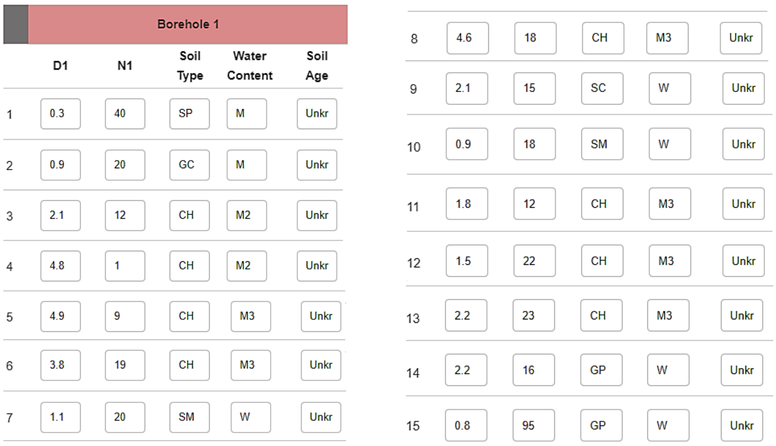
Equivalent linear analysis has been adopted for simulating the seismic response behaviour of a soil column model. Vertically propagating seismic waves are modelled as a combination of harmonic waves possessing different frequencies. The soil amplification results are identical to results from popular commercial software: SHAKE2000 (Schnabel, 1992), EERA (Ordonez, 2000), and Strata (Kottke & Rathje, 2009). The result is consistent with the more sophisticated nonlinear soil dynamic analyses for a maximum strain of 1% for clayey soils and 0.5% for sandy soils. The users are alerted when the maximum strain exceeds these limits.

6 Case study

The practical application of the procedure is illustrated by the use of a case study featuring a 'class- D' soil site in Melbourne with a 2500-year return period event (kpZ of 0.144'g). The structure to be designed is a 5-storey reinforced concrete building with a natural period of 0.5 seconds. A genuine borehole record is retrieved from geotechnical investigations in Northern Melbourne. The detail of input parameters defined in the program is presented in Table 1 and Figure 1. The description of the acronym used in Figure 1 is shown in Table A1. The program allows the use of copy-paste of the input information from an Excel spreadsheet.

Table 1. Soil and bedrock input parameters for the case study.

Input Parameters	Value
I. Shear Wave Velocity Conversion Model	PEER Model
II. Soil Dynamic Property Model	Darendeli Model
III. Initial Vertical Stress from Structure	Default (50 kPa)
IV. Energy Ratio	Default (1)
V. Water Level	3.3 (m)
VI. Bedrock Shear Wave Velocity	Melbourne-siltstone (1700 m/s)
VII. Bedrock Density	Melbourne-siltstone (2300 kg/m3)



Borehole 1

	D1	N1	Soil Type	Water Content	Soil Age
1	0.3	40	SP	M	Unkr
2	0.9	20	GC	M	Unkr
3	2.1	12	CH	M2	Unkr
4	4.8	1	CH	M2	Unkr
5	4.9	9	CH	M3	Unkr
6	3.8	19	CH	M3	Unkr
7	1.1	20	SM	W	Unkr
8	4.6	18	CH	M3	Unkr
9	2.1	15	SC	W	Unkr
10	0.9	18	SM	W	Unkr
11	1.8	12	CH	M3	Unkr
12	1.5	22	CH	M3	Unkr
13	2.2	23	CH	M3	Unkr
14	2.2	16	GP	W	Unkr
15	0.8	95	GP	W	Unkr

Figure 1. Program interface for defining soil layer characteristics (D1 and N1 columns refer to layer thickness in meter and SPT blow counts).

On running the program, the following information is generated as the output: shear wave velocity profile with plot shown in Figure 2, the site period which is 0.68 sec, the conditional mean spectra and the ground motion ensembles as shown in Figure 2, selected ground motions (Table 2), and site-specific response spectra and soil surface ground motion ensemble for the primary and orthogonal direction (Figure 4). Practicing engineers and researchers can use this information to find out the dynamic characteristic of the soil and the site, use the output accelerograms for the full time-history analysis of the structure, and use the response spectrum for the seismic design and for the comparison with the code spectrum. The program can be valuable for stakeholders such as Standards Australia for future decision making regarding seismic analysis and design.

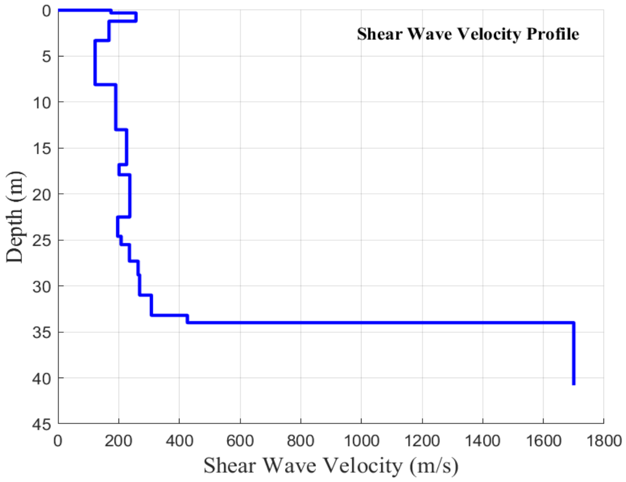
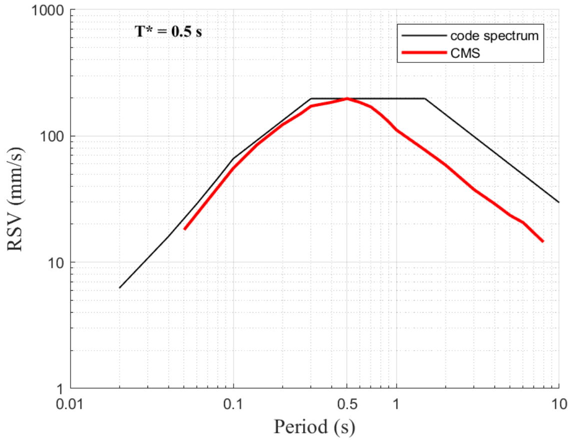
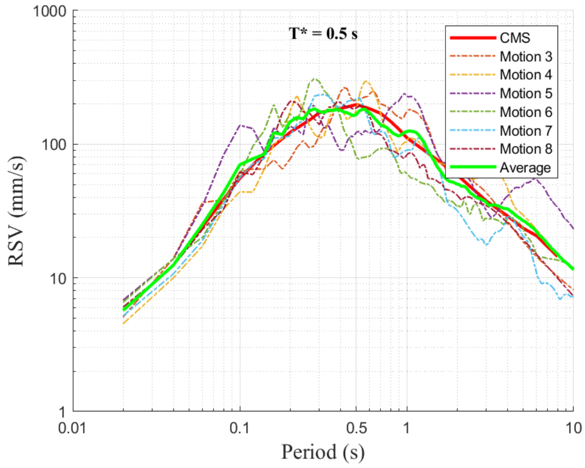


Figure 2. Program output of the shear wave velocity profile.



(a) Comparison of the CMS (0.5 s) and code velocity response spectrum (Site B_e).



(b) Bedrock ground motion ensemble in velocity response spectrum for 0.5 s reference period.

Figure 3. Program output of the CMS (a) and bedrock ground motion ensemble (b).

Table 2. Program output of the selected ground motion information.

Ref. Number	Earthquake Name	Reference Period (s)	Year	Station Name	Magnitude	Rjb (km)	Scaling Factor*
1	Whittier Narrows-02	0.2	1987	Mt Wilson - CIT Seis Sta	5.27	16.45	1.20
2	Chi-Chi_ Taiwan-02	0.2	1999	KAU050	5.9	80.57	1.46
3	N. Palm Springs	0.5	1986	Cranston Forest Station	6.06	27.21	0.89
4	Whittier Narrows-01	0.5	1987	Brea Dam (L Abut)	5.99	19.12	0.92
5	Chi-Chi_ Taiwan-05	0.5	1999	CHY024	6.2	42.45	0.77
6	Chi-Chi_ Taiwan-05	0.5	1999	TCU138	6.2	41.46	0.95
7	Whittier Narrows-01	0.5	1987	Beverly Hills - 12520 Mulhol	5.99	25.91	1.23
8	N. Palm Springs	0.5	1986	San Jacinto - Soboba	6.06	22.96	0.75
9	Coalinga-01	1	1983	Parkfield - Stone Corral 3E	6.36	32.81	1.14
10	Northridge-01	1	1994	San Gabriel - E Grand Ave	6.69	38.86	0.81
11	San Fernando	1	1971	Lake Hughes #12	6.61	13.99	0.84
12	Coalinga-01	1	1983	Parkfield - Cholame 4W	6.36	45.49	0.86
13	Iwate_ Japan	2	2008	Maekawa Miyagi Kawasaki	6.9	74.82	0.88
14	Chuetsu-oki_ Japan	2	2007	Horinouchi Uonuma City	6.8	29.9	0.82

*The acceptable scaling factor of 0.5 to 1.5 (Naeim et al., 2004) is considered in the program.

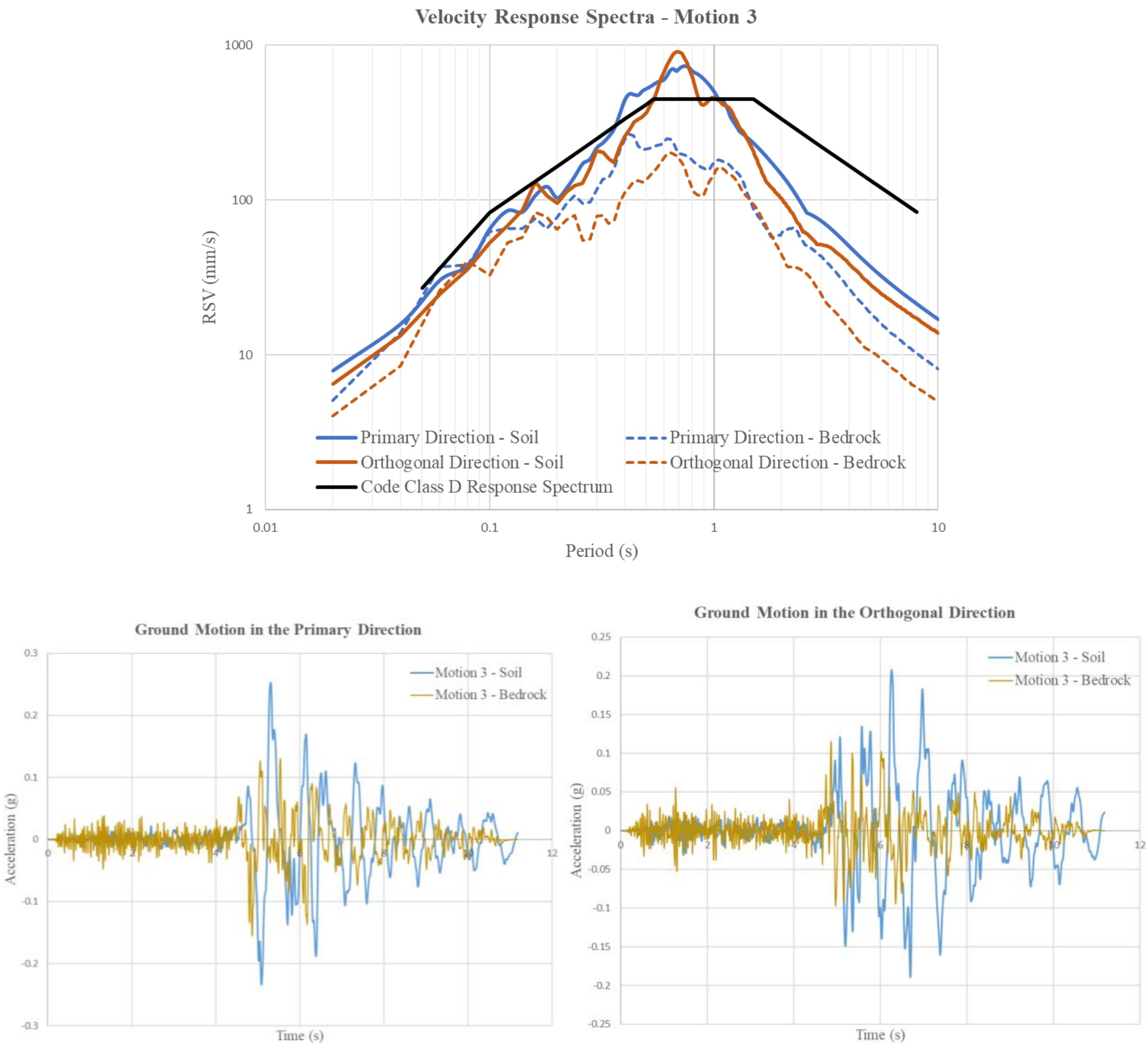


Figure 4 Program output of the soil surface ground motion ensemble in velocity and acceleration.

7 Conclusion

This paper is a companion to the online ‘Quake Advice program’ which facilitates fast development of site-specific response spectra and surface ground motion accelerograms for seismic design or assessment of buildings in Australia. Detailed procedures used in the program have been discussed in this paper to clarify modelling techniques, necessary assumptions, and default parameters. The ultimate output from the ‘Quake Advice program: https://quakeadvice.org)’ includes an ensemble of 12 to 16 pairs of orthogonal surface ground motions and the corresponding site-specific response spectra. The site-specific response spectra are potentially cost-saving compared to the code spectrum in certain period ranges and better represent soil behaviour under seismic loading.

8 Appendix

Table A1. Description of the acronym used in the program.

Acronym	Soil Type	Acronym	Soil Type	Acronym	Soil Description	Acronym	Soil Description
ML	Low plasticity silt	*GW*	Well-grade gravel	VS	Very Soft	VL	Very Loose
MH	High plasticity silt	*GP*	Poorly-grade gravel	S	Soft	L	Loose
CL	Low plasticity clay	*GM*	Silty gravel	F	Firm	MD	Medium Dense
CI	Medium plasticity clay	*GC*	Clayey gravel	St	Stiff	D	Dense
CH	High plasticity clay	*SW*	Well-grade sand	VSt	Very Stiff	VD	Very Dense
		SP	Poorly-grade sand	H	Hard		
		SM	Silty sand				
		SC	Clayey sand				
Acronym	Water Content	Acronym	Water Content				
M1 (W<PL)	Moist, dry of plastic limit	*D*	Dry				
M2 (W≈ PL)	Moist, near plastic limit	*M*	Moist				
M3 (W>PL)	Moist, wet of plastic limit	*W*	Wet				
W1 (W≈LL)	Wet, near liquid limit						
W2 (W>LL)	Wet, wet of liquid limit						

9 References

Abrahamson, N. A., Silva, W. J., & Kamai, R. (2014). Summary of the ASK14 ground motion relation for active crustal regions. Earthquake Spectra, 30(3), 1025-1055.

Allen, T. I. (2012). Stochastic ground-motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters. Geoscience Australia Record, 69, 55.

Baker, J. W., & Allin Cornell, C. (2006). Spectral shape, epsilon and record selection. Earthquake Engineering & Structural Dynamics, 35(9), 1077-1095.

Baker, J. W. (2011). Conditional mean spectrum: Tool for ground-motion selection. Journal of Structural Engineering, 137(3), 322-331.

Chiou, B. S. J., & Youngs, R. R. (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. Earthquake Spectra, 30(3), 1117-1153.

Darendeli, M. B. (2001). Development of a new family of normalized modulus reduction and material damping curves. The university of Texas at Austin.

Dhakal, R. P., Lin, S. L., Loye, A. K., & Evans, S. J. (2013). Seismic design spectra for different soil classes. Bulletin of the New Zealand Society for Earthquake Engineering, 46(2), 79-87.

Hardin, B. O., & Drnevich, V. P. (1972). Shear modulus and damping in soils: measurement and parameter effects (terzaghi leture). Journal of the soil mechanics and foundations division, 98(6), 603-624.

Hu, Y., Lam, N., Khatiwada, P., Menegon, S. J., & Looi, D. T. W. (2021). Site-Specific Response Spectra: Guidelines for Engineering Practice. CivilEng 2021, 2, 712–735.

Imai, T., & Tonoughi, K. (2021, February). Correlation of N value with S-wave velocity and shear modulus. In Penetration Testing (pp. 67-72). Routledge.

Jayaram, N., Lin, T., & Baker, J. W. (2011). A computationally efficient ground-motion selection algorithm for matching a target response spectrum mean and variance. Earthquake Spectra, 27(3), 797-815.

Kottke, A. R., & Rathje, E. M. (2009). Technical manual for Strata. Berkeley, California: Pacific Earthquake Engineering Research Center.

Melchers, R. E. (1990). Newcastle earthquake study. Newcastle Earthquake Study, xx.

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.

Naeim, F., Alimoradi, A., & Pezeshk, S. (2004). Selection and scaling of ground motion time histories for structural design using genetic algorithms. Earthquake spectra, 20(2), 413-426.

Ohta, Y., & Goto, N. (1978). Empirical shear wave velocity equations in terms of characteristic soil indexes. Earthquake engineering & structural dynamics, 6(2), 167-187.

Ordonez, G. (2002). A computer program for the 1D analysis of geotechnical earthquake engineering problems. In Berkeley: Univ. Calif.

Schnabel, P. B. (1972). SHAKE: A computer program for earthquake response analysis of horizontally layered sites. EERC Report 72-12, University of California, Berkeley.

Somerville, P., Graves, R., Collins, N., Song, S. G., Ni, S., & Cummins, P. (2009). Source and ground motion models for Australian earthquakes. In Proc. 2009 Annual Conference of the Australian Earthquake Engineering Society (pp. 11-13).

Standards Australia (2007). AS 1170. 4-2007 Structural Design Actions. In Part 4: Earthquake Actions in Australia.

Standards Australia (2017). AS 1726-2017 Geotechnical Site Investigations.

Tang, Y., Lam, N., Tsang, H. H., & Lumantarna, E. (2019). Use of macroseismic intensity data to validate a regionally adjustable ground motion prediction model. Geosciences, 9(10), 422.

Tsang, H. H., Sheikh, M. N., & Lam, N. T. (2012). Modeling shear rigidity of stratified bedrock in site response analysis. Soil Dynamics and Earthquake Engineering, 34(1), 89-98.

Vucetic, M., & Dobry, R. (1991). Effect of soil plasticity on cyclic response. Journal of geotechnical engineering, 117(1), 89-107.

Wair, B. R., DeJong, J. T., & Shantz, T. (2012). Guidelines for estimation of shear wave velocity profiles. Pacific Earthquake Engineering Research Center.