

Accelerograms for Dynamic Analysis under the New Australian Standard for Earthquake Actions

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Abstract

The new Australian Standard for Earthquake Actions requires buildings exceeding 50 m in height and located in areas with hazard factor of $Z \geq 0.08$ (which applies to most capital cities including Canberra, Sydney, Melbourne, Adelaide and Perth) to be designed for earthquake actions based on dynamic analyses. This paper presents a methodology for generating and using artificial accelerograms for obtaining site-specific design response spectra, which could be used for dynamic analyses. This time-history analysis approach of determining earthquake actions can result in more efficient designs in comparison with using response spectra specified by the Standard. An ensemble of accelerograms simulated for both rock and soil conditions are available in an electronic file named: “*accelerograms for public access.xls*” which can be downloaded free from the journal website for shared usage by all. The accelerogram file also contains listing of the baseline corrected displacement time-histories which are required for input into shaking table experiments and certain seismic simulation programs.

Keywords : Artificial Accelerograms, Time-history, Earthquake, Seismic loading, Australia

1. Introduction

This paper presents an ensemble of artificial accelerograms developed using stochastic simulations that are both appropriate for both the “hard rock” and “rock” conditions in Australia. The generated accelerograms have been used as input to SHAKE analyses (Idriss & Sun, 1992) for simulating ground motions on a soft soil site. Sample accelerograms simulated for both rock and soft soil conditions are available in electronic form for access through the journal website.

The draft new Australian Standard for Earthquake Actions (AS/NZS 1170.4 Doc. D5212-5.1: June 2005) requires normal building structures exceeding 50m in height and located in areas with hazard factor, Z , of 0.08 to be designed in accordance with Earthquake Design Category III (EDC III) in which earthquake actions are to be determined by dynamic analyses. This applies generally to buildings exceeding 15-16 storeys in capital cities around Australia including Canberra, Sydney and Melbourne. For cities with slightly higher seismicity such as Adelaide and Newcastle, EDC III requirements are extended to buildings exceeding 25m in height (7-8 storeys) and founded on Class D and E sites.

Dynamic analyses may take the form of response spectral analyses (RSA) or time-history analyses (THA). THA is considered to provide a more realistic representation of the actual response of the structure than RSA, particularly when the response is characterized by non-linear (inelastic) behaviour or significant torsional coupling behaviour. When time-history analyses are performed in engineering design, several representative ground motions should be used in order that the sensitivity of the response of the structure to random variations in the excitations can be tracked. The requirement for multiple analyses means that large number of accelerograms representing a range of conditions have to be sought.

Accelerograms that were recorded locally in Australia were typically taken from small magnitude events, aftershocks, or from long epicentral distances. Near-field motions of engineering significance are very difficult to capture due to the infrequent, and seemingly random, characteristics of intraplate earthquakes. What is currently available is insufficient to meet seismic design requirements. Strong motion accelerograms that were recorded from outside the Australian continent may mis-represent local conditions even though the records could be taken from regions with similar levels of seismicity (eg. Central and Eastern North America).

In countries with a paucity of strong motion data, like Australia, the use of accelerograms generated artificially by computer based on stochastic simulations has become a viable alternative for THA. The purpose of this paper is to present accelerograms that have been generated for engineering applications using program GENQKE that was developed at the University of Melbourne (Lam et al, 2000a; Lam, 1999). In view of the wide engineering readership of the paper, emphasis is on examining the peak ground velocity and response spectral properties of the accelerograms which are of direct engineering interest. Detailed coverage of the seismological aspects of the subject are beyond the scope of this paper but specific details on seismological modelling for Australian conditions are given in Lam et al (2003). The simulation methodology used has been well established and review articles on this subject can be found in the literature (eg. Lam et al 2000a).

It is shown that separate modelling is required for (i) “hard rock” conditions of Western and Central Australia and (ii) “rock” conditions of Eastern Australia. Accelerograms simulated for rock outcrop conditions in both these regions are presented in Section 2. Response spectra of the generated accelerograms have also been calculated. Results were averaged and presented systematically for a range of magnitude and distances. Samples are shown in Section 3. The peak

ground velocity behaviour inferred from the calculated response spectra were then compared against the well known Gaull's model which was developed from analyses of Intensity data of local historical events recorded in Australia. The verification analyses also compared data collected from the 1989 Newcastle earthquake against computer simulations. Results of the comparative analyses provide support to the claim that the generated accelerograms are generally consistent with local conditions (refer Section 4). Further verification analyses addressing the long-period behaviour of the accelerograms are presented in Section 5. Finally, accelerograms simulated for a Class D (deep or soft soil) site have been obtained using the program SHAKE and artificial accelerograms generated for rock conditions as input bedrock motion (refer Section 6). Response spectra for both rock and soft soil conditions are presented for comparison with the design response spectra stipulated by the new Australian Standard for earthquake actions.

2. Artificial Accelerograms

Sample acceleration time-histories on "rock" conditions characteristics of Eastern Australia are presented in Figures 1 & 2 to show the increase in the duration of the accelerogram with earthquake magnitude and distance in accordance with the relationship defined in Lam et al (2000a). These accelerograms can be modified to represent the filtering effects of soil sediments using well-established standard procedures in which bedrock accelerograms are used as the input motion. Ground shaking could be significantly prolonged on soft soil sites increasing the risk of damage to structures.

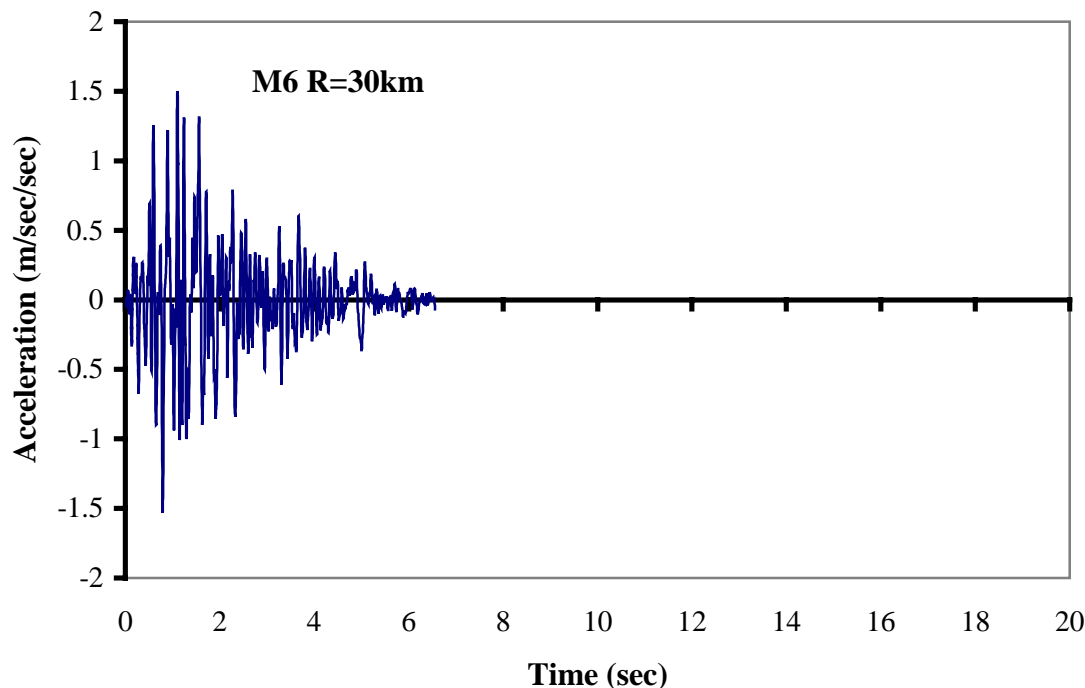


Figure 1 Time-histories of simulated accelerograms for earthquake scenario of M6 R=30km on "rock" characteristics of Eastern Australian conditions

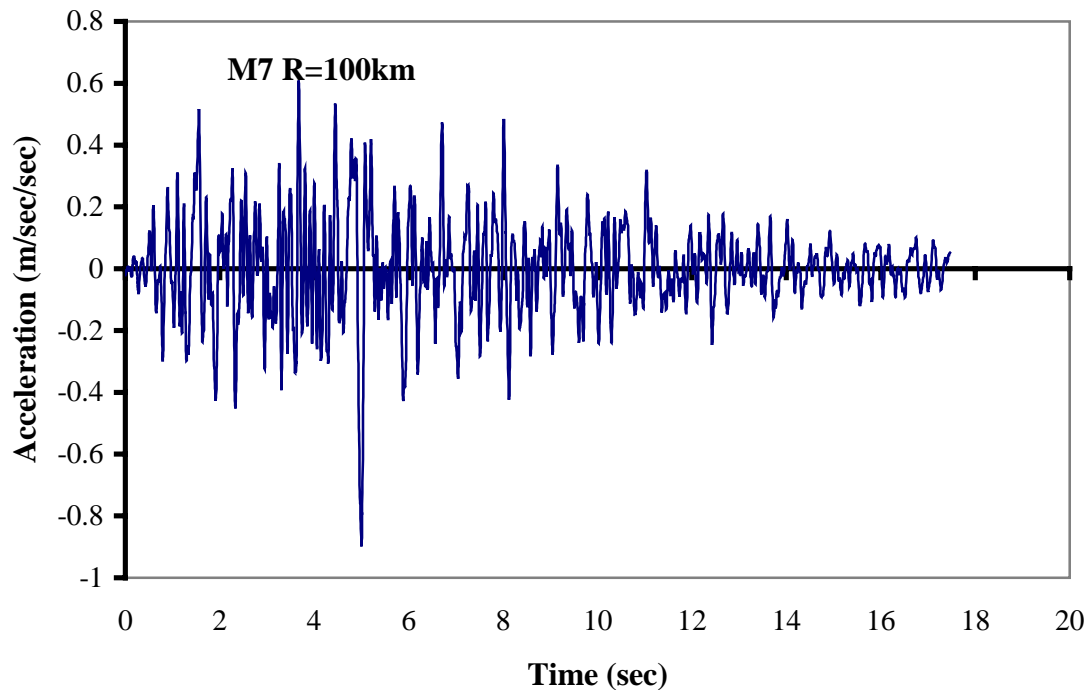


Figure 2 Time-histories of simulated accelerograms for earthquake scenario of M7 R=100km on “rock” characteristics of Eastern Australian conditions

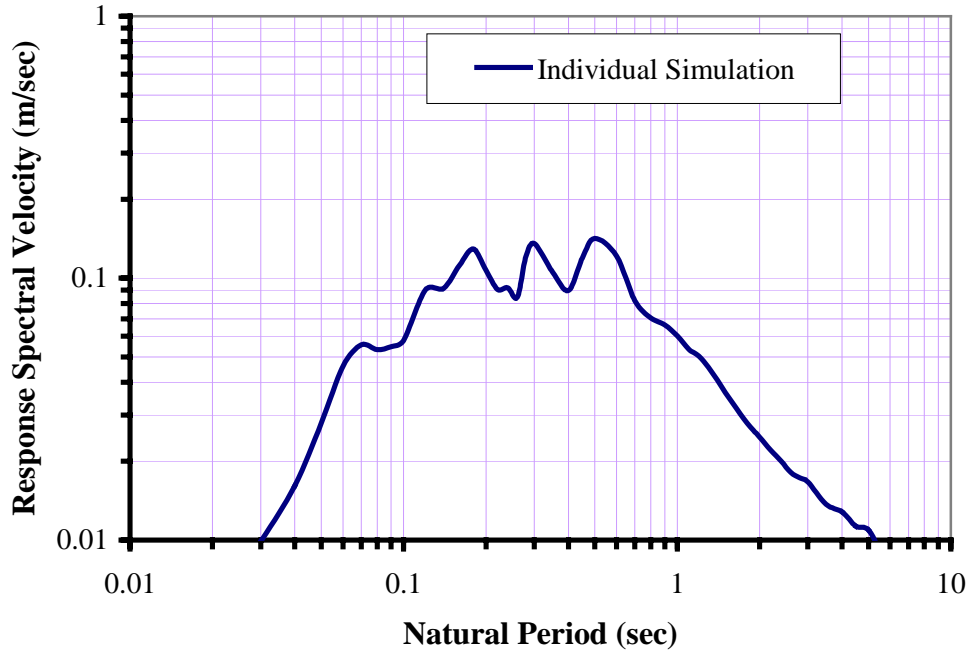
3. Response Spectra

3.1 Sensitivity study on sample size

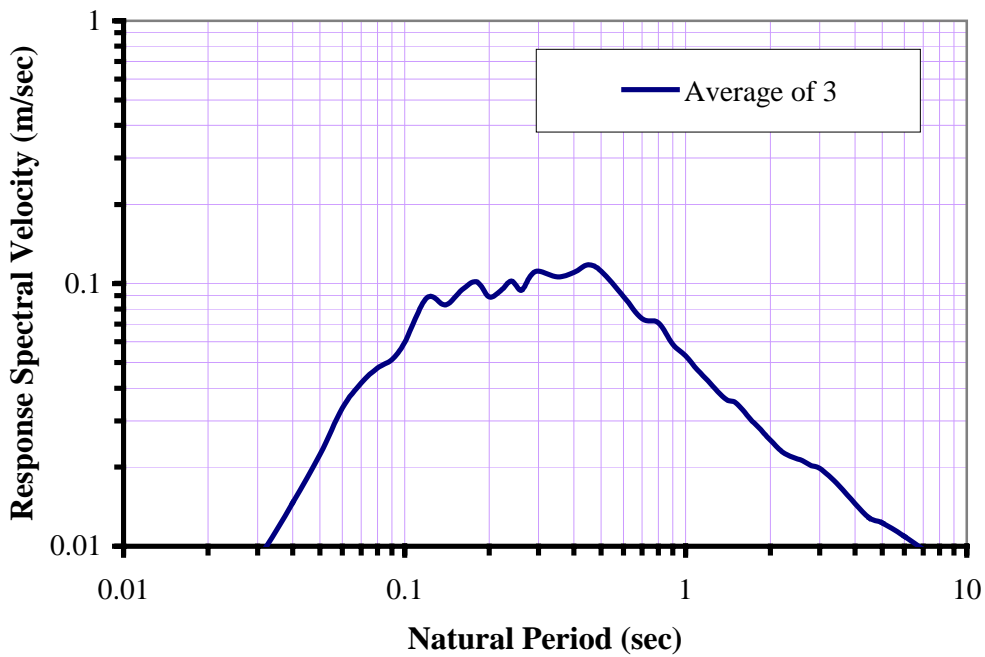
Initially, the response spectrum of an individual simulated accelerogram was calculated. This response spectrum based on a single accelerogram was then compared with the average of 3, 6 and 18 accelerograms. Results of this comparative study are shown in Figures 3a – 3d for a Magnitude M=6, R=30 km earthquake. The irregular appearance of the response spectrum based on a single simulation is clearly noticeable, indicating a significant bias at certain periods. It is the opinion of the authors that a minimum of 4-6 randomly generated accelerograms has to be included in the analyses to effectively suppress the biases (as evidenced by the smoothness of the averaged response spectra associated with larger sample sizes).

3.2 Response spectra of accelerograms simulated for Eastern Australia

Eighteen random simulations have been produced for each earthquake scenario defined by a magnitude-distance (M-R) combination for the “rock” conditions of Eastern Australia. A response spectrum was then calculated for each simulation and results were averaged. A selection of the averaged response spectra are presented in Figures 4a -4c.

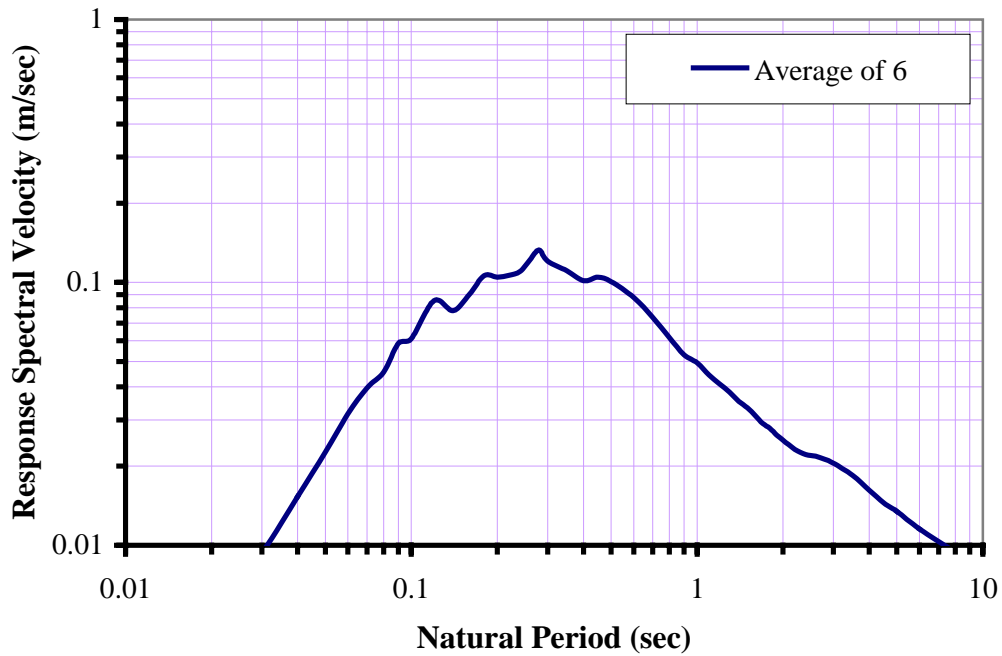


(a) Individual simulation

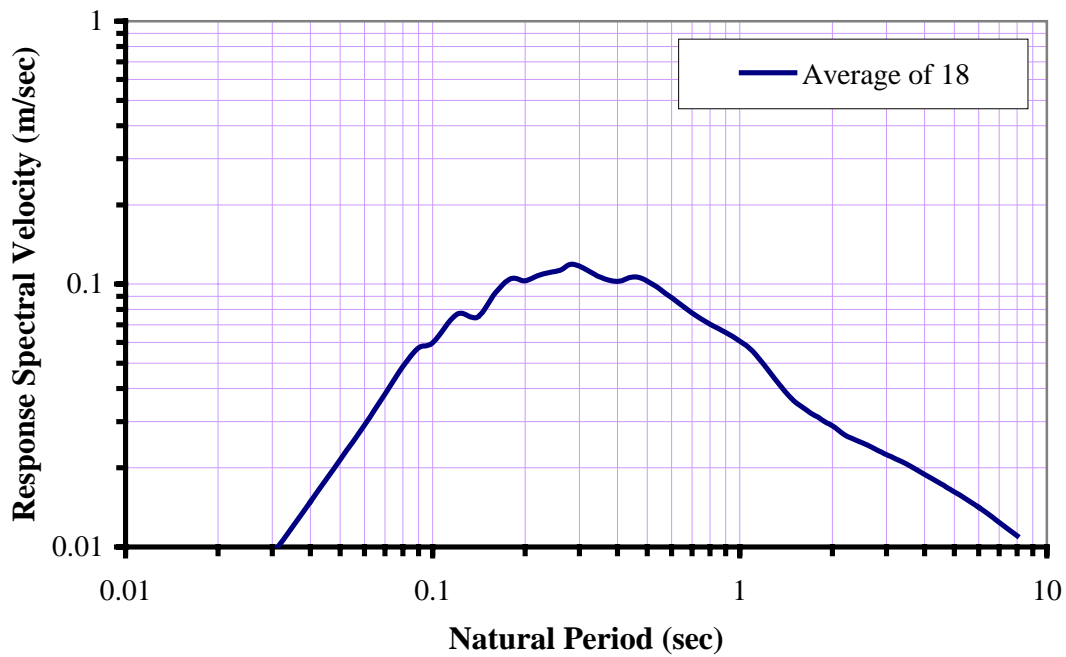


(b) Average of 3 simulations

Figure 3. Sample size comparison of averaged response spectra



(c) Average of 6 simulations

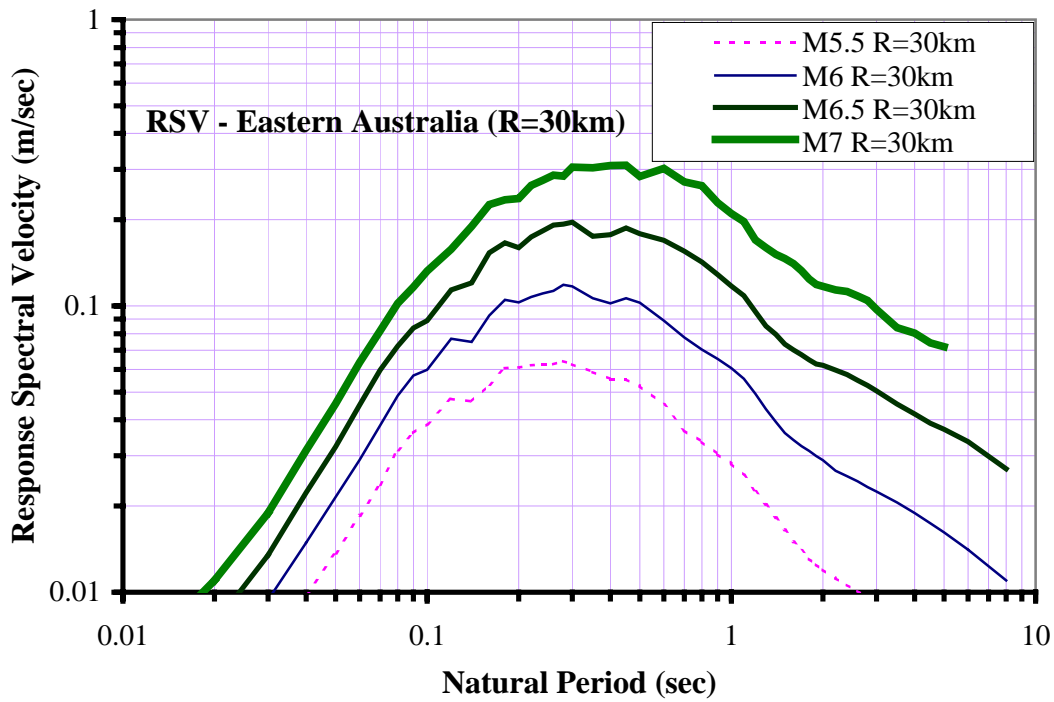


(d) Average of 18 simulations

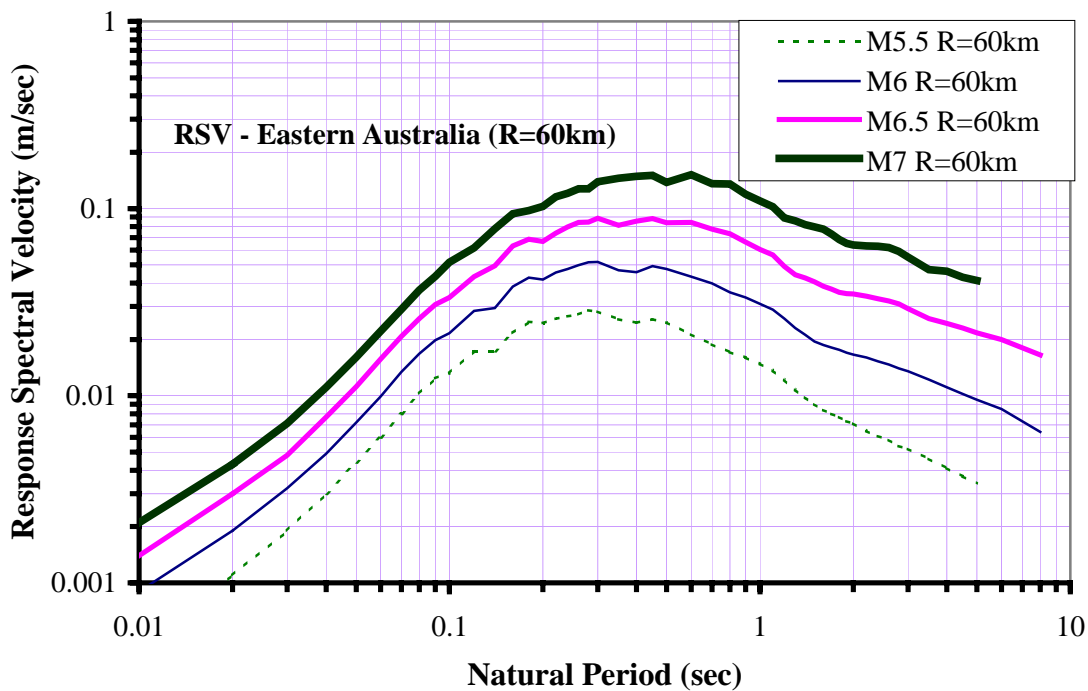
Figure 3. Sample size comparison of averaged response spectra (cont'd)

3.3 Response spectra of accelerograms simulated for Western and Central Australia

Eighteen random simulations have also been produced for each earthquake scenario defined by a magnitude-distance (M-R) combination for the “hard rock” conditions of Western and Central Australia. A response spectrum has been calculated for each simulation and results averaged. The averaged response spectra are presented systematically in Figures 5a -5c.

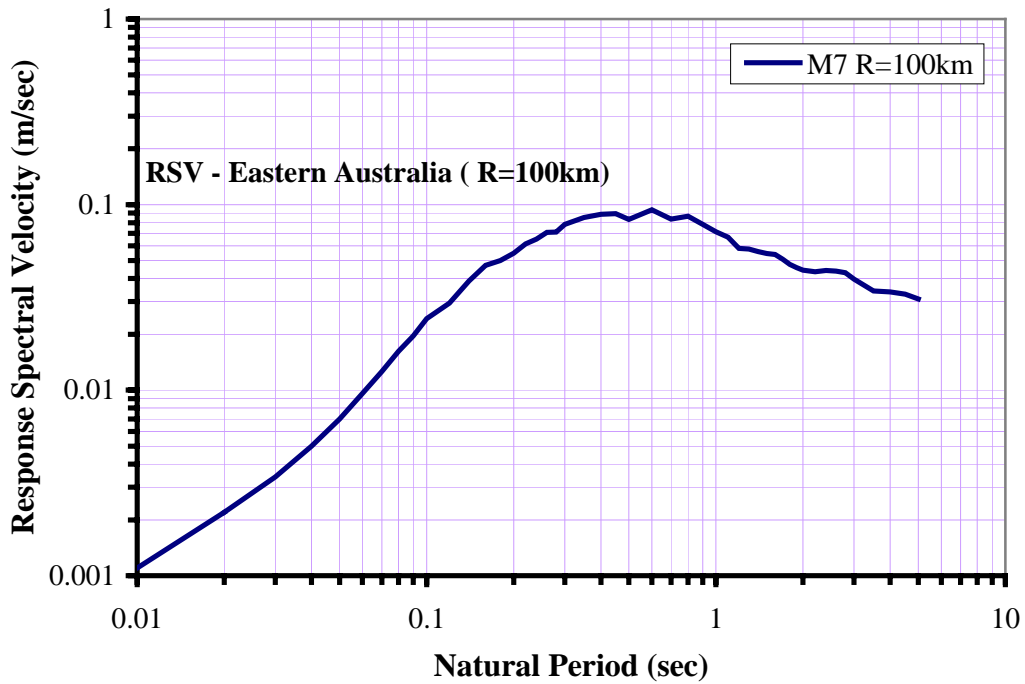


(a) R= 30 km



(b) R= 60 km

Figure 4. Response Spectra of accelerograms simulated for Eastern Australia



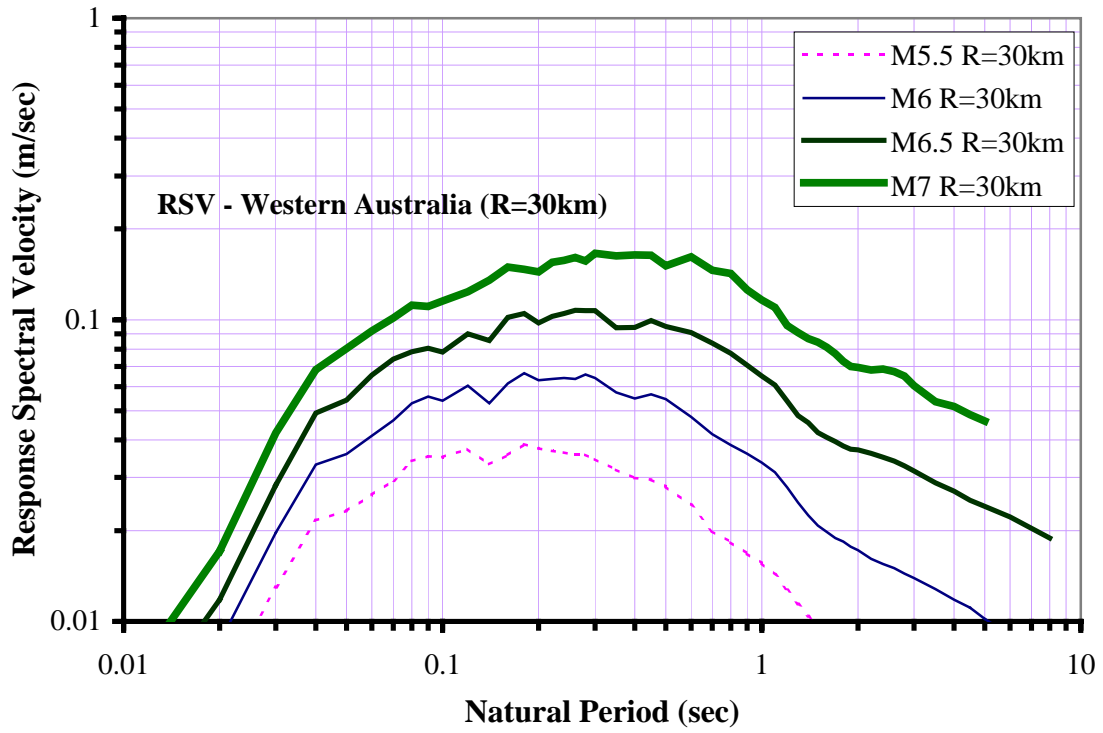
(c) R= 100 km

Figure 4. Response Spectra of accelerograms simulated for Eastern Australia (cont'd)

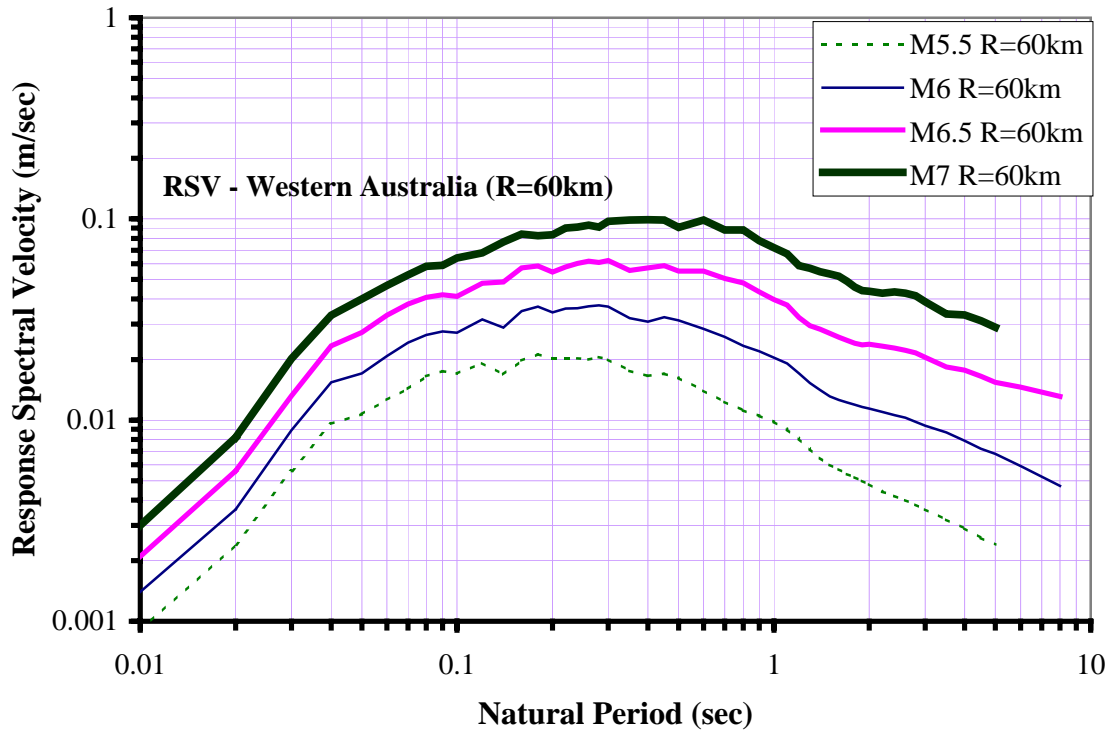
An important parameter of engineering interests characterising each of the response spectra is the notional averaged peak ground velocity (PGV), which is defined herein as the highest point on the averaged velocity response spectrum divided by 1.8 (based on the recommendations of Wilson & Lam, 2003 citing the work of Somerville et al, 1998). Note, the actual PGV can be some 10-15% lower than the notional PGV. This notional averaged PGV is summarised in Table 1 below for each M-R combination.

Table 1 PGV (mm/sec) of simulated motions for Eastern Australia

Distance\Magnitude	M5.5	M6	M6.5	M7
10 km	132	242		
20 km	58	109	180	
30 km	36	66	109	172
45 km	21	38	63	102
60 km	16	29	49	84
80 km			39	67
100 km				52

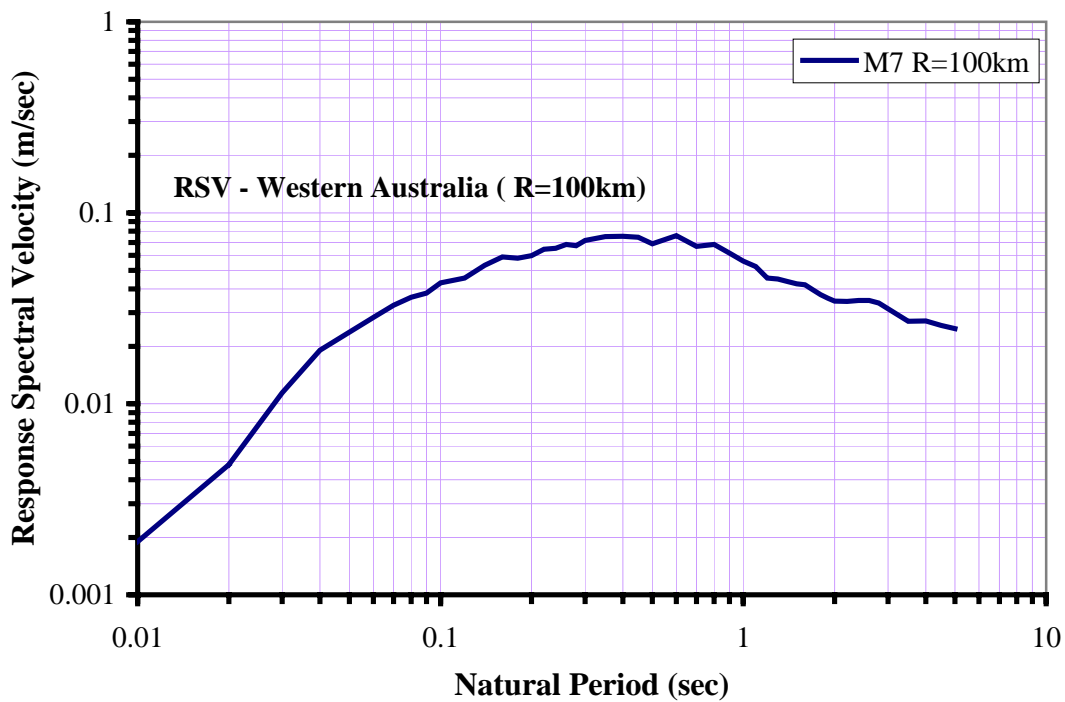


(a) R= 30 km



(b) R= 60 km

Figure 5. Response Spectra of accelerograms simulated for Western & Central Australia



(c) R= 100 km

Figure 5. Response Spectra of accelerograms simulated for Western & Central Australia
(cont'd)

The notional averaged peak ground velocity is also summarised in Table 2 below (as done for Eastern Australia). It is noted that the PGV's of accelerograms simulated for Eastern Australia are significantly higher than those simulated for Western & Central Australia for the same magnitude-distance (M-R) combinations.

Table 2 PGV (mm/sec) of simulated motions for Western & Central Australia

Distance\Magnitude	M5.5	M6	M6.5	M7
10 km	77	126		
20 km	34	58	95	
30 km	21	36	60	97
45 km	12	22	37	61
60 km	11	20	34	57
80 km			30	51
100 km				42

4. Comparisons with Instrumented and Intensity Data

Sections 4 and 5 are concerned with benchmarking simulated accelerograms and their response spectra and demonstrating their accuracies.

Response spectra recorded from a few small to moderate magnitude earthquakes occurring in central Australia and Eastern Canada have been compared with those simulated using program GENQKE. Modelling has been relatively straightforward in such environment given that frequency contents of seismic waves radiated from the source of the earthquake is not significantly modified in the transmission of waves through these stable continental interior regions of "hard rock" conditions. Consequently, good agreement has been found between computer simulations and field measurements (Lam et al, 2000b,c). Good simulation accuracies have also been demonstrated with case studies involving long distance earthquakes that affected Singapore, India *etc.* (refer Chandler & Lam, 2004). However, earthquake case studies that can be used to verify the accuracies of the presented simulation methodology is generally limited and comparisons have only been made on *ad-hoc* basis.

A systematic approach to benchmarking simulated accelerograms is to compare their ground motion parameters (such as *PGV's*) with predictions by existing empirical models (eg. Hutchinson et al, 2003). In Australia, attenuation modelling with instrumented data has only been undertaken very recently in Western Australia by Allen et al (2004). Attenuation modelling was based wholly on Modified Mercalli Intensity (*MMI*) data reported on iso-seismal maps of local historical earthquake events. A macro-seismic attenuation model was developed by Gauli et al (1990) in accordance with such data. The proposed attenuation relationship in terms of *MMI* for Eastern and Western & Central Australia is represented by equation (1a) and (1b) respectively.

$$MMI = 1.5 M - 3.9 \log R + 3.9 \quad (1a)$$

$$MMI = 1.5 M - 3.2 \log R + 2.2 \quad (1b)$$

A separate attenuation relationship has been developed for Northeastern Australia (Queensland region) which has been found to be intermediate between that of Western and Southeastern

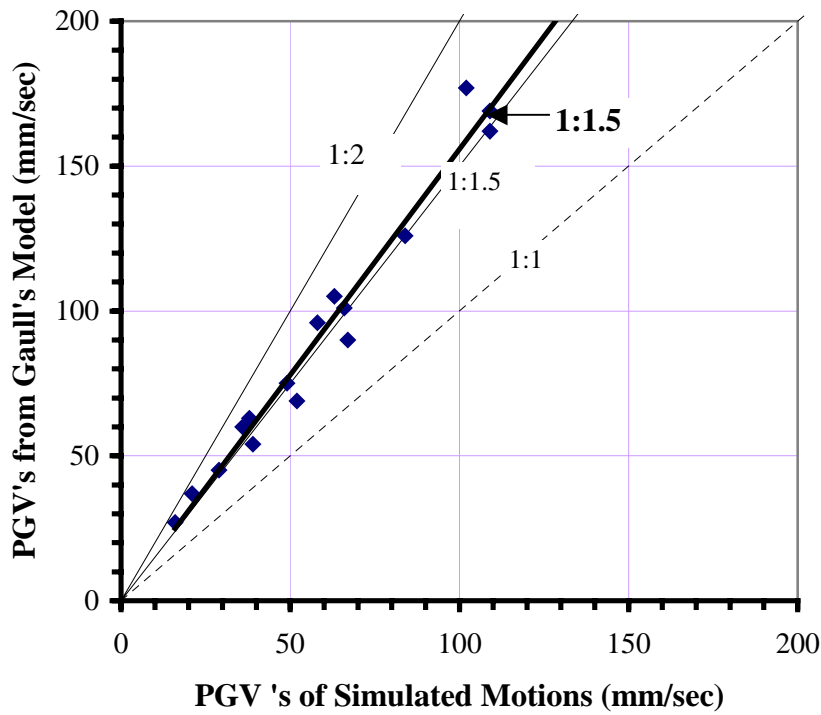
Australia. In this study, the conditions of Southeastern Australia (where the major capital cities of Canberra, Sydney and Melbourne are located) is taken to apply to the whole of Eastern Australia.

The modelled **MMI** values have been translated into the respective notional peak ground velocities (**PGV**'s) based on the well known conversion relationship of equation (2).

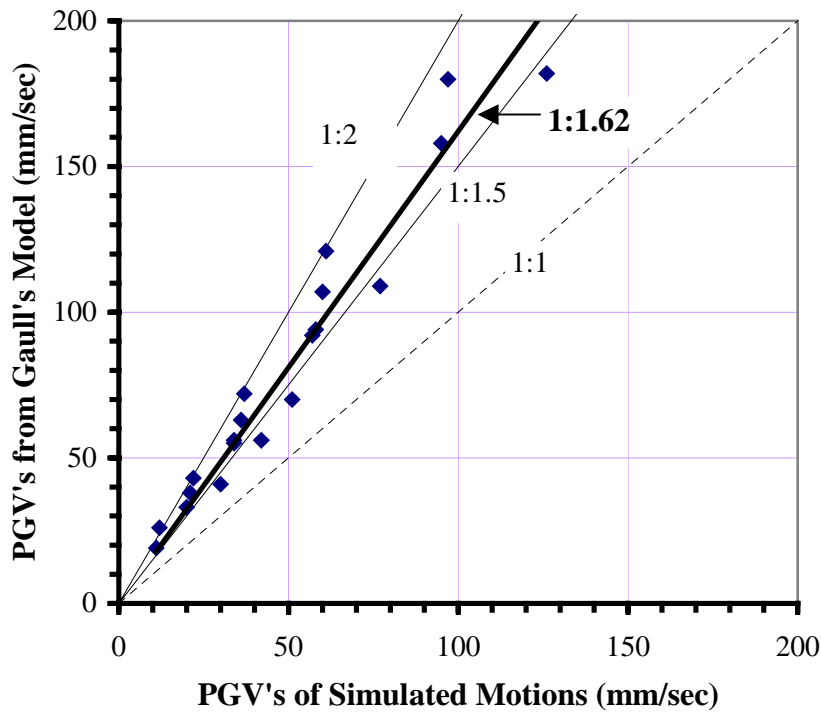
$$2^{MMI} = 7/5 \text{ PGV (mm/sec)} \quad (2)$$

Since the predicted **PGV** values were originally based on observations of damage in historical earthquakes, the predictions are meant to be for common (or "average") site conditions, and not specifically for rock sites, or hard rock sites, unlike seismological models used for simulating artificial earthquake accelerograms.

The **PGV**'s obtained from the simulated accelerograms were then correlated with the **PGV**'s calculated from the Gaull's model as shown in Figure 6a and 6b for rock and hard rock conditions respectively. The ratio between the two sets of data is the implied amplification factors of an "average" site. The implied average site factor is shown to be constrained at around 1.5-1.6 which is compared to the amplification factor of 1.4 stipulated by the new Draft Australian Standard for Class C sites. Note, Class C site is described as "shallow soil" site and is taken as the common site class of average conditions consistent with the definition of the Earthquake Intensity. This reasonable agreement in the predicted amplification factor of a common site supports the use of the simulated accelerograms for seismic risk analyses in both regions of Australia. The suitability of alternative attenuation models in representing Australian conditions could be tested using a similar approach.



(a) Eastern Australia

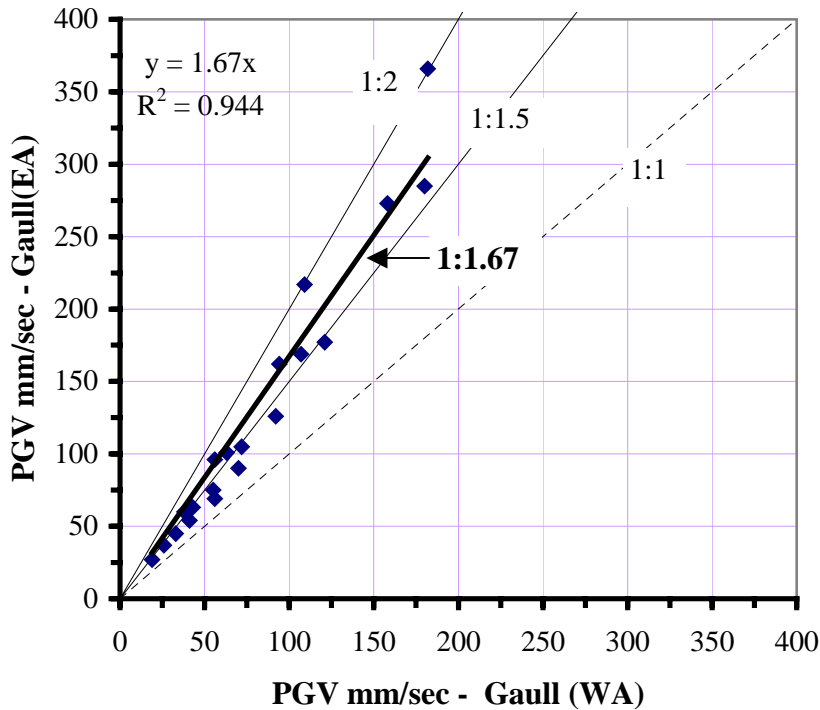


(b) Western & Central Australia

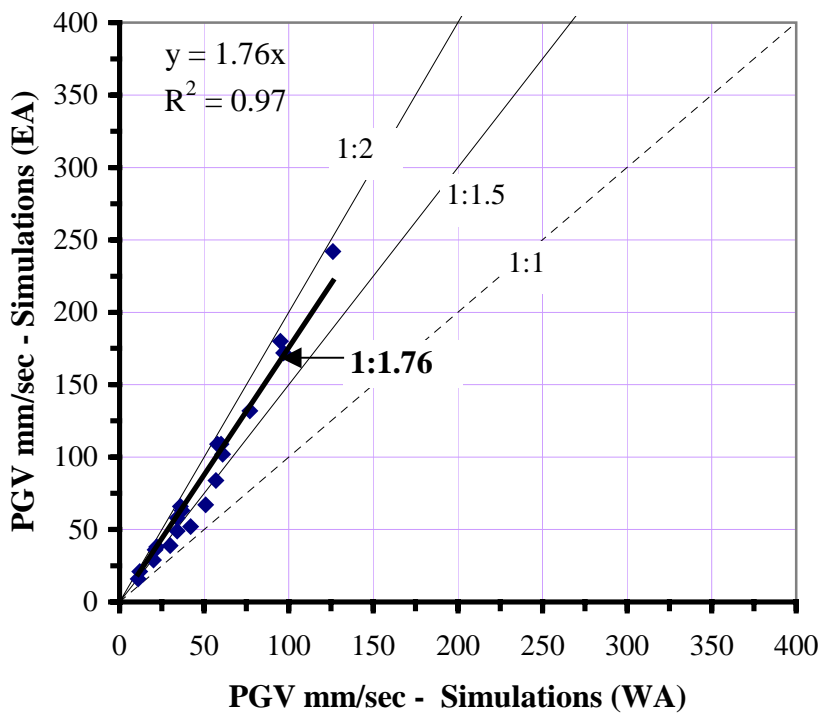
Figure 6. Peak ground velocities of simulated motions versus predictions by Gaull's Model

The notional PGV estimated for an M5.5 earthquake is 132 mm/sec at R=10 km and 58 mm/sec at R=20 km as shown in Table 1. The PGV at 15km is approximately 90 -100 mm/sec by linear interpolation. An Intensity on the Modified Mercalli scale in the order of VII can be inferred for rock (or very stiff) sites from the calculated PGV based on equation (2). This earthquake

scenario is comparable to the 1989 earthquake which struck the city of Newcastle on the eastern coast of New South Wales and resulted in 11 deaths and over 2 billion dollar of damage. The inferred Intensity value is in agreement with what is shown on the Iso-seismal map of the event on the western part of the city (Melchers, 1990).



(a) Gaull's Model



(b) Simulations

Figure 7 Crustal factors inferred from regional differences

The differences in the PGV's predicted for the two regions of Australia provide indications of the extent of crustal modifications (given that there are negligible crustal modifications in hard

rock conditions of Western & Central Australia). Thus, a crustal factor can be inferred from the ratio of the notional PGV estimated for Eastern Australia and that for Western & Central Australia. This ratio was calculated for every M-R combinations based on the Gaull's model (Figure 7a) and the simulated accelerograms (Figure 7b). A mean crustal factor of 1.67 was inferred from the Gaull's model. This is compared to a mean crustal factor of 1.76 obtained similarly from the simulated accelerograms.

5. Velocity-Displacement corner period behaviour

An effective way to characterize the long-period (up to 5 sec) behaviour of earthquake ground motions is to calculate the corner period which defines the transition between the velocity-controlled and displacement-controlled sections of the response spectrum (Lam *et al*, 2000c; Lam & Chandler, 2005). The calculations may be based on equation (3).

$$T_{corner} = 2\pi \frac{RSD_{5sec}}{RSV_{max}} = 2\pi \frac{RSD_{5sec}}{1.8PGV} \quad (3)$$

During the 1990's, the Australian Geological Survey Organisation (AGSO) undertook a detailed study of 13 accelerograms measured at rock sites from reverse thrust fault events with magnitude ranging from 5.4 - 6.6 (Somerville *et al*, 1998). Records were normalised to a peak ground velocity (PGV) of 50 mm/sec, and the proposed normalised design response spectrum is shown below in Figure 8. The corner period of the averaged spectrum is shown to be around 0.7 sec.

The long-period behaviour of the accelerograms simulated in this study (for both Western and Eastern Australia) has been checked by calculating the corner periods for individual earthquake scenarios and compared with the benchmark model of Somerville, *et al.*, (1998) as shown in Figure 8. Results of the comparison are shown in Figure 9 for earthquake scenarios at the reference hypocentral distance of 30 km. The magnitude dependent behaviour of the corner frequency was identified in the study by Lam *et al* (2000c) from the simulation motions. The comparison of Figure 9 once again shows good agreement between the simulated motions and the recorded motions as represented by the model of Somerville *et al* (1998). Recognizing this, the design response spectra stipulated by the new Australian Standard for earthquake actions has the corner period set conservatively at 1.5 sec representing a major earthquake event in the order of magnitude M=7.

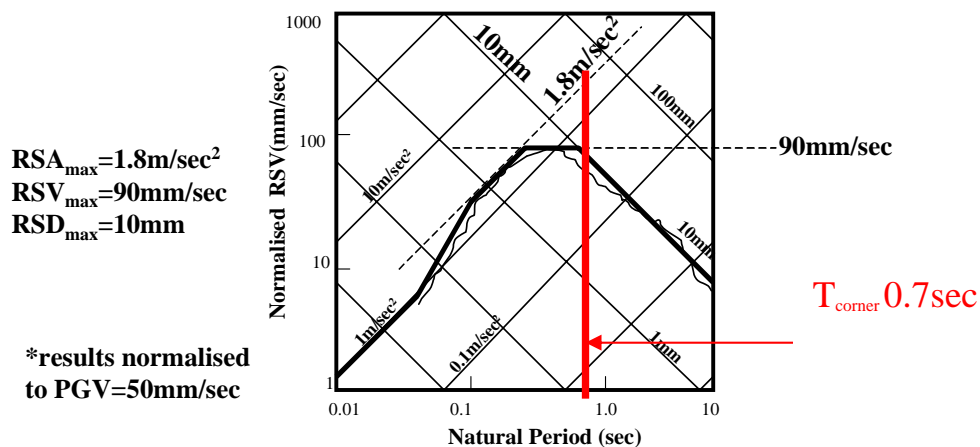


Figure 8. Normalised Empirical Spectrum Model of Somerville

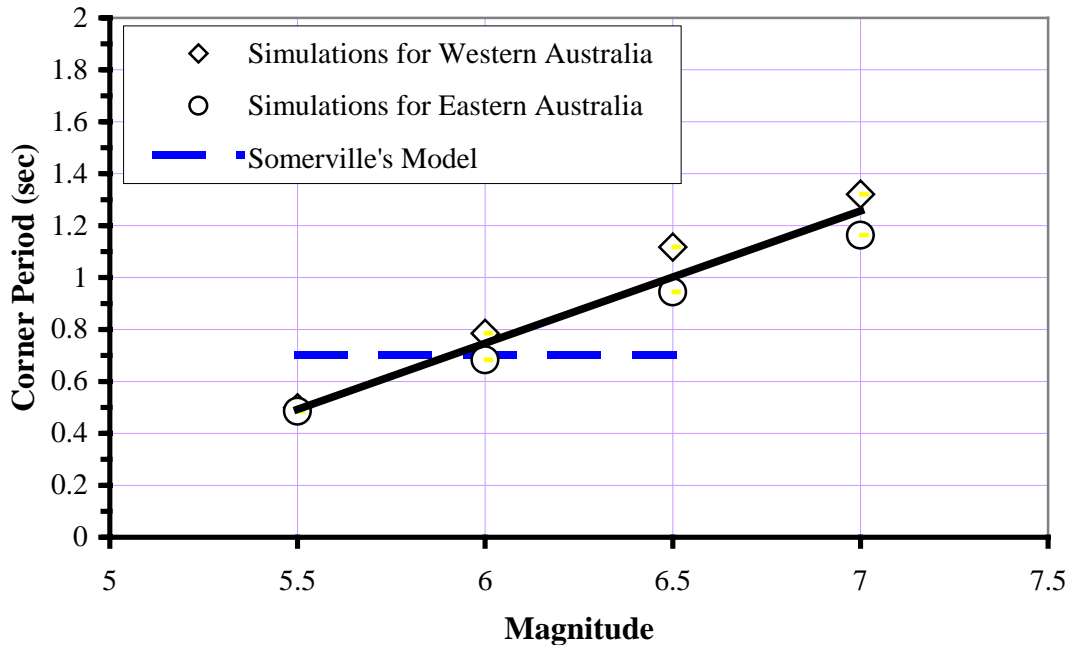


Figure 9 Corner periods at velocity-displacement transition

6. Simulations for a deep or soft soil site

Accelerograms presented in the earlier parts of this paper were based on hard rock and rock conditions which can be described as site category Class A and B respectively according to the new Australian Standard for earthquake actions (AS/NZS 1170.4 Doc. D5212-5.1: June 2005). A more onerous sub-soil condition is considered in this section. A borehole record representing such condition is shown in Figure 10a. The shear wave velocity profile of the soil sedimentary layers, totaling 55m in thickness as shown in Figure 10b, was inferred from the borehole record using relationships recommended in Lam & Wilson (1999). The site natural period is estimated accordingly at around 1 second which suggests a Class D site category.

Site response analyses were undertaken using program SHAKE (Idriss & Sun, 1992) based on a multitude of earthquake scenarios with varying magnitude-distance (M-R) combinations producing PGV of about 60 mm/sec on the rock surface (which is consistent with a hazard factor, Z, of 0.08 as stipulated by the Standard for Melbourne, Sydney and Canberra). It is shown in Figures 11a-11d that the more critical scenario for soil response pertains to the one with a larger earthquake magnitude while the rock PGV is kept constant. Thus, the soil response spectrum simulated for the M=7 scenario (Figure 11d) is most critical and hence conservative for design applications. Simulations based on the M=6.5 scenario (Figure 11c) seem to match best with the design response spectrum stipulated by the Standard. Thus, the acceleration time-history corresponding to the M=6.5 earthquake scenario is recommended for use in time-history analyses for design purposes for site sub-soil conditions comparable to that shown in Figure 10.

For other sub-soil conditions, accelerograms should be simulated using a site response analysis program such as SHAKE and representative rock accelerograms as input information.

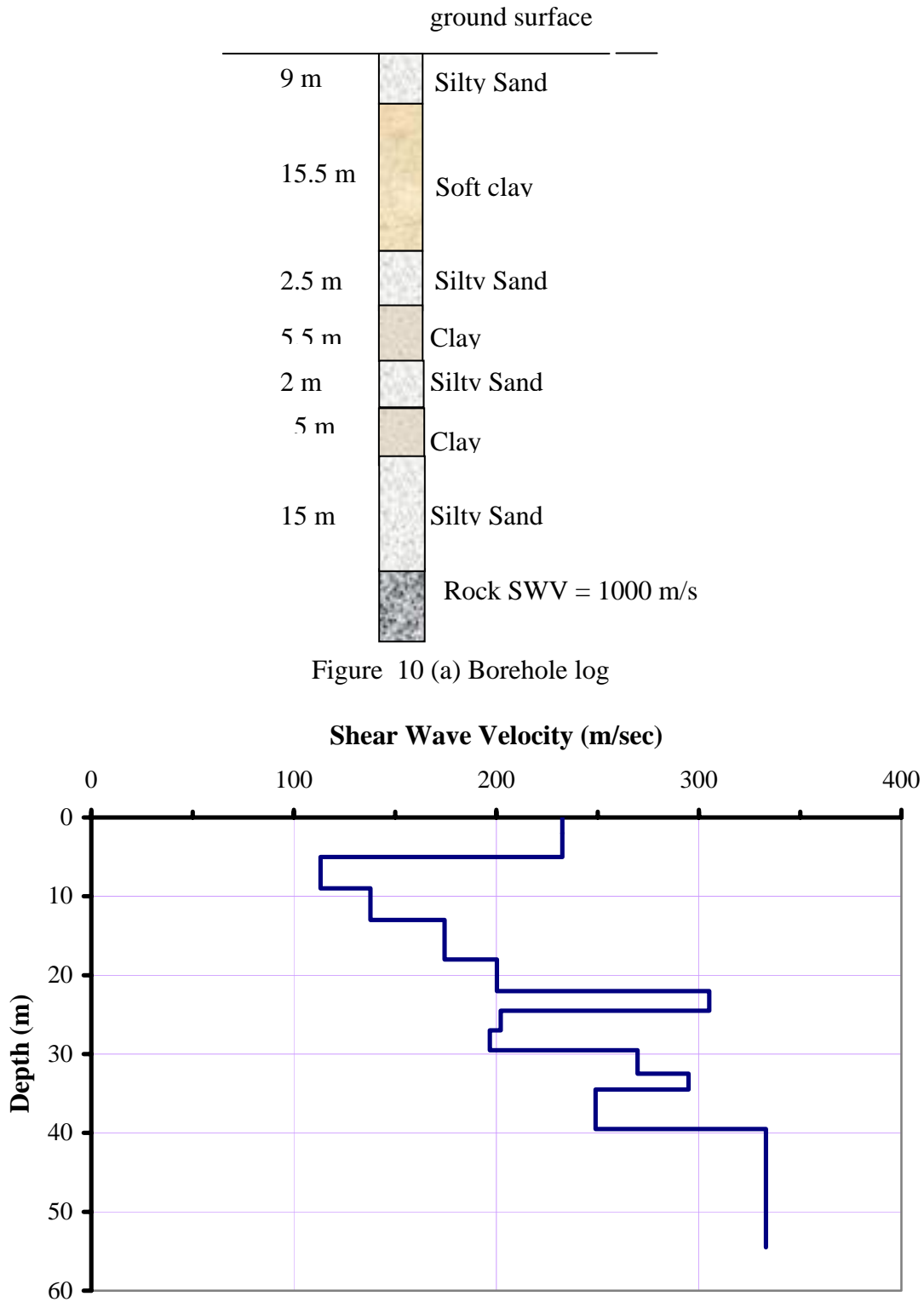
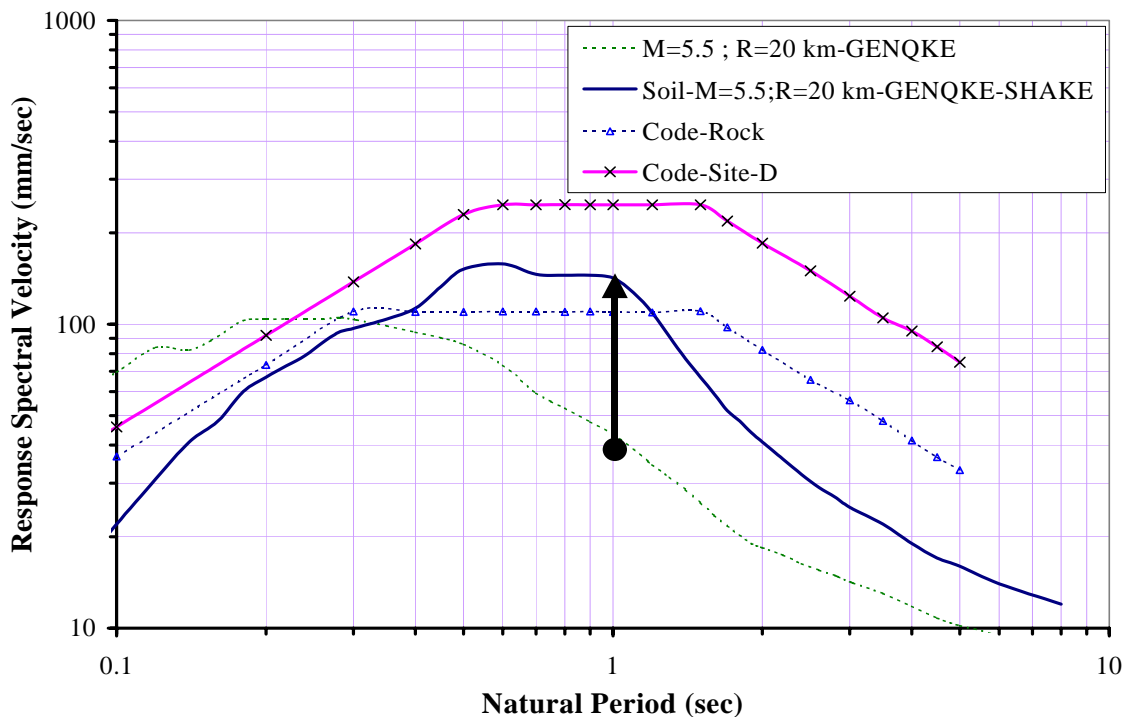


Figure 10. (a) Borehole log and (b) Shear wave velocity profile for example Soft Soil (class D) site

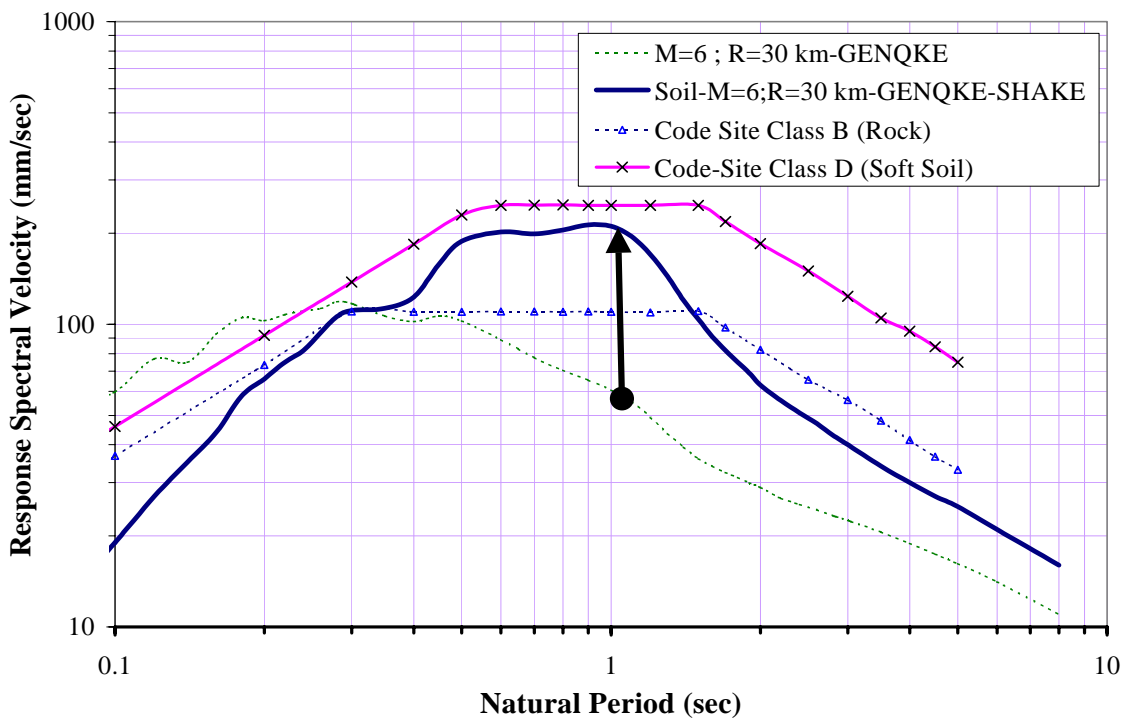
An example “rock outcrop” accelerogram associated with the design scenario of $M=6.5$ and $R=45\text{km}$ is shown (in Figure 12a) along with the accelerogram simulated for the surface of the soft soil site (in Figure 12b). An electronic file containing accelerograms simulated for this earthquake scenario for different site classes can be accessed through the journal website. The two simulated acceleration time-histories have similar amplitude but very different frequency contents, which is evident from the corresponding ensemble averaged response spectra presented in the different formats in Figures 13a-d. Explanations of the response spectrum formats are given in Wilson & Lam (2003).

The most critical displacement demand is shown to occur at the site natural period as indicated by the “corner point” on the velocity spectrum (Figure 13b), a single dominant peak on the displacement spectrum (Figure 13c) and a “nose” shaped feature on the ADRS diagram (Figure 13d). The vertical arrow shown along with the “broken line” on the velocity and displacement response spectra highlights a maximum soil amplification ratio in the order of about 1: 4 at this critical period. This displacement amplification behaviour is not evident in the response spectrum presented in the conventional acceleration format of Figure 13a (noting that peaks appearing on the acceleration spectrum are positioned differently to the peak on the displacement spectrum). It is noted that the seismic displacement demand can become more onerous than that presented in this section if the site natural period is higher than 1 second.

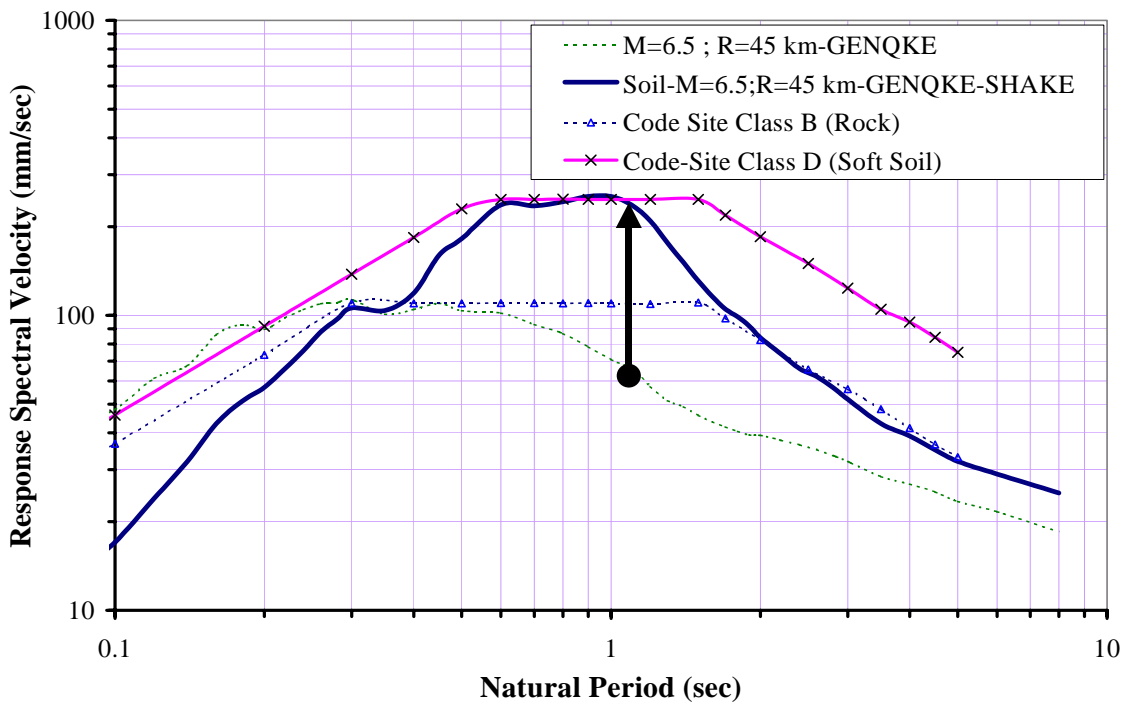
The borehole log and corresponding shear wave velocity profile for an example Class C site is also shown in Appendix A. That particular site has a shallower soil profile than the example Class D site of Figure 10. However, the site specific velocity response spectrum may “locally“ exceed that of a Class D site at the site natural period of 0.6 sec (which is most onerous for a Class C site). Accelerograms simulated for this site Class C model are also available for access through the journal website.



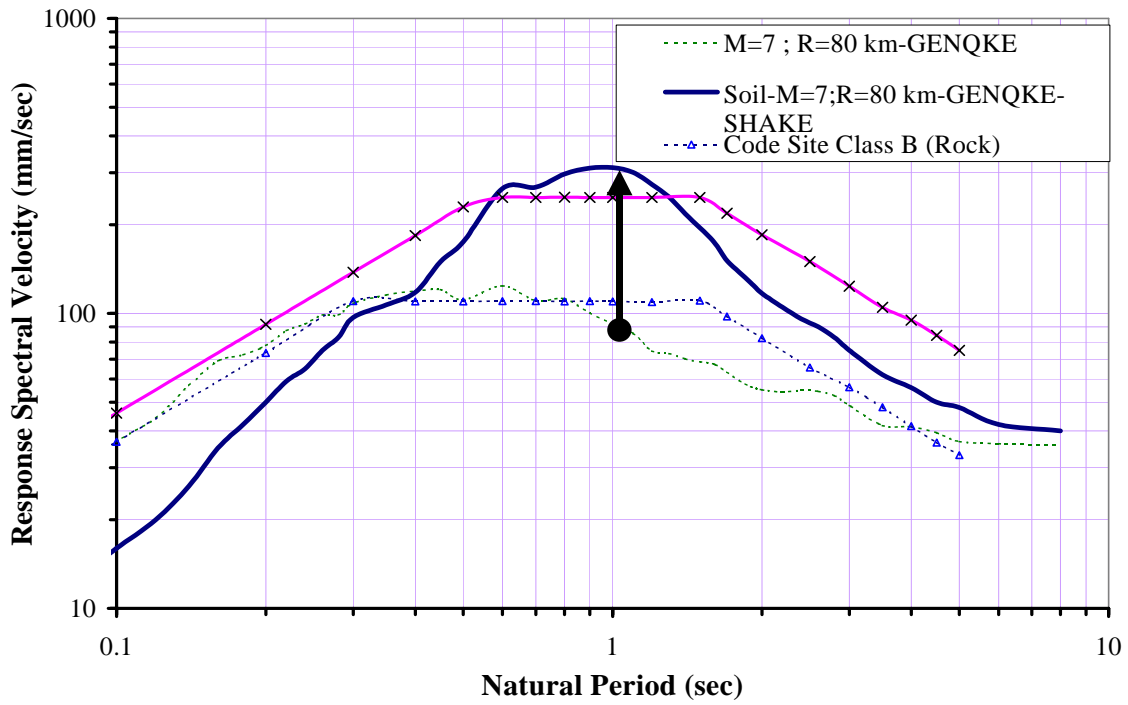
(a) $M=5.5$, $R= 20 \text{ km}$



(b) M=6, R= 30 km

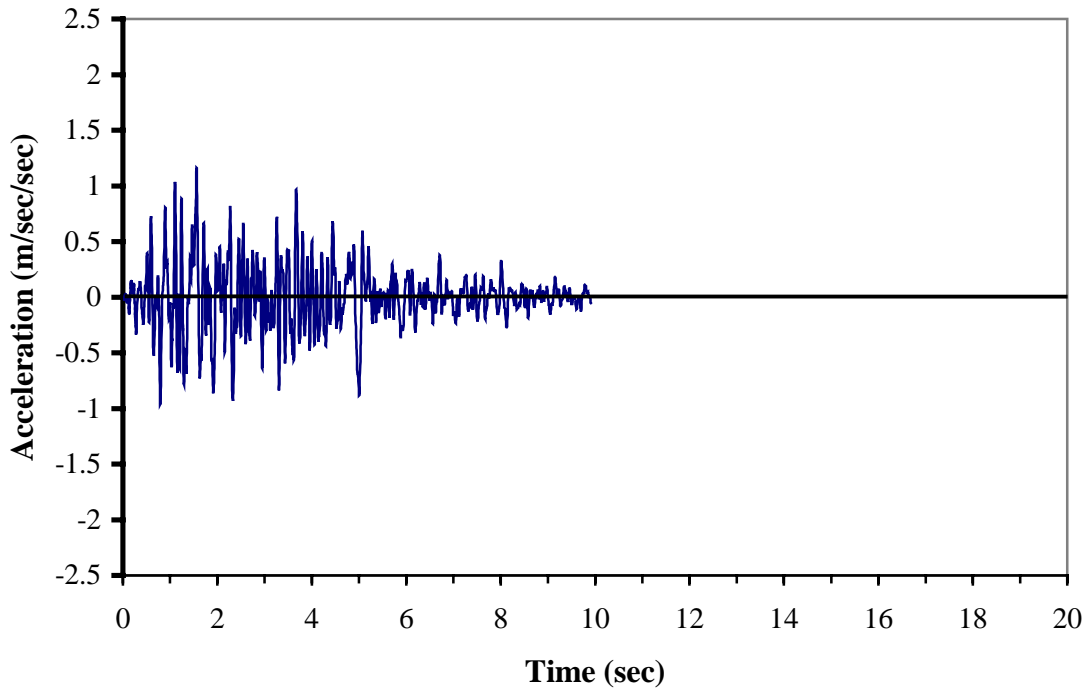


(c) M=6.5, R= 45 km

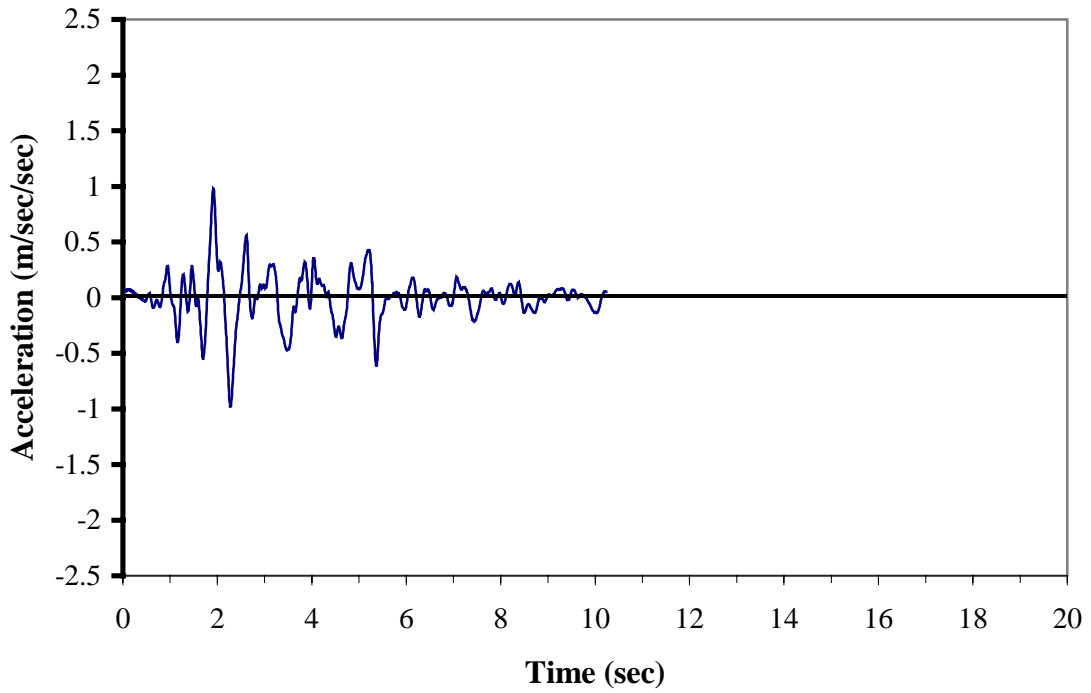


(d) M=7, R= 80 km

Figure 11. Velocity response spectra simulated for rock and soft soil conditions for comparison with design response spectra stipulated by the new Australian Standard (cont'd)

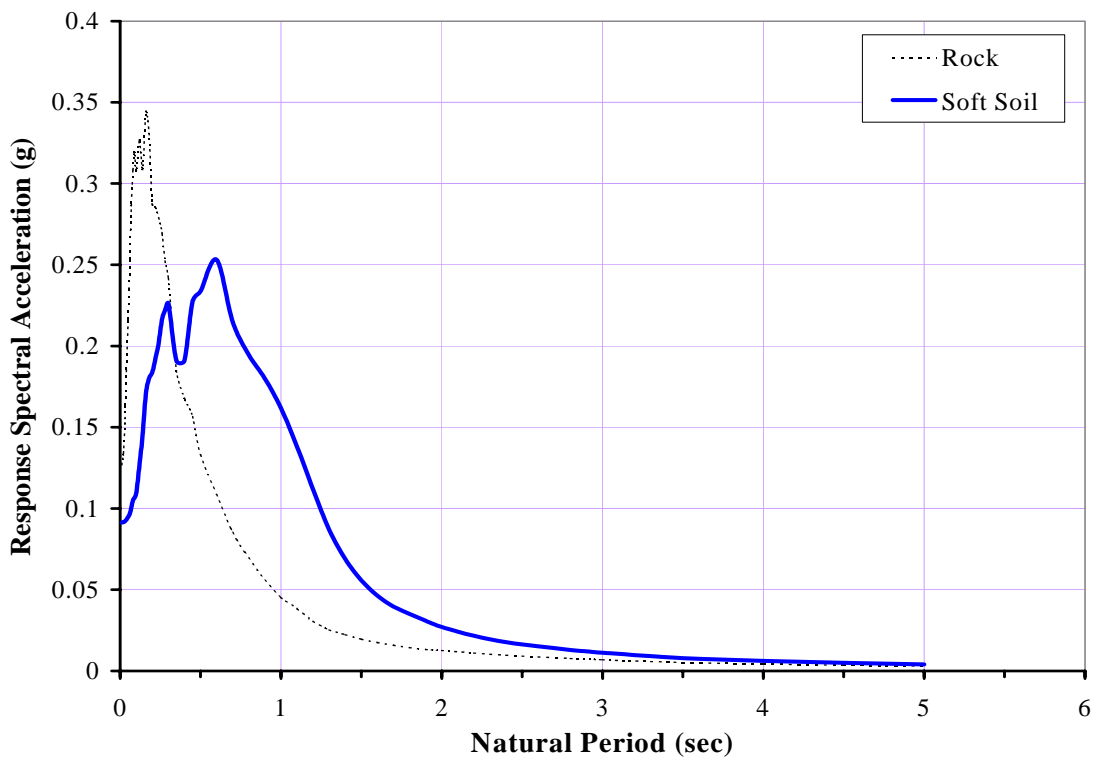


(a) Class B Rock site



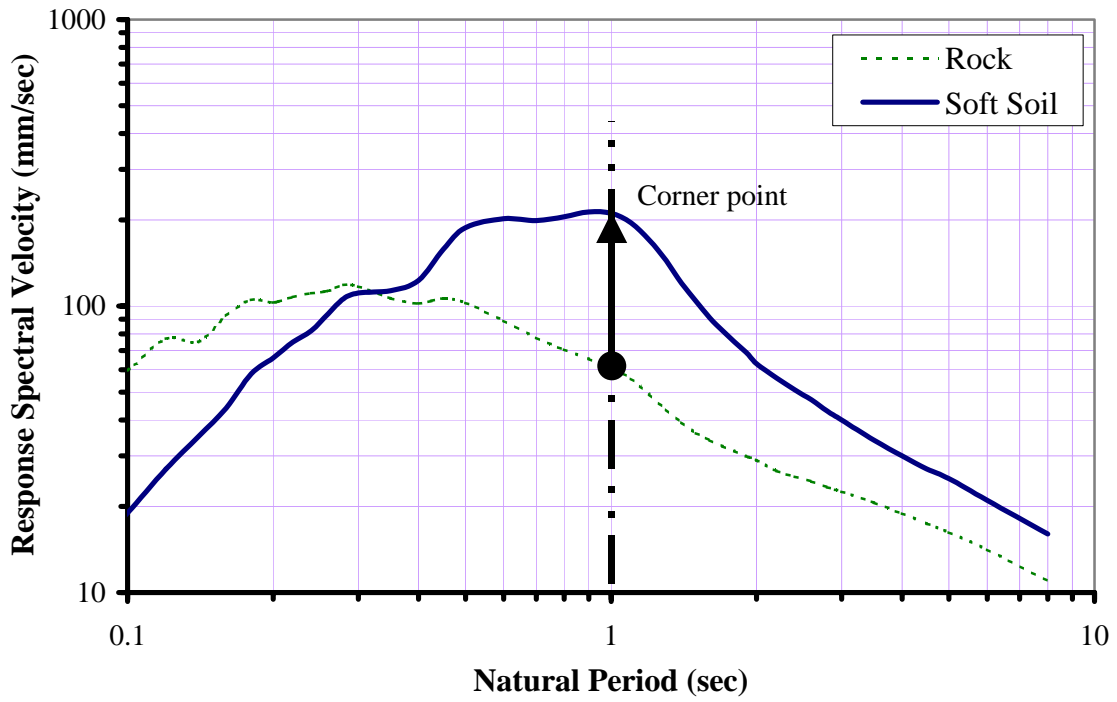
(b) Class D Soft Soil site

Figure 12 Accelerograms simulated for M=6.5 R=45 km earthquake scenario spectra

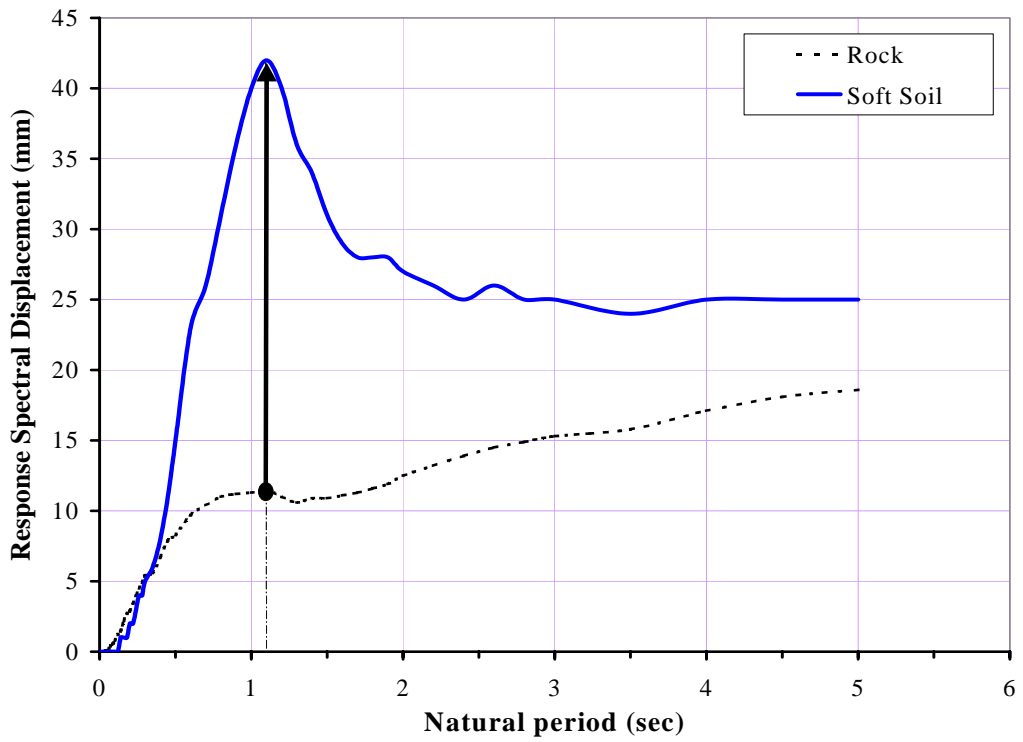


(a) Acceleration response spectra

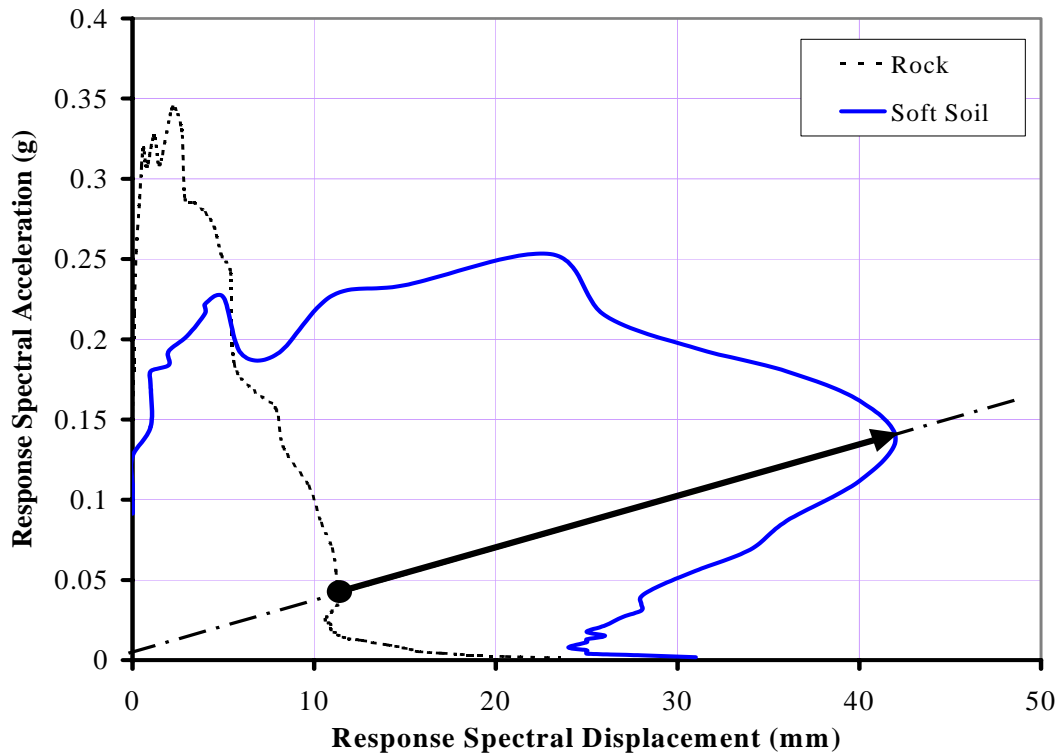
Figure 13 Rock and soft soil spectra in different formats



(b) Velocity response spectra



(c) Displacement response spectra



(d) Acceleration-Displacement Response Spectrum (ADRS) Diagrams

Figure 13. Rock and soft soil velocity response spectra in different formats (cont'd)

7. Conclusion

Artificial accelerograms have been generated by computer based on stochastic simulations of the seismological model. Separate modelling is required for (i) "hard rock" conditions of Western and Central Australia and (ii) "rock" conditions of Eastern Australia.

An important parameter of engineering interests characterising each of the response spectra is the notional averaged peak ground velocity (PGV), which is defined herein as the highest point on the averaged velocity response spectrum divided by 1.8. The *PGV's* obtained from the simulated accelerograms have been correlated with the *PGV's* calculated from Gaull's model. The ratio between the two sets of data, which is shown to be constrained at around 1.5-1.6, is close to the amplification factor stipulated for a Class C (or "average") site consistent with the definition of the Earthquake Intensity.

The differences in the *PGV's* predicted for the two regions of Australia provide indications of the extent of crustal modifications. A mean crustal factor of 1.67 was inferred from the Gaull's model. This compares favourably with a mean crustal factor of 1.76 obtained from the simulated accelerograms.

The velocity-displacement transition behaviour of the accelerograms simulated in this study has been checked by calculating the corner periods for individual earthquake scenarios and comparing with the benchmark model of Somerville. The comparison shows good agreement between the simulated motions and the Somerville model in terms of their corner period behaviour. The design response spectra stipulated by the new Australian Standard for earthquake

actions have the corner period set conservatively at 1.5 second representing a major earthquake event in the order of magnitude $M=7$.

The borehole record of a soft soil site with 55m deep sedimentary layers and site natural period of around one second (subsoil category Class D) was subject to site response analyses using the program SHAKE. The most critical displacement demand calculated for the soil surface is indicated by the “corner point” on the velocity spectrum and the single dominant peak on the displacement spectrum. The most critical scenario when PGV is kept constant pertains to the one with a larger earthquake magnitude. The $M=6.5$ scenario seems to provide the best match with the design response spectrum stipulated by the new Standard. Therefore, acceleration time-histories corresponding to this earthquake scenario are recommended for use in time-history analyses for design purposes, and are available in an electronic format for access through the journal web address. For sub-soil conditions which are more onerous than that shown in Figure 10 (eg. site natural period exceeding 1 second), accelerograms should be simulated using a site response analysis program such as SHAKE and with accelerograms simulated for a Class A or B site as the input bedrock excitations.

7. References

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Appendix A – Borehole log and shear wave velocity profile for a Class C site

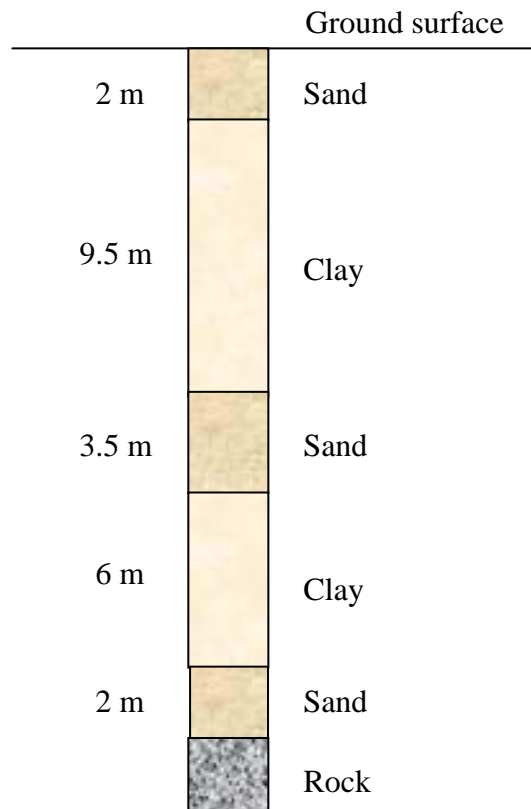


Figure A1 Borehole log of an example Class C site

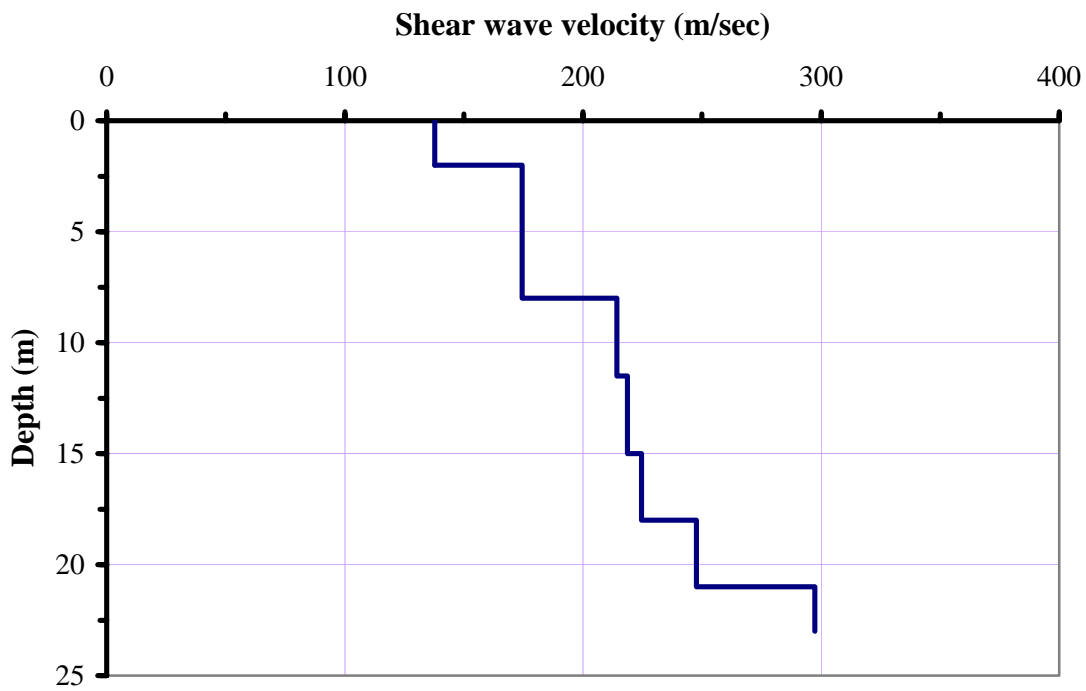


Figure A2 Shear wave velocity profile for an example Class C site