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Seismic Hazard Assessment and Site Response Evaluation in Perth Metropolitan Area

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ABSTRACT :

Perth is the capital city of Western Australia, its seismic hazard has in the past been considered to be quite low. However, in recent decades the population and metropolitan area itself has increased considerably. Furthermore, Michael-Leiba (1986) demonstrated that the seismicity to the east of the city had also increased compared with historical times. Hence, both the seismic threat and the vulnerability of Perth Metropolitan Area (PMA) to earthquake damage have significantly increased. During that time interval there has been much research trying to quantify this hazard. As only very limited number of earthquake strong ground motion records are available in southwest Western Australia (SWWA), previous studies of seismic hazard of PMA were predominantly based on the ground motion attenuation model derived from central and eastern North America (CENA). In principle, these adoptions seemed valid because both CENA and SWWA are located in the stable continental intraplate region. However, some bias in prediction for SWWA ground motion and seismic risk may be produced since there are a lot of different factors in different regions, e.g. ground motion characteristics and site conditions. Hence, in this paper, a seismic risk analysis of PMA based on the updated local ground motion attenuation model is performed. Responses of the three site classes in PMA are calculated. The response spectra on rock and soil sites are estimated and compared with the respective design spectrum defined in the Current Australian Earthquake Loading Code. Discussions on adequacy of the design spectrum against that of seismic analysis in this study are made.

KEYWORDS: seismic hazard, site response, Perth

1. INTRODUCTION

Perth is the largest city in Western Australia and home to three-quarters of the state's residents. The city is also the fourth most populous urban area in Australia and in recent years has the fastest growth rate among the major cities in Australia. Unfortunately, with this growth comes a proportional increase in the vulnerability to natural disasters.

Furthermore, in recent decades, there have been a lot of earthquake activities just east of Perth in a zone that has been named the “Southwest Seismic Zone” (SWSZ). Three large earthquakes have ruptured the surface and caused considerable destruction in the zone including the 1968 Meckering earthquake, the 1970 Calingiri earthquake and the 1979 Cadoux earthquake. In fact Michael-Leiba (1986) showed that there has been an approximately 5-fold increase in the mean yearly number of ML greater than or equal to 4.5 main shocks during the period 1949-1983 compared to 1923-1948. Also with ML 5 and 6, there was none during the earlier period. Evidence that this increased seismicity is continuing since then is provided in the Meckering and more recently the Burakin regions where events of magnitudes exceeding ML5 have occurred. A sequence of more than 20,000 (mostly) small earthquakes has also occurred near Burakin since the beginning of 2001. Hence there is consensus in the seismic fraternity that seismic hazard in Western Australia has increased and this translates into how important it is for engineers to be aware of this and get updated information such as what is provided in this paper for their aseismic design.

Following the seismicity study of Western Australia by Everingham (1968), Gaull and Michael-Leiba (1987) defined earthquake source zones in Western Australia for seismic risk estimation using the Cornell-McGuire method. As only very limited number of earthquake strong ground motion records are available in southwest Western Australia (SWWA), the estimates presented by Gaull and Michael-Leiba (1987) were based on a two-stage process, i.e., a) estimation of mean isoseismal radii from local isoseismal maps; and b) conversion to PGA and PGV using existing intensity-SGM models. Since there was no reliable attenuation model in SWWA, many seismic risk analysis for Perth (Dhu *et al.*, 2004 and Jones *et al.*, 2006) and the design response spectrum in current Australian Earthquake Loading Code (AS 1170.4-2007) were based on the attenuation models developed for Central or eastern North America (CENA). These attenuation models were used because both CENA and SWWA are located in the stable continental intraplate region.

However, the reliability of these CENA models in predicting SWWA strong ground motions is still under discussion. Some recent studies (Hao and Gaull, 2004, Kennedy *et al.*, 2005) show that none of these models yielded very satisfactory prediction of the recorded strong ground motions in SWWA. For example, Hao and Gaull (2004) compared five CENA ground motion models, and concluded that these five models derived by different researchers differ significantly in the lower magnitude range among themselves although they were all derived from the recorded CENA data. Hence, using CENA attenuation models to perform seismic hazard analysis for PMA might bias the ground motion estimates.

Hao and Gaull (2004) modified the Atkinson and Boore (1995) model based on the available strong ground motion records in SWWA, and showed that the modified model yielded good prediction of the recorded ground motions for moderate magnitude (< ML5.5) events, however, since the vast majority of strong motion records used to modify the model was from earthquakes of magnitude ML4.5 or below, its reliability in representing larger SWWA earthquakes is yet to be known. To overcome this, a combined stochastic and Green's function simulation method was adopted by Liang *et al.* (2008) to develop attenuation models of PGA, PGV and ground motion spectral accelerations for SWWA. The new attenuation models are derived from a large simulated database covering a large distance range, an appropriate magnitude range and provide a more reliable prediction for available SWWA records than other models considered. Therefore, it is expected the new equations are likely to provide the more reliable seismic hazard results in SWWA.

As the selection of an appropriate ground motion attenuation relation for use in probabilistic earthquake hazard evaluation is almost always critical to the results, in this study, the attenuation model presented by Liang *et al.* (2008) is employed to derive the design response spectra of rock site ground motions corresponding to the 475-year return period earthquake and the 2475-year return period earthquake in SWWA. Responses of the three site classes in PMA defined by McPherson and Jones (2006) are calculated. Statistical variations of the various soil thicknesses and their shear wave velocity are considered using Monte Carlo simulation and their effects on the site response spectrum are examined. The design response spectra on rock and soil sites are compared with the respective design spectrum defined in the Current Australian Earthquake Loading Code. Discussions on adequacy of the design spectrum against that of seismic analysis in this study are made.

2. DESIGN RESPONSE SPECTRUM FOR ROCK SITE

The computer program SEISRISK III (Bender and Perkins, 1987) is used in this study to perform probabilistic seismic hazard analysis (PSHA). SEISRISK III is one of a series of computer programs developed by the US Geological Survey to calculate maximum ground motion levels that have a specified probability of not being exceeded during a fixed time period at each of a set of sites uniformly spaced on a two-dimensional grid. The earthquake sources are modelled as either points located randomly within seismically homogeneous source zones or as finite length ruptures that occur randomly along linear fault segments. A detailed discussion of the computational methodology is outside the scope of this paper. Those wishing more detailed information about the program should refer to the original documentation. However, a brief description of some key assumptions and input parameters relating to the calculation of earthquake hazard is included below.

2.1 Seismic Source Zones and Recurrence Relationship

The definition of seismic source zones and their recurrence relationships in SWWA have been made by Gaull and Michael-Leiba in 1987. Some modifications presented in Hao and Gaull (2004) were applied to the original zone boundaries and recurrence relationships to include the most recent activity in the Burakin area. This updated seismic source zone map shown in Figure 1 and recurrence relationship model listed in Table 1 are largely adopted in this study. It should be noted that the recurrence relationship for Zone 4 is calculated from Background zone in Table 2 of Gaull and Michael-Leiba (1987). Because the SEISRISK programme does not have the facility for "Background Seismicity" as in the Cornell McGuire Programme, it was decided to introduce a fourth zone between Zone 3 and Zone 2 and use the normalised recurrence rates of seismicity as defined in Table 1 and call it "Background Zone". Because this zone falls under and adjacent to the PMA, it is thought the relatively low seismicity level may well be significant.

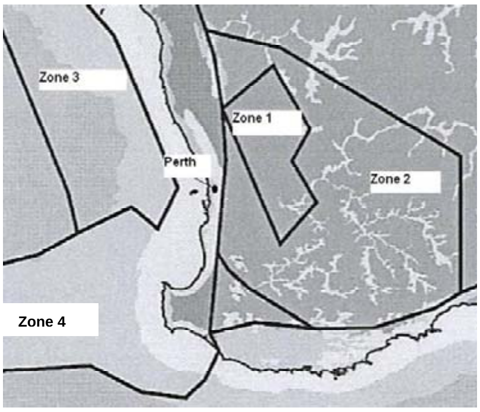

Figure 1. Seismic Source Zones surround PMA (Hao and Gaull, 2004)

Table 1. ML Recurrence Parameters for Seismic Source Zones

SZ	A	b
1	2.88	0.75
2	4.22	1.27
3	3.1	0.85
4	1.78	1

Note: Zone 4 A-value is per 10,000 square kilometres.

2.2 Attenuation Relation for SWWA

As discussed above, an appropriate attenuation relation should be used in this study for the PMA site because of possible biases associated with attenuation relationships developed from the database recorded in different regions. For example, Douglas (2004) has shown that there seems to be a significant difference in ground motions between California and Europe. Therefore, Liang *et al.* (2008) attenuation model, developed based on local earthquake database, is adopted in this study. The standard error of estimate of the attenuation model is considered in the calculation to take variability in the attenuation function into account.

2.3 The PGA

PGA on rock site in PMA with a 10% and a 2% probability of being exceeded in 50 years are calculated using Liang *et al.* (2008) attenuation model and shown in Figure 2 and Figure 3, respectively. As can be seen in Figure 2, PGA on rock site ranges from 0.14g in the north-east through to 0.09g in the south-west for the return period of 475 years. Comparing to the PGA of 0.09g with the same probability given in the current Australian earthquake loading code, the code underestimates PGA in the north-east part of PMA. The PGA for return period of 2475 years is estimated in the range of 0.24g to 0.36g.

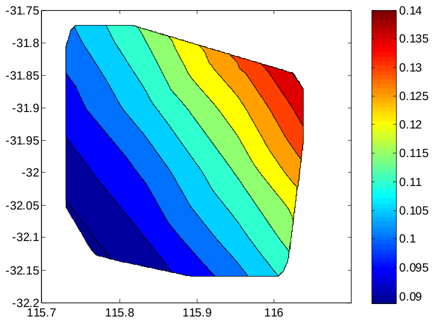

Figure 2. Rock site PGA in PMA with a 10% chance of being exceeded in 50 years (equivalent to the return period of 475 years)

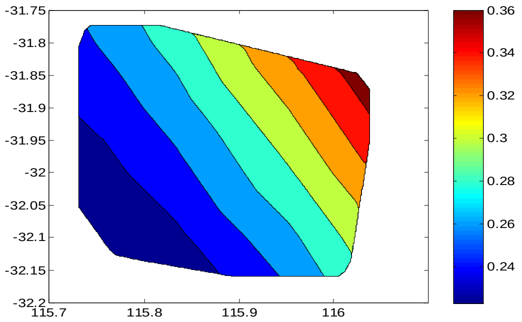

Figure 3. Rock site PGA in PMA with a 2% chance of being exceeded in 50 years (equivalent to the return period of 2475 years)

It is interesting to compare these estimated PGA's from Figure 2 for downtown Perth with those of Hao and Gaull (2004). Interpolating from Figure 2 above, the PGA which has a 10% chance of exceedance in 50 years on rock-sites is about 0.105 g. This is slightly greater than what was predicted by Hao and Gaull (2004) where an equivalent estimate of about 0.09 g was obtained. The difference in the two results could be easily explained with the higher standard deviation of 1.17 in this study compared with 0.7 in Hao and Gaull (2004) paper.

2.4 Probabilistic Seismic Hazard Spectra

The 5% damped spectral accelerations corresponding to the probabilistic seismic hazard levels for return period of 475 years are estimated at periods of 0.02, 0.05, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, and 4.5 second by using the above attenuation model. The spectral accelerations observed at the central business district (CBD) of Perth (longitude 115.85° and latitude 32.00°) is used in this study. The comparisons of the calculated spectral accelerations and those of the code spectrum are given in Figure 4. The comparisons show that the spectral accelerations on rock site corresponding to the 475-year return period in general lie between the code spectrum of strong rock and rock site within the range of 0sec to 0.5sec. However, the code spectrum might underestimate spectral acceleration at the period range of 0.5sec to 2sec. This might be because the attenuation model appears to predict higher spectral acceleration in this frequency range than that of CENA models. This characteristic has been observed in many individual dataset recorded surround SWWA, such as Burakin events. For example, Allen *et al.* (2006) indicated that the WA model predicts higher Fourier amplitudes at low frequencies than Atkinson (2004). Nevertheless, further investigations are needed as new data come to hand. Since the natural period for most of buildings lies within the range of 0.5sec to 2sec, inadequacy of the design spectrum will deeply affect the seismic design of buildings. Further studies are deemed necessary to investigate the behaviour of buildings under the calculated spectral acceleration.

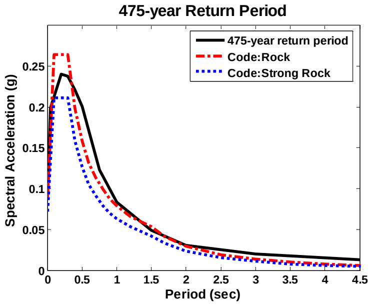

Figure 4. Comparisons of the calculated spectral acceleration and the code spectral acceleration

3. SITE RESPONSE EVALUATION IN PMA

McPherson and Jones (2006) divided PMA into 4 soil classes based on the soil properties, borehole data, seismic cone penetrometer test (SCPT) data and microtremor data. The limestone dominated site is deemed as rock site as the mean shear wave velocity is 900m/s. Other three sites listed in Table 2 are considered with site response analysis in this study. The uncertain soil properties, regolith thickness and shear wave velocities, are assumed to be normally distributed with an assumed coefficient of variation listed in Table 2. The mean value and standard deviation of amplification spectrum and surface ground motion response spectrum are calculated using Monte Carlo simulation method. Detailed site response analyses with consideration of soil nonlinear behaviour are carried out using SHAKE2000. Owing to the lack of nonlinear soil properties in PMA, those derived by Seed and Idriss (1970), Sun *et al*. (1988) and Schnabel (1973) are used in this study to model the nonlinear soil modulus value and damping ratio for sand, clay and rock, respectively. The input bed rock motion shown in Figure 5 and Figure 6 is simulated to match the calculated response spectrum for the 475-year return period.

Table 2. Regolith thickness, shear wave velocities for site classes
(from McPherson and Jones, 2006)

Site Class	Mean thickness (m)	STD thickness (m)	C.O.V.	Mean SWV (m/s)	STD SWV (m/s)	C.O.V
Shallow sand (SS)	20	13	65%	294	43	15%
Deep sand (DS)	42	14	33%	300	82	27%
Mud-dominated (MS)	18	13	72%	330	179	54%

STD: standard deviation, C.O.V.: coefficient of variation; SWV: shear wave velocities.

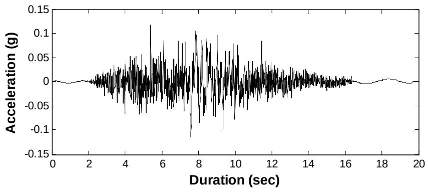

Figure 5. Simulated time history for rock outcropping motion

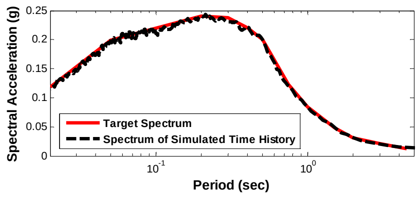

Figure 6. Simulated time history matching the calculated response spectra for 475-year return period

3.1 Monte Carlo Simulation

To investigate the distribution of amplification ratio and surface ground motion spectra, site response of shallow sand site is calculated as an example. The mean value and coefficient of variation of regolith thickness, shear wave velocity listed in Table 2 are adopted for Monte Carlo simulation. A convergence test is conducted to check the number of Monte Carlo simulations required to obtain converged simulation results. The amplification spectrum values at 0.3sec, 1.0sec, 2.5sec and 4.5sec are used as the quantity for the convergence test. It is found that the mean value and standard deviation of the amplification spectrum remained virtually unchanged after 200 simulations. The 200 simulated data for amplification spectrum values at the selected periods all display a lognormal distribution. To verify these observations, a Kolmorogov–Smirnov goodness-of-fit test (K–S test) is carried out. The significance level alpha for the test is 0.01 in this study.

Figure 7 illustrates the density histograms of the amplification spectrum at 0.3sec, 1.0sec, 2.5sec and 4.5sec, and the corresponding lognormal distribution function. All parameters pass the K-S test with a 1% significance level, indicating a good-fit. Table 3 gives the results of Monte Carlo simulation and K-S test.

Numerical results indicated that the amplification spectrum with variation in regolith thickness and shear wave velocities have lognormal type characteristics in Monte Carlo simulation. Since design surface response spectra were obtained by multiplying the bedrock design response spectra by amplitude dependent spectral ratios for a range of structural periods, lognormal distribution of surface ground motion spectrum with variation in regolith thickness and shear wave velocities can be expected. In this study, lognormal distribution of the amplification spectrum and surface ground motion spectrum are assumed.

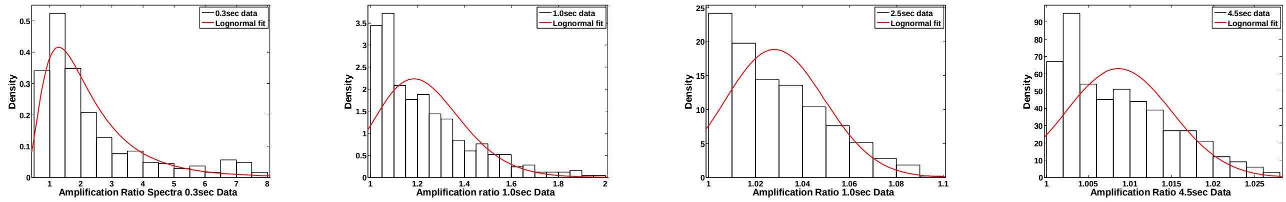

Figure 7. Probability density for amplification spectrum at 0.3sec, 1.0sec, 2.5sec and 4.5sec and the corresponding lognormal distribution function

Table 3. Monte Carlo simulation and K-S test result for amplification ratio spectrum

	Mean	Standard deviation	The test statistic	The critical value
AMP at 0.3sec	2.17	1.45	0.1083	0.1142
AMP at 1.0sec	1.23	0.18	0.1124	0.1142
AMP at 2.5sec	1.03	0.02	0.1137	0.1142
AMP at 5.0sec	1.01	0.01	0.1128	0.1142

3.2 Amplification spectrum and surface ground motion spectrum

Amplification spectrum and surface ground motion spectrum with uncertain regolith thickness and shear wave velocities for three sites listed in Table 2 are calculated using Monte Carlo simulation method. The mean and standard deviation of natural period and amplification for each site are listed in Table 4. Notice that the mean amplification in Table 4 is defined as the mean value of the peak amplification value for each Monte Carlo run. Comparing with the previous study by Gaull (2003), the natural period of SS site is close to that of zone 1, in which the nature period for zone 1 is estimated within the range of 0.1 sec to 0.3 sec and the ground conditions are characterised by sand at shallow depth with mean thickness of 10m. The natural period for zone 2 of deep sand site with mean thickness of 20m to 40m in Gaull (2003) is estimated within the range of 0.3 sec to 0.7 sec. As shown in Table 4, the mean DS natural period calculated in this study is slightly longer than that in Gaull (2003). The natural period of MS site is similar to that in zone 4 around the south of Swan River and the east of Canning River where Gaull (2003) indicated that sediments resonating at between 0.1sec and 0.3sec. It should be noted that the amplification ratio is more than 12 in most of MS sites. This means that the structures with similar natural period (around 0.3 sec) and located on MS sites will suffer more than 12 times of bedrock motions. Figure 8 illustrates the amplification spectrum calculated using Monte Carlo simulation method, mean and mean plus one standard deviation of the simulated data for the sites.

Table 4. Natural period and amplification ratio for each site

Site Class	Mean Natural Period (sec)	STD Natural Period (sec)	Mean AMP	STD AMP
SS	0.37	0.15	6.33	1.10
DS	0.80	0.20	5.56	0.48
MS	0.32	0.26	12.08	3.59

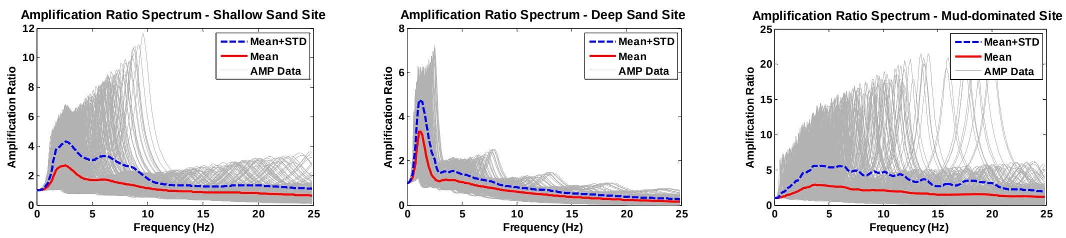

Figure 8. Amplification ratio spectrum

The comparisons of the calculated spectral accelerations and the current code spectral accelerations for shallow sand site are given in Figure 9. As shown, the current design spectra underestimate that from the mean spectral accelerations corresponding to the 475-year return period design event, especially in the period range of 0.1sec to 1.1sec. Spectral accelerations from mean plus one standard deviation exceed code specification in the period below 1.1sec. It means that the structures with natural period less than 1.1sec designed under the current code are more vulnerable to 475-year return period earthquake at SS site.

As can be seen in Figure 10, the current design spectra slightly underestimates the mean spectral accelerations corresponding to the 475-year return period design event in a small range of 0.6sec to 1.2sec.The mean plus one standard deviation spectrum do exceed the current code specification in the range of 0.4sec to 1.4sec. Code spectrum is conservative at this site for period below 0.4sec.

Examining the spectral accelerations presented in Figure 11 reveals that the current code spectral values are significantly lower than those derived from the mean and the mean plus one standard deviation spectra at period below 2sec, indicating that the current code underestimates surface ground motion at this site.

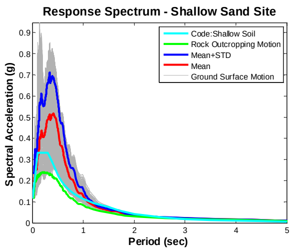

Figure 9. Comparison of SS site response spectrum and the current code spectrum

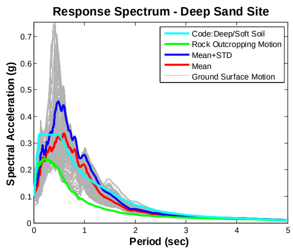

Figure 10. Comparison of DS site response spectrum and the current code spectrum

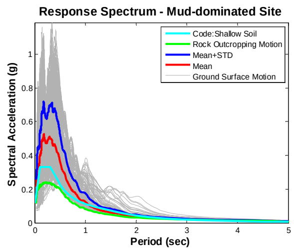

Figure 11.Comparison of MS site response spectrum and the current code spectrum

4. CONCLUSION

A probabilistic seismic hazard assessment has been carried out for PMA. The results of the seismic hazard assessment are presented in terms of horizontal peak ground acceleration and uniform hazard response spectrum for structural periods up to 4.5 seconds for bedrock ground conditions. It is found that PGA on rock site ranges from 0.14g in the north-east through to 0.09g in the south-west for the return period of 475 years. The current code value underestimates PGA in most of the PMA especially to the north-east. The PGA for return period of 2475 years is estimated in the range of 0.24g to 0.36g. From the results of this study it is suggested that the code spectrum for rock underestimates the spectral accelerations at the CBD of Perth in the period range of 0.5sec to 2sec.

The dynamic site response analyses of three typical site classes in PMA are performed. The variations of regolith thickness and shear wave velocities are taken into account by using Monte Carlo simulation method. The comparisons show that the calculated mean spectral values for SS and MS site exceed significantly those of the code spectrum at period lower than 1sec. It indicated that structures with natural periods lower than 1sec are expected to be at the greatest risk of earthquake damage at SS and MS sites.

The parameters for seismic source zones and recurrence relationships employed in this study are still under discussion. For example, the b-Value of 1.0 for all Zones was used in Dhu et al. (2004) and the value of 0.75 for Zone 1 was obtained in Hao and Gaull (2004)'s paper. Michael-Leiba (1986) indicated that earthquake risk calculation does not appear to be stationary as the seismicity in some historic periods does not fit a Poisson distribution. As these parameters are critical in defining the hazard for Perth, it is strongly recommend that a follow-up study to redefine the seismic zone and recurrence rates using the latest seismicity data should be carried out.

REFERENCES

Allen, T. I., Dhu, T., Cummins, P. R. and Schneider, J. F. (2006). "Empirical Attenuation of Ground-Motion Spectral Amplitudes in Southwestern Western Australia," *Bull. Seism. Soc. Am.* **96**, 572-585.

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

Atkinson, G. M. (2004). "Empirical attenuation of ground-motion spectral amplitudes in southeastern Canada and the northeastern United States," *Bull. Seism. Soc. Am.* **94**, 1079-1095.
Atkinson, G. M. and Boore, D. M. (1995). "Ground motion relations for eastern North America," *Bulletin of the Seismological Society of America* **85**, 17-30.

Bender, B. and Perkins, D. M. (1987). "SEISRISK III: A Computer Program for Seismic Hazard Estimation.," *U.S. Geological Survey Bulletin 1772, U.S. Department of the Interior.*

Dhu, T., Sinadinovski, C., Edwards, M., Robinson, D., Jones, T. and Jones, A. (2004). "Earthquake risk assessment for Perth, Western Australia," *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver.

Douglas, J. (2004). "Use of analysis of variance for the investigation of regional dependence of strong ground motions," *Proceedings of Thirteenth World Conference on Earthquake Engineering*.

Everingham, I. B. (1968). "Seismicity of Western Australia," *Bureau of Mineral Resources, Australia***:** *Report 132*.

Gaull, B. (2003). "Seismic parameters for the upper sediments of the Perth Basin," *AGS Symposium*.

Gaull, B. A. and Michael-Leiba, M. (1987). "Probabilistic earthquake risk maps of southwest Western Australia," *BMR Journal of Australian Geology and Geophysics* **10**, 145-151.

Hao, H. and Gaull, B. (2004). "Design earthquake ground motion prediction and simulation for PMA based on a modified ENA seismic ground motion model for SWWA." Mt Gambier, Australia, *Proceedings of the Annual Australian Earthquake Engineering Society Conference*.

Jones, T., Middelmann, M. and Corby, N. (2006). "Natural hazard risk in Perth, Western Australia." Canberra, Geoscience Australia**:** Chapter 5.

Kennedy, J., Hao, H. and Gaull, B. (2005). "Earthquake Ground Motion Attenuation Relations for SWWA," *Proceedings of the Annual Australian Earthquake Engineering Society Conference*, Albury.

Liang, J., Hao, H., Gaull, B. A. and Sinadinovski, C. (2008). "Estimation of strong ground motions in Southwest Western Australia with a combined Green's function and stochastic approach," *Journal of Earthquake Engineering*, 12: 382-405.

Michael-Leiba, M.O. (1986). "Temporal variation in seismicity in the Southwest Seismic Zone, Western Australia: implications for earthquake risk assessment," *BMR Journal of Australian Geology & Geophysics, 10.*
McPherson, A. and Jones, A. (2006). "Appendix D: PERTH BASIN GEOLOGY REVIEW and SITE CLASS ASSESSMENT." *Perth Basin Geology.*

Schnabel, P. B. (1973). "Effects of Local Geology and Distance from Source on Earthquake Ground Motions," University of California, Berkeley, California.

Seed, H. B. and Idriss, I. M. (1970). "Soil Moduli and Damping Factors for Dynamic Response Analysis." *Report No. EERC 75-29, Earthquake Engineering Research Center.* Berkeley, California, University of California.

Sun, J. I., Golesorkhi, R. and Seed, H. B. (1988). "Dynamic Moduli and Damping Ratios for Cohesive Soils." *Report No. EERC 88-15*, University of California, Berkeley.