1. INTRODUCTION

In the past, seismic risk in Western Australia has been considered low since the population was small and quite spread out. However, in recent decades, there has been a lot of earthquake activity just east of Perth in an area known as the South-West Seismic Zone. The most notable of these earthquakes is the 1968 Meckering earthquake that occurred 130km east of Perth and had a Richter magnitude (M_L) of 6.9. This earthquake caused almost total destruction in the small country town of Meckering and moderate damage in the Perth Metropolitan Area (PMA). Compared to 1968, the population of Perth has considerably increased and the types of structures in and around Perth have changed significantly from low-rise masonry buildings in 1968 to the many high-rise RC frame structures present now. If the Meckering Earthquake were to occur today, there would be considerably more damage caused.

Hence, the vulnerability of Perth is increasing and this has led to several investigations into the seismic risk of Western Australia (WA) and the PMA. An important part of risk assessment is the ability to predict the potential ground motion caused by an earthquake at a particular distance from the earthquake source. Ground motion attenuation models are used to do this by calculating peak ground acceleration (PGA) and peak ground velocity (PGV) from the earthquake magnitude and the distance from the earthquake.

There are only a very limited number of strong ground motion (SGM) records available in WA therefore it is not possible to derive a reliable attenuation model using only this data. An attenuation model was developed by Gaull (1988) that was largely based on small magnitude events recorded in WA. Other models used currently in WA were actually developed for eastern North America (ENA) and are used in this state because the geophysical conditions of these two locations are relatively similar.

Although these attenuation models are regularly used in WA, there has not been much study completed to determine how accurate the predictions made by the models are for PGA and PGV in WA. The aim of this study is to discover the most accurate attenuation models for PGA and PGV of strong seismic ground motion on rock sites in WA. This is done by an analysis of the accuracy of the models commonly used for WA, in particular the models proposed by Atkinson and Boore (1997) and Toro *et al.* (1997) for ENA, and Gaull (1988), and others proposed in this paper based mainly on simulated and the limited recorded data.

2. RECORDED SEISMIC GROUND MOTIONS FOR WESTERN AUSTRALIA

To find the attenuation model that best represents WA SGM events on rock sites, existing models were compared to the available WA records. It was decided to use only events from magnitude M_L 4 or above in this analysis. Only 10 of the 14 events available were from rock sites and hence were chosen to minimise variation due to site effects. Table 1 lists these records in order of occurrence. As can be seen in the table, the epicentral distances range from 6 to 96 km. Three components of PGA and PGV are given, east-west, north-south and vertical.

No.	M_L	Epicenter	Epicenter Distance [km]	Depth [km]	Site Condition	PGA [mm/s^2]			PGV [mm/s]		
						EW	NS	Vertical	EW	NS	Vertical
1	6.2	Cadoux	87	6	hard granite outcrop	150	128.11	93.28	6.63	4.13	6.81
2	6.2	Cadoux	93	6	thin alluvium granite	293.06	305.67	245.46	19.34	21.08	27.18
3	6.2	Cadoux	96	6	thin alluvium granite	219.94	170.25	148.61	26.9	12.21	10.03
4	4.5	Cadoux	6	5	weathered bedrock	2611.88	2888.38	920.83	27.63	27.81	15.69
5	4.5	Cadoux	8	5	granite outcrop	1542.69	1008.33	938.89	26.14	11.39	9.28
6	4.5	Cadoux	13	5	weathered bedrock	439.21	473.5	558.33	9.73	8.85	10.54
7	5.5	Meckering	78	6	hard granite outcrop	98.71	26.13	31.41	1.38	0.54	0.59
8	4.5	Cadoux	70	2	hard granite outcrop	71.56	48.75	39.19	0.73	0.42	0.42
9	4.1	Meckering	25	6	hard granite outcrop	138.75	116.02	47.8	1.2	0.65	0.29
10	4.1	Meckering	90	6	weathered bedrock	5.51	12.57	8.04	0.16	0.29	0.11

Table 1 Recorded ground motions in WA

In some studies, amplification factors have been used to normalize the data; however there is not much certainty of amplification factors for Western Australia sites and therefore the results could be unreliable. In a study by Gaull (1988) it was found that the amplitudes at alluvial sites were about twice that on other sites of similar distance from an earthquake epicenter. Therefore, amplification factors were chosen not to be used in this study.

3. EXISTING ANTENUATION MODELS USED IN WESTERN AUSTRALIA

This study compares the values from the WA records in Table 1 with three commonly used attenuation equations for PGA and PGV in Australia. These include an equation developed by Toro *et al.* (1997) for PGA and equations for PGA and PGV presented by Atkinson and Boore (1997) for ENA, and the equations for PGA and PGV for WA developed by Gaull (1988).

Different types of distances are used in the models: R represents the epicentral distance in kilometers, R_{hypo} is the hypocentral distance and R_{slant} is the slant distance (taken to equal to hypocentral distance in this paper) both in kilometers. M_w is the moment magnitude of an earthquake and M_L is the Richter scale magnitude.

As there are so few records available for WA, it is common to turn to models used in other areas of similar geophysical features. In this study the ENA relationships by Toro, et al. (1997) and by Atkinson & Boore (1997) are analysed for their accuracy in estimating SGM in WA. Geoscience Australia has completed some research on the use of models from ENA in WA, although no recommendations could be provided as to which, if any, (ENA) model would be most appropriate for Australian conditions (Dhu et al., 2004).

Ground motion attenuation equations for PGA have been developed by Toro, et al. (1997) for rock sites in the mid-continent of ENA (Equation 1) and the Gulf of ENA (Equation 2). The PGA models have been based on the predictions of a stochastic model for source excitation and a model of path effects that considers multiple rays in a horizontally layered model of the crust. These models were derived from ENA rock site data from earthquakes of moment magnitude 4 or more over distances less than 200km and other relevant data.

$$\ln PGA = 2.2 + 0.81(M_W - 6) - 1.27 \ln R_M - (1.16 - 1.27)\max\left[\ln\left(\frac{R_M}{100}\right), 0\right] - 0.0021 R_M \qquad \text{[g]} \tag{1}$$

$$R_M = \sqrt{R^2 + 9.3^2}$$

$$\ln PGA = 2.91 + 0.92(M_w - 6) - 1.49 \ln R_M - (1.61 - 1.49)\max\left[\ln\frac{R_M}{100}, 0\right] - 0.0014 R_M \qquad \text{[g]} \tag{2}$$

$$R_M = \sqrt{R^2 + 10.9^2}$$

The quadratic equations by Atkinson and Boore (1997) were derived by regression of a subset of simulated ground-motion data for ENA. The simulation was performed using a stochastic prediction model of the earthquake source spectrum. The subset of data included hypocentral distances of up to 500km for events of moment magnitude greater than 6.5 but only near distances of up to 25km for smaller events to 4.5 moment magnitude. The Atkinson and Boore (1997) attenuation equations are as follows:

$$\ln PGA = 1.841 + 0.686(M_w - 6) - 0.123(M_w - 6)^2 - \ln R_{hypo} - 0.00311 R_{hypo} \qquad \text{[g]} \tag{3}$$

$$\ln PGV = 4.697 + 0.972(M_w - 6) - 0.0859(M_w - 6)^2 - \ln R_{hypo} \qquad \text{[cm/s]} \tag{4}$$

The attenuation relationship by Gaull (1988) is one of the few models developed for southwest WA (SWWA) using actual WA recordings. Only about 10% of the 200 events in the database at that time were digitised and included in the analyses. Because periods less than 0.1 s are not generally of engineering significance, the chosen time-histories were band-pass filtered and corresponding amplitudes measured. Hence, the resultant equation (5) represents estimates of PGA’s in the period band of 0.1-0.5 s and is intended for events of magnitudes M_L 4.5 to 7 and slant distances varying from 5km to 200km. Five PGA observations from the ML6.2 Cadoux earthquake and two mathematically estimated observations based on ringing bell and over toppling of structures in Perth during the Meckering earthquake were used to assist with amplitudes in the upper magnitude range. The PGV equation (Equation 6) is recommended for earthquakes of M_L 2 to 6.3.

$$\log PGA = \left[\frac{5\log R_{slant} + 3}{20}\right](M_L - 6) - 0.77\log R_{slant} - 0.0045 R_{slant} + 1.2 \qquad [\text{m/s}^2] \tag{5}$$

$$\log PGV = 0.6 M_L - 1.14 \log R_{slant} - 0.005 R_{slant} - 0.33 \qquad \text{[mm/s]} \tag{6}$$

4. DEVELOPMENT OF NEW ATTENUATION EQUATIONS

The database of SGM recordings in tectonically stable regions such as WA is still too sparse to permit the development of empirical attenuation relations based purely on recorded data. A relationship derived from only this data will be highly biased and unreliable. Therefore, to be able to create a new attenuation relationship for WA, more SGM recordings would be needed.

To supplement the existing records for WA, PGA and PGV were extracted from the ground motion time histories simulated using a modified SWWA ground motion model (Hao & Gaull, 2004). This model was derived by modifying the Atkinson and Boore Model (1995) as it was found best predicting the limited available strong ground motion records in WA. The model was modified to best fit the available strong ground motion records in WA (Hao & Gaull, 2004). In this study, simulations of ground motions for earthquake events of Richter scale magnitudes of 4 to 7.5 in 0.5 magnitude-unit increments were carried out. For larger magnitudes (6 to 7.5) the distance range was up to 200km and for smaller magnitudes (4 to 5.5) the distance range was only to 100km. This constrains the attenuation to match the relative slow decay of motions that is applicable for larger earthquakes. It has been proven that the simulations of strong motion time histories can give reasonable predictions of available WA seismic motion records (Hao & Gaull, 2004) and therefore the database used to derive the models is reliable. Twenty simulations for each magnitude-distance combination were carried out. The averages of the PGA and PGV for each magnitude-distance combination simulation were evaluated. These averages were then used with the values of PGA or PGV of the WA records to find the best fitting regression model.

It is practical that for engineering application an equation for the prediction of SGM should be in relatively simple form and easy to apply. Ground motion is affected by both the earthquake magnitude and distance; hence these should be the independent variables in the equation for PGA and PGV. The suggested best fitting equations in this study are:

$$\ln PGA = 8.985 + 0.708 M_L - 3.373 \ln R + 0.215 \ln R^2 + 0.1 M_L \ln R \qquad [\mathrm{mm/s^2}] \qquad (7)$$

$$\ln PGV = 4.174 + 1.27 M_L - 4.374 \ln R - 0.071 {M_L}^2 + 0.325 \ln R^2 + 0.181 M_L \ln R \qquad [\mathrm{mm/s}] \qquad (8)$$

5. COMPARISON OF MODELS TO WESTERN AUSTRALIAN RECORDS

To evaluate how well the new attenuation models predict the WA records when compared to the existing models, all models were plotted with the records and comparisons were made from the results of how well the new model fit the data.

It should be noted that Table 2 has been taken directly from the original study (Kennedy, 2004), in which direct comparison was made with Gaull's attenuation relationship (Equation 5) without considering the period bands of the original relationship. A correction of the PGA's so that the period constraint discussed in the text above is taken into account will be pursued in a later publication. When this correction is carried out, the residuals, especially for events with low slant distances, may be greatly reduced.

	Toro et al. (Mid-continent)	**Toro et al. (Gulf)**	**Atkinson and Boore**	**Gaull**	**NEW MODEL**
average residual	90.64	284.07	-287.34	245.70	**89.17**
average residual (using absolute values)	305.43	254.73	535.12	292.92	**129.08**
residual sum of squares	5340478	10862713	4443342	8409067	**1264849**
error variance	314145	638983	261373	494651	**74402**
standard error of the estimate	560.49	799.36	511.25	703.31	**272.77**
R^2	0.61	0.20	0.67	0.38	**0.907**
percentage error (using absolute values)	145.90	101.77	331.80	56.93	**50.23**

Table 2 Summary of comparison results for PGA models

Figure 1 shows the new model plotted with the WA records. The new model presents better results for average residual (using actual residuals and absolute value of residuals), smaller residual sum of squares and lower percentage error than all of the existing models. The model also shows that it delivers a better explanation of the variation in the PGA of the records with a coefficient of determination of close to one. The standard error of the estimate of this model is closer to zero than for any other model, which means it most accurately describes the data.

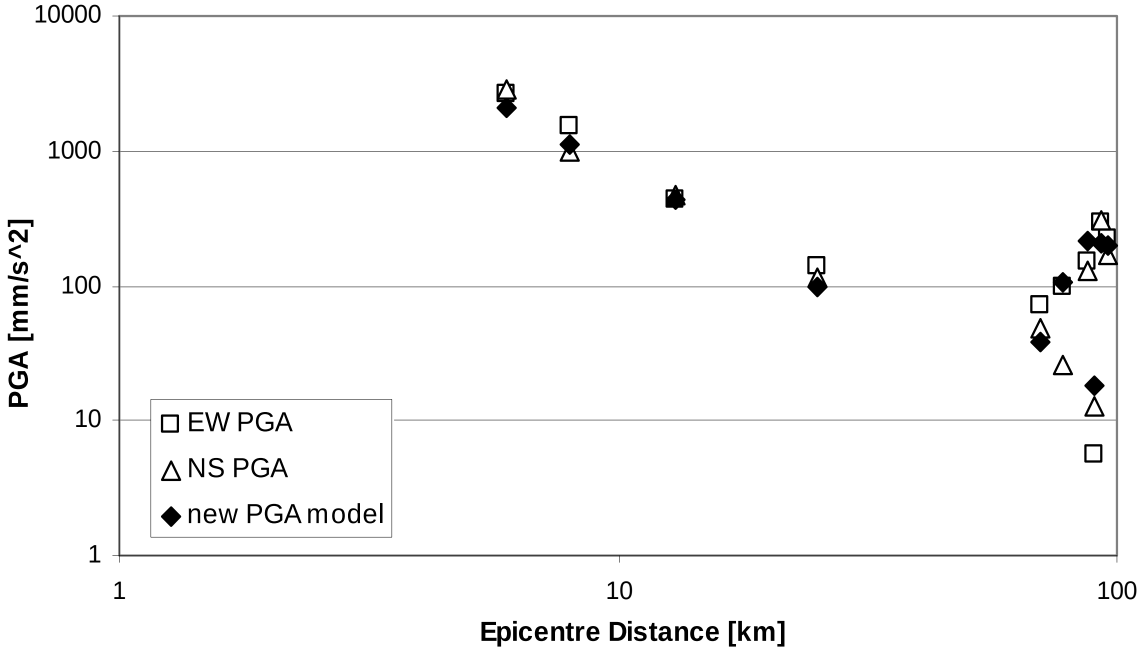

Figure 1 WA records plotted with predictions from the new PGA model

Table 3 presents a summary of the results of tests carried out to assess the goodness of fit of each PGV model for the WA records:

	Atkinson and Boore	**Gaull**	**NEW MODEL**
average residual	-2.17197	3.607288	**5.15**
average residual (using absolute value)	5.222365	5.051215	**5.32**
residual sum of squares	805.3894	1284.919	**1512.84**
error variance	44.74385	71.3844	**88.99**
standard error of the estimate	6.689085	8.448929	**9.43**
R^2	0.62242	0.397608	**0.29**
percentage error (using absolute values)	289.6576	77.17855	**35.20**

Table 3 Summary of comparison results for PGV models

Figure 2 shows plots of the predictions of the new PGV model with the WA records. This figure shows that the new model underestimates most of the WA records. Compared to the other models used for PGV hazard analysis, the new model presented the lowest average percentage error for the predictions of the available WA records, therefore providing the closest estimates of the records. However, the predictions of the model by Atkinson & Boore (1997) for the WA records displayed evidence that this model is able to explain a higher proportion of the variation in the values of the records and describes the data more accurately.

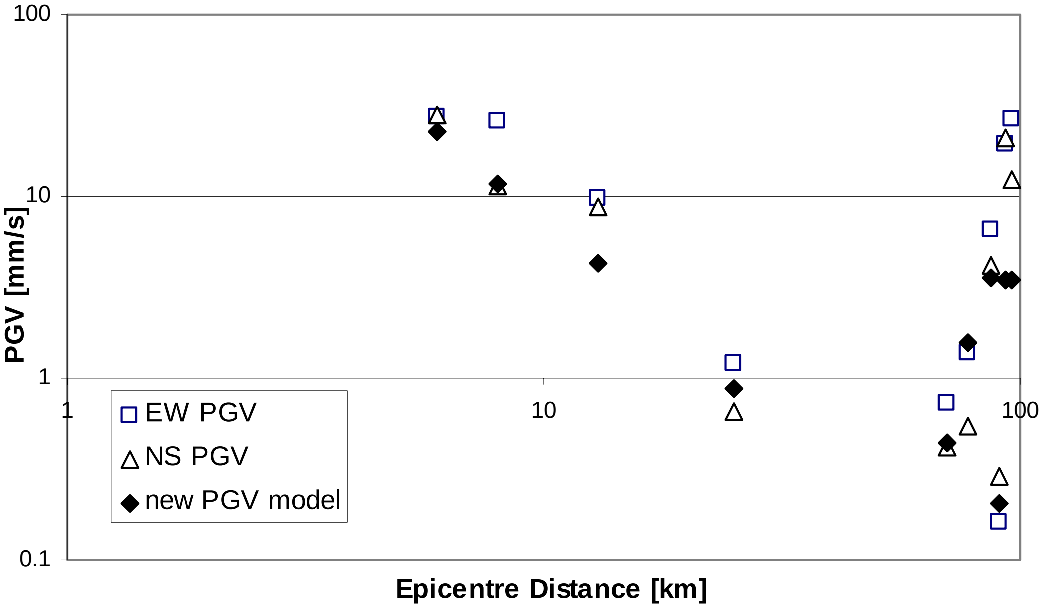

Figure 2 WA records plotted with predictions from the new PGV model

6. CONCLUSIONS

Four existing PGA attenuation models were tested against the available WA records. It was found that the models for PGA currently used in WA do not provide a sufficient level of accuracy to be used confidently for hazard analysis when the values predicted by these models were compared to the records. Two attenuation models for PGV were also analysed for their accuracy in predicting the WA records. Likewise, neither models provided predictions for the WA records with a high enough level of accuracy to be used confidently for hazard analysis in WA.

Supplementing the WA records with the results of the simulations of SGM provided a large database from which to derive new attenuation models for SGM on rock sites in WA. As there are only ten such records available for WA, no other attenuation model used in WA currently has been derived using the same size database of SGM events from WA.

The model for PGA derived from this database provides an excellent fit for the data. Predictions of the WA records listed in Table 1 also provided a reasonably accurate estimate. When these predictions were compared to those of the existing PGA models used in WA currently, the new model, on average, proved to offer more accurate results. Therefore, from the results of these comparisons of the new model to the PGA models currently used in Western Australia, it is concluded that the new PGA model provides the best approximation for strong motion events on rock sites in WA.

The conclusion from the results of the PGV models is that the new model provides the closest predictions for PGV in WA on rock sites and is therefore recommended for hazard analysis in WA. There is, however, recommendation of further study into adjusting the model by Atkinson & Boore for PGV for use in WA as this model provides the best description of the attenuation of PGV in WA out of all the models studied. Using different coefficients in this model to scale the predictions down may yield closer estimates of the WA records.

7. REFERENCES

Atkinson, GM and Boore, DM (1997) Some Comparisons between Recent Ground-Motion Relations, Seismological Research Letters 68(1), pp 24-40.

Atkinson GM and Boore DM (1995) New ground motion relations for eastern North America, Bull. Seism. Soc. Am., Vol. 85, pp17-30.

Dhu, T., Sinadinovski, C., Edwards, E., Robinson, D., Jones, T. & Jones, A. (2004) Earthquake risk assessment for Perth, Western Australia, 13th World Conference on Earthquake Engineering, Canada, paper no. 2748.

Gaull, B (1988) Attenuation of Strong Ground Motion in Space and Time in southwest Western Australia, Proceedings, Ninth WCEE 2, pp 361-388.

Hao, H. and Gaull, B (2004) Prediction of Seismic Ground Motion in Perth Western Australia for Engineering Application, 13th World Conference on Earthquake Engineering (Paper No. 1892).

Kennedy, J (2004) Prediction of Strong Ground Motion in Western Australia, Honors Year Thesis, School of Civil and Resource Engineering, The University of Western Australia

Toro, G, Abrahamson, N and Schneider, J (1997) Model of Strong Seismic Ground Motions from Earthquakes in Central and Eastern North America: Best Estimates and Uncertainties, Seismological Research Letters 68 (1), pp 41-57.