SEISMIC ATTENUATION MODELLING FOR MELBOURNE BASED ON THE SPAC-CAM PROCEDURE

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ABSTRACT:

A pilot study conducted in Melbourne involving shear wave velocity (SWV) profiling in the bedrock formation is used to illustrate a new approach for predicting the potential seismic attenuation characteristics for the region. A complete SWV profile for the entire seismogenic depth of the earth's crust is first developed by combining the SWV profiles measured by the Spatial Auto-Correlation (SPAC) method with regional information provided by a global crustal database. Secondly, the crustal amplification function calculated from the representative SWV profile is combined with predicted attenuation parameter values (*kappa* κ and Q_0) to form a complete filter function representing the potential wave modification characteristics of the earth's crust in the area. Thirdly, a seismic attenuation model is developed by combining this filter function with the source function of the earthquake, using a stochastic procedure and the framework of the Component Attenuation Model (CAM). Lastly, the developed attenuation relationship is compared with seismic Intensity information obtained from three historical earthquakes that affected Melbourne and its surrounding region. The modelling described in this paper only deals with seismic wave modifications within the bedrock formation whilst modifications within the soil sedimentary layers are to be addressed in separate analyses.

1. INTRODUCTION

A passive seismological monitoring technique termed the Spatial Auto-Correlation (SPAC) method has been used to measure shear wave velocity (SWV) profiles down to a depth of some 100 metres into Silurian mudstone around the Melbourne area. Seven surveys were carried out on five sites in different suburbs to develop an average SWV profile for bedrock formations in the area. The companion paper (Roberts *et al.*, 2004) presents details of the surveys including geometries of the geo-phone configurations, measured auto-correlation spectra, theoretical spectra which match with the measured spectra, and the predicted SWV profiles.

In this paper, the typical SWV profiles obtained in the companion paper have been used to develop a seismic attenuation relationship for the city and its suburbs. A complete SWV profile for the entire seismogenic depth of the earth's crust has been developed by combining the representative SWV profile measured by SPAC with regional information provided by the Global Crustal Model: CRUST2.0 (2001). A set of crustal amplification functions so calculated from the representative SWV profile has then been combined with predicted attenuation parameter values (*kappa* κ and Q_0) to form a set of complete filter functions representing the potential wave modification characteristic of the earth's crust in the area. Artificial accelerograms were generated by stochastic simulations based on combining these filter functions with the seismic source function. Velocity response spectra have been computed using the ETAMAC computer program, for a series of magnitude-distance (M-R) combinations, to develop a response spectrum attenuation relationship for the surveyed region. It is noted that the analysis methodology presented herein is based on de-coupling the modification effects of the bedrock from that of the overlying soil sediments. Only mechanisms occurring within the bedrock are addressed in this paper.

The developed attenuation relationship is then presented in terms of the peak ground velocity (PGV) for comparison with values inferred from Modified Mercalli Intensity (MMI) data of three historical earthquakes that affected Melbourne and its surrounding region from long distances, and with magnitudes ranging between 5 and 6.5.

It is noted that the field surveys undertaken so far have been very limited. Thus, the information presented are insufficient to constitute a representative sample for an area. The objective for this paper is to introduce the modelling approach using the pilot study for illustration purposes.

2. CRUSTAL SHEAR WAVE VELOCITY (SWV) PROFILES

Figure 1 summarises all the bedrock SWV profiles obtained in the companion paper (Roberts *et al.*, 2004). A complete representative SWV profile of the earth's crust down to a depth of 8 km has been developed using the procedure described below. Since the effects of the soil sediments are excluded from the modelling and considered in separate analyses, the profiles presented herein are purely within bedrock whilst the upper (soil sedimentary) part of the original profiles have been removed.

On a global scale, the thickness of the upper sedimentary layer can be in the order of tens of metres to a few kilometres. In the region surrounding Melbourne, the thickness of the upper sedimentary layer Z_s has been determined as 500 m using CRUST 2.0(2001), which is also considered as the depth to the surface of the crystalline crustal rock layer Z_C. According to the model SWV profile developed by Chandler *et al.* (2004a), referred herein as the "Chandler's SWV model", the SWV (V_s) variation in the Upper Sedimentary Layer can be expressed in the form shown by equation (1).

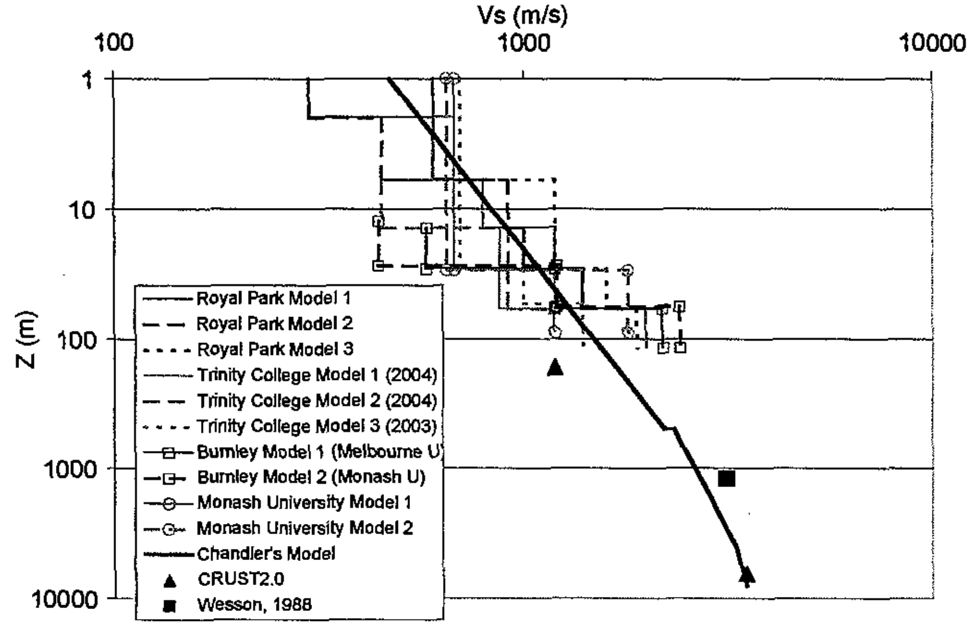

Figure 1 Shear wave velocity (SWV) profiles for the Melbourne area

$$V_{s,C}(Z) = V_{s,30}\left(\frac{Z}{30}\right)^{\frac{1}{4}} \tag{1}$$

In order to obtain the value of $V_{s,30}$, the following formula is proposed

$$\sum\left[\log\left(V_{s,i}(Z_i)\right) - \log\left(V_{s,C}(Z_i)\right)\right] = 0 \tag{2}$$

where $V_{s,i}(Z_i)$ is the SWV at the mid-depth Z_i of each layer from each velocity profile model, whilst subscript "*C*" denotes Chandler's SWV Model. There are a total of 10 SWV profile models as shown in the above figure with some 46 data points within the upper 100 m. (The depth 100 m is considered to be highly reliable when using the SPAC technique). Using the proposed methodology, $V_{s,30}$ is determined as 1100 m/s.

Together with the regional information obtained from CRUST2.0, $V_{s,8000}$ = 3500 m/s, the complete representative bedrock SWV profile can be obtained using the proposed modelling methodology. Hence,

Upper Sedimentary Layer: $V_{s,C}(Z) = 1100\left(\frac{Z}{30}\right)^{\frac{1}{4}}$ $\quad Z < 500m$ (3a)

Transition Layer: $$V_{s,C}(Z) = 3304\left(\frac{Z}{4000}\right)^{\frac{1}{6}} \qquad 500m < Z < 4000m \qquad (3b)$$

Crystalline Crustal Layer: $$V_{s,C}(Z) = 3500\left(\frac{Z}{8000}\right)^{\frac{1}{12}} \qquad 4000m < Z \qquad (3c)$$

The proposed SWV model belongs to the same class of model pioneered by Boore & Joyner (1997) which is based on de-coupling amplification effects of the SWV gradient from co-existing attenuation effects arising from energy absorption mechanisms which include wave scattering.

3. DEVELOPMENT OF A REGIONAL SEISMOLOGICAL MODEL

The representative SWV profile modelled in Section 2 has been used to develop a filter function for the earth's crust. This filter function characterising the "path" effects comprises the following four component factors:

(i) Upper crustal amplification factor *V(f)*
(ii) Upper crustal attenuation factor *P(f)*
(iii) All path attenuation factor *Q(f)*
(ii) Mid crustal amplification factor γ_{mc}

In addition to the enlisted factors, the adopted seismological model has also accounted for factors representing the effects of geometrical attenuation, free-surface amplification, energy partitioning and radiation pattern. Refer Lam et al (2000b) for a review of the seismological model.

The upper crustal amplification factor can be approximated by the "quarter wave-length" rule (Boore and Joyner, 1997) based on the principle of conservation of energy:

$$V = \sqrt{\frac{\rho_A V_A}{\rho_B V_B}} \qquad (4)$$

where ρ_A, ρ_B, V_A and V_B are the densities and SWV respectively, for the media through which shear waves propagate (from medium A to B). A shear wave velocity gradient will result in waves with shorter wave-lengths (ie. higher frequency wave components) being amplified more according to equation 4. The correlation of the amplification factor V with frequency is shown in Figure 2 (refer thin broken line). An increase in the value of V with increasing wave frequency is noted.

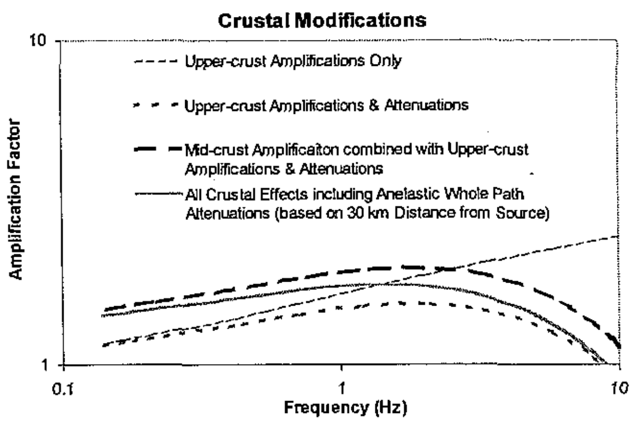

Figure 2 Crustal amplification and attenuation functions for Melbourne area

The upper crustal attenuation factor, which represents the attenuation of waves in the upper 4 km of the earth's crust, is defined by equation (5) (Atkinson and Silva, 1997):

$$P(f) = e^{-\pi f \kappa} \tag{5}$$

where the parameter κ (*kappa*) can be measured from analysis of the Fourier transform of seismic waves recorded from the very near-field (Anderson and Hough, 1984). Recommendations for the value of κ have been made for California, British Columbia and various regions in Europe (as summarized in Chandler *et al.* 2004b), but information available in regions of low and moderate seismicity around the world remains very restricted. In view of this and difficulties in capturing near-field data, a model which relates the κ parameter and the SWV of the earth's crust has been developed by Chandler *et al.* (2004b), and is referred herein as the Chandler's Kappa Model. This model was developed from empirical curve-fitting in conjunction with analytical modelling and is based on the premise that the lower the SWV of the earth's crust, the higher the level of energy absorption. Factors affecting the value of κ other than SWV are manifested by scatter in the correlation (refer Figure 3). According to Chandler's Kappa Model, a κ value of 0.033 is inferred by a SWV of $V_{s,30}$ = 1.1 km/sec. Substituting κ = 0.033 into equation (5) gives the frequency-dependent crustal attenuation function, which is combined with the amplification function obtained above.

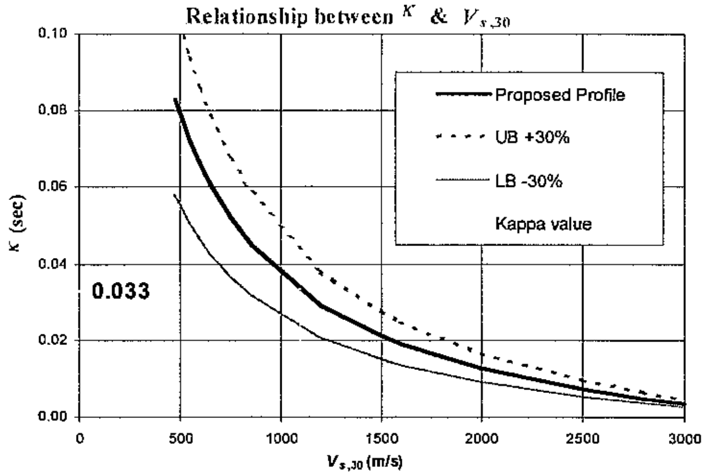

Figure 3 Determination of the κ parameter (after Chandler *et al.* 2004b)

Next, the whole path attenuation factor *An(f)* which is defined by equation (6) is considered.

$$An(f) = e^{-\frac{\pi f R}{Q\beta}} \tag{6}$$

In the study by Chandler *et al* (2004b), Q_o (Q at 1 Hz) is estimated at 278 based on the measured SWV. This estimated value for Q_o is interestingly comparable to the value of 204 estimated for California (Atkinson and Silva, 1997). The *Q(f)* function for Melbourne is then defined by equation (7) with the exponent value of "0.6" estimated in accordance with the recommendations by Mak *et al* (2004) :

$$Q(f) = 278(f)^{0.6} \tag{7}$$

Substitution of equation (7) into equation (6) gives the estimated whole path attenuation factor for the Melbourne region (refer Figure 2). Finally, the mid-crustal amplification factor for SWV of 3.5 km/sec at the source of the earthquake (taken at 5 - 8 km depth) is estimated at 1.3 (Lam *et al.* 2000a). Each of the filter functions representing various crustal modification effects are shown in Figure 2, along with the combined filter function which accounts for all crustal effects (but not including geometrical attenuation).

4. STOCHASTIC GROUND MOTION SIMULATIONS

The crustal filter function developed in Section 3 has been combined with the generic intraplate source model of Atkinson (1993) to define the frequency contents of future earthquakes affecting the Melbourne area. Artificial accelerograms were simulated stochastically using the computer program GENQKE (Lam *et al.* 2000b). The response spectra calculated from some 18 accelerograms with random phase angles were averaged for a series of magnitude-distance (M-R) combinations, as shown in Figure 4.

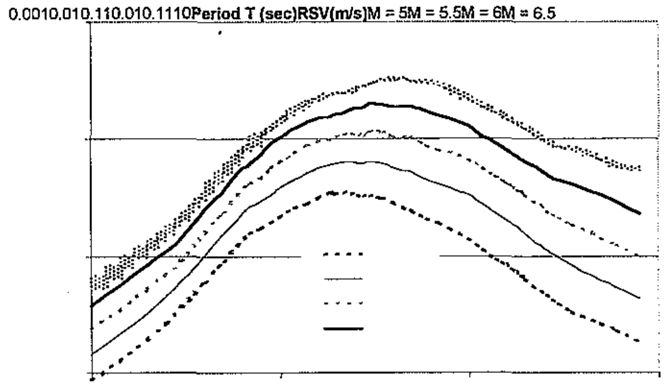

Figure 4 Response spectra for a series of M-R combinations (R=30km)

Finally, the attenuation relationship developed for Melbourne using the SPAC-CAM methodology presented in this paper is shown in terms of the peak ground velocity (PGV) in Figure 5. The PGV was taken as the highest response spectral velocity divided by 1.8 according to Wilson and Lam (2003) citing the work of Somerville *et al* (1998). Superimposed onto Figure 5 are PGV's inferred from MMI data of three historical earthquakes which affected Melbourne (McCue, 1995). Refer legend in Figure 5 for details. The transformation from MMI to PGV (mm/sec), was based on recommendations by Newmark and Rosenblueth (1972) as defined by equation (8).

$$2^{MMI} = \frac{7}{5} PGV \ \textit{(PGV in mm)} \qquad (8)$$

It is shown in Figure 5 that the recorded (and inferred) PGV's and the modelled PGV's have discrepancies by a factor of 1.2-1.7 at 100km distance (which is equivalent to approximately half an *MMI* unit). Such discrepancies can be explained by the fact that the modelled PGV's are based on rock conditions whereas the PGV's inferred from MMI data refer to average site conditions. The objective of comparing the two sets of data is simply to show that they do not contradict in terms of order of magnitude.

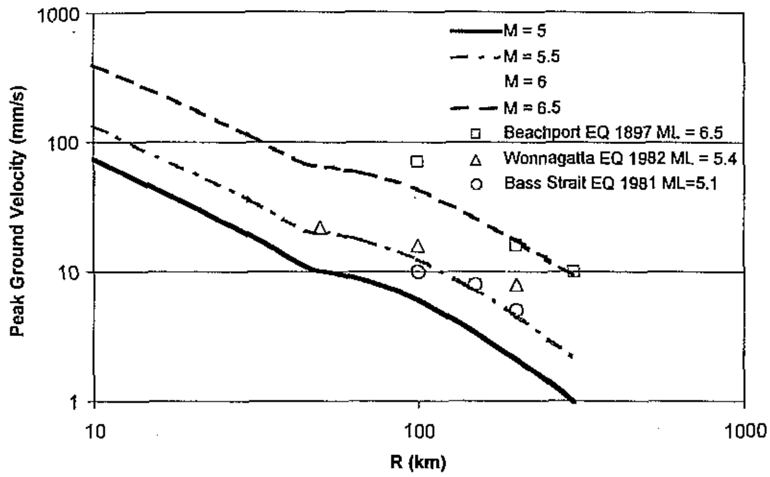

Figure 5 Peak Ground Velocity (PGV) attenuation relationship developed for Melbourne

5. CONCLUSIONS

- A pilot study is described in this paper to illustrate a new approach for determining the SWV profile for the bedrock formation in an area. Field measurements using SPAC technique were used in conjunction with seismic refraction data reported for the Melbourne area and subsequently incorporated into the Global Crustal Model.
- Crustal amplification factors were calculated from the modelled representative SWV profile using the quarter-wavelength rule and attenuation functions calculated in accordance with correlations developed for the κ and Q_0 parameters.
- Filter functions characterising the crustal amplification and attenuation effects in the bedrock formation were obtained.
- Artificial accelerograms (hence response spectra) were then generated by stochastic simulations based on the calculated filter functions to develop a PGV attenuation relationship for average rock sites in Melbourne. The developed relationship does not contradict with inferences from historical MMI data.

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