Peak Ground Velocity Modelling for Australian Intraplate Earthquakes

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ABSTRACT: *Modelling the attenuation of peak ground velocity for intraplate earthquakes in Australia is faced with numerous challenges including the lack of quality instrumental earthquake data from close distances. Furthermore, the significant variation in the crustal conditions within the Australian continent means that more than one attenuation relationship is required to suit different conditions even though the entire continent is wholly within the Indo-Australasian tectonic plate. The modelling approach adopted in this study is based on a convenient separation of the source, crustal and path attenuation effects in the modelling. Each of these effects is represented by separate component factors. The accuracy of this Component Attenuation Model (CAM) was evaluated using historical Intensity data collected in Australia over the past one hundred years. It can be shown by the analysis of the residuals that CAM provides better predictions of the Intensities and peak ground velocities than a number of commonly used attenuation models. Most recorded Intensity values are in agreement with the CAM calculations within 0.5 Intensity units.*

Keywords: Intraplate; Australia; Attenuation; Intensities; Component Attenuation model

1. Introduction

The design response spectrum in the current Australian earthquake loading standard [1] is scaled in accordance with the design peak ground velocity (*PGV*) estimated for a return period of around 500 years. Thus, modelling the attenuation of the peak ground velocity is a key element in the development of the seismic hazard model for Australia. Modelling by conventional regression analysis cannot be applied directly in an intraplate region such as Australia due to the paucity of strong motion earthquake data. A reasonable amount of seismological data has been collected from instrumentation of earthquake tremors in different parts of Australia. However, there are difficulties in extrapolating ground motion properties for a large earthquake event from observations of small events [2]. Consequently, response spectrum models for these regions are typically based on overseas codified models (refer commentary in Ref. [1]) or attenuation models such as those developed by Toro [3] and Sadigh [4]. The choice of a "suitable" model requires experienced seismologists to exercise judgement based partly on the comparison with data recorded locally (typically from small earthquake events and tremors). The development of such attenuation models for Australia have been developed in a somewhat *ad-hoc* and often non-transparent manner with a significant amount of "judgement".

The significant variation in the crustal conditions within the continent (as reported in Dowrick [5]) means that more than one attenuation relationship is required to suit different conditions even though the entire continent is wholly within the Indo-Australasian tectonic plate. Thus, the well known attenuation relationships developed from Central and Eastern North America are not automatically suitable for all intraplate situations.

Recommendations developed from a non-transparent process can lead to problems in code development and implementation. Addressing this, code recommendations for Australia have been presented recently in a more transparent format [6]. The global trend in earthquake engineering towards a performance-based approach is associated with the need for a better understanding of both seismic hazard and system behaviour.

The modelling approach adopted in this study is that the source effects (Section 2), the crustal effects (Section 3) and the path attenuation effects (Section 4) are addressed as separate components based on the concepts developed in Refs. [7-10]. The *PGV's* on rock sites for any given earthquake magnitude, distance and crustal conditions could be predicted by taking the product of the source factor, crustal factor, geometrical factor and anelastic attenuation factor (i.e. $\alpha.\gamma.G.\beta$) as shown by Eq. (1).

$$PGV(mm/sec) = \alpha(M).G(R,D)\beta(Q,R,M). \gamma\,(Crustal\ Type) \quad (1)$$

where M is the moment magnitude, R is site-source distance, D is depth to Moho, Q is Quality Factor.

Each of these factors will be described in the rest of the paper under separate headings. This framework of predicting ground motion parameters is known as the Component Attenuation Model (*CAM*) which was first introduced in Ref. [9]. A multitude of attenuation models developed overseas have been used as reference to assist in the modelling of the component factors to suit different conditions within the continent. Local Modified Mercalli Intensity (*MMI*) data has also been used in developing and verifying the model. In fact, such Intensity information from iso-seismal maps has been used in the past in developing local attenuation models (e.g. Gaull [11]) which is referenced in this paper. The *PGV's* predicted using the *CAM* factors will be compared with a range of earthquake data including *MMI* data extracted from iso-seismal maps of historical events (Section 5), observations from the well publicized 1989 Newcastle earthquake [12] (Section 6) and with a few available instrumental recordings of engineering significance $M \geq 5$, Section 7.

2. Source Factor (a)

The source factor (α), which is in "*mm/sec*", is defined by Eq. (2).

$$\alpha(M) = (70/c)\,(0.35+0.65(M-5)^{1.8}) \quad (2)$$

where c is the ratio of the maximum response spectral velocity and the peak ground velocity and was taken to be equal to 1.8 in the study.

The source effect defined by the α factor is the peak ground velocity estimated at a reference hypocentral distance of 30*km* based on the generic "hard rock" crustal condition defined in Ref. [13] for Central & Eastern North America (*CENA*). The shear wave velocity of this "hard rock" crust is approximately 2800*m/sec* at 30*m* depth and is increased slightly to 3000*m/sec* at 300*m* depth. The crustal condition of *CENA* has been used as the reference condition as seismic waves are subject to less crustal attenuation and modification in such conditions compared with other conditions. Geological conditions similar to *CENA* could be found in Western Australia and in the Scandinavian Peninsular which are both characterized by hard crustal conditions of ancient (Pre-Cambrian) geological formation. Corrections to the estimated source effects would be needed for different crustal conditions as described in Section 3. The use of 30*km* as the reference hypocentral distance is to avoid complications associated with near-fault effects which are normally beyond considerations in regions of low and moderate seismicity.

Modelling for intraplate earthquake ground motions were pioneered in *CENA* where various seismological models were developed [3,14-18]. The source effects as defined above have been predicted by stochastic simulations [8, 9] of the Atkinson source model [15] and the Toro model [3] based on *CENA* conditions. These predictions are listed in Table (1) along with similar predictions by Dahle

Table 1. PGV (mm/sec) predicted at 30km distance for hard rock conditions.

Magnitude	Stochastic Simulations of the Atkinson Source Model for CENA (This Study) Ref. [7] Provides a Summary	Toro Model for Inner-Continental Region of CENA [3]	Dhale Model for Scandinavian Peninsular [19]	Gaull Model for Western Australia [11]
5	12-13	12-13	10-11	11-12
5.5	19	20-21	18	19-21
6	35	38-39	33-34	32-36
6.5	60	75	63	53-59

[19] for the Scandinavian Peninsular and by Gaull [11] for Western Australia. Predictions by the latter model were based on modified Mercalli Intensity (*MMI*) data. The conversion from *PGV* to *MMI* was based on the equation, 2*MMI* = 7/5 *PGV* (*mm/sec*), recommended by Newmark and Rosenblueth [20]. It is inferred from the model that a unit increase in *MMI* corresponds to a two-fold increase in the *PGV*. A correction factor has been applied to allow for the difference between the condition of an "average site" implied in the *MMI* data analysed by Gaull [11] and that of a reference "hard rock" site. This correction factor is estimated to be between 1.8 and 2.0.

The adopted *MMI-PGV* conversion equation is compared in Figure (1) with numerous other Intensity-velocity relationships developed in North America, China and Italy. (Literature references for the other relationships shown in Figure (1) can be found in Ref. [21]). The comparison shows significant discrepancies in the estimated Intensity values due to different Intensity scales being used. For example, the relationship proposed by Panza [22] was based on the Mercalli Cancani Sieberg (*MCS*) scale as opposed to the *MMI* scale. However, importantly, the slopes of the *PGV*-Intensity correlations are highly consistent across studies carried out in different regions using different Intensity scales. Figure (1) shows that a unit increase in Intensity would consistently result in a two-fold increase in *PGV*. Consequently, regional factors which incorporate influences of the source effects (this section) and crustal effects (Section 3) could be obtained by studying Intensity attenuation relationships collected from worldwide sources.

The comparison shown in Table (1) provides useful evidences to support the hypothesis that the seismic source demand properties of intraplate earthquakes are insensitive to regional conditions,

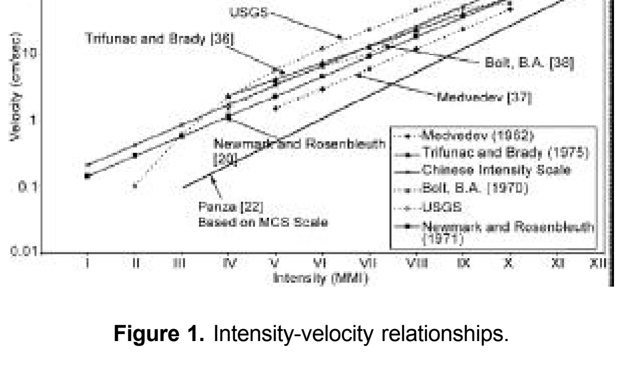

Figure 1. Intensity-velocity relationships.

given that the *PGV's* predicted by a diversity of models developed for "hard rock" conditions are fairly consistent. The deviation of the Atkinson model [15] from the Toro model [3] at large magnitude (*M*>6.5) is due to some basic differences in the adopted functional form in the source spectral shape [15]. There is still no universal consensus on which model is preferred due to the lack of larger magnitude intraplate earthquake records. However, from Table (1), the majority of the model seems to be in better agreement with the Atkinson model than with the Toro model. Despite the highlighted differences between the models, there are overall consistencies amongst the listed predictions.

3. Crustal Factor (γ)

The predicted *PGVs* listed in Section 2 is based on the "hard rock" conditions of the glaciated continental interiors in *CENA* where there are negligible amplification by the earth crust. The *PGVs* predicted for other crustal conditions such as Western North America (*WNA*) should be higher for any given earthquake magnitude and hypocentral distance and could be obtained by taking the product of α and γ. This crustal amplification effect represented by the γ factor is partly contributed by the shear wave velocity gradient as described in Ref. [13]. Various crustal amplification mechanisms have been reviewed and quantified recently for *WNA* in the seismological evaluations of Refs. [17, 18]. The γ factor representing the amplification in the *PGV* on a "generic rock" crust (as defined in Ref. [13] for average *WNA* conditions) could be obtained by stochastic simulations of the seismological model which has separated the crustal effects and the path attenuation effects from the source effects. The shear wave velocity of this generic "rock" crust is approximately 750*m/sec* at 30*m* depth and is increased to about 2000*m/sec* at some 300*m* depth. (Note, it is important to distinguish this crustal amplification effects from the site amplification factor associated with surface sediments. This latter condition has not been included in the crustal effects as defined herein).

It is known that southeastern Australia (*SEAus*) has relatively younger geological formation than western Australia (*WAus*) although the crustal properties between different regions within Australia is considered to be more moderate than the contrasts between *CENA* and *WNA*. The crustal conditions of SEAus have been found to be similar to *WNA* in terms of the rate of attenuation of seismic waves [23]. In the context of crustal amplification, the term "*SEAus*" referred herein is taken to include South Australia, Victoria, New South Wales and Queensland. Crustal conditions in Northern Territory and Central Australia are taken to be in the same category as "*WAus*". Further citations to the geophysical literature can be found in Ref. [21] which also presents a comparison of the shear wave velocity profiles obtained from different parts of Australia.

Information from iso-seismal maps collected from a number of Australian earthquakes including the *M*6.9 Meckering earthquake of 1969 and the *M*6.2 Cadoux earthquake of 1979 have been used to study earthquake attenuation behaviour [11]. In view of variations in crustal properties across the continent, separate attenuation relationships were developed for (i) Western Australia (*WAus*) which is characterised by "hard rock" conditions and (ii) South-Eastern Australia (*SEAus*) which is characterised by the softer "rock" conditions. The developed relationships are shown by Eqs. (3a) and (3b) respectively.

$$MMI = 1.5M_L - 3.2logR + 2.2 \quad \text{(WAus)} \qquad (3a)$$

$$MMI = 1.5M_L - 3.9logR + 3.9 \quad \text{(SEAus)} \qquad (3b)$$

(Note, the relationship proposed in Ref. [11] for Northeastern Australia is intermediate between Eqs. (3a) and (3b)).

The *MMI's* predicted from both equations could be translated into *PGV's* using the Newmark-Rosenblueth expression [20]. Ratios of the *PGV's* predicted for the adjacent regions of different geological characteristics are purely indicative of the crustal effects (in the relatively "younger" crustal region) provided that the source characteristics of the two regions are similar. Since both regions are wholly within the same tectonic plate, it is reasonable to assume similar source mechanism and characteristics.

Similarly, the "Continental" region of *CENA* and the adjacent "Mexican Gulf" regions modeled by Toro [3] are expected to have similar source characteristics, being adjoining regions in *CENA*. Thus, again, the ratios of the *PGV's* predicted for the two regions could be taken as indicative of the crustal amplification effects in the "younger" crustal region surrounding the Mexican Gulf.

The objective of this section is to make inferences of the crustal amplification factor (γ) using five different approaches which are summarised as follows:

A. Ratio of *PGV's* predicted by Gaull [11] for *WAus* and *SEAus*.
B. Ratio of *PGV's* predicted by Toro [3] for the inner continental region and the Gulf region of *CENA*.
C. The authors' own estimate of the crustal factor in *WNA* based on stochastic simulations of the seismological model using *CAM* (this study). An overview of *CAM* is provided in Ref. [7].
D. Crustal factor for *WNA* as recommended by Atkinson and Boore [17].
E. Ratio of *PGVs* predicted by Sadigh [4] for *WNA* and by Toro [3] for the inner continental region of *CENA*.

The γ factor as inferred from the Gaull's relationship for Australian earthquakes (Approach A) is shown in Table (2) to be highly consistent with factors inferred from other attenuation models (eg. Approaches B-D). This factor is shown to be generally insensitive to the earthquake magnitude, being around 1.6. This γ factor combining with the source factors listed in Table (1) provides predictions for intraplate earthquakes occurring in "young" geological conditions. The rationale of this approach has been explained by imagining that the source of intraplate earthquakes in *CENA* have been put into the Californian (*WNA*) crust [18].

The ratios identified with Approach *E* were based on *PGVs* predicted by the Sadigh model (for *WNA*) divided by *PGVs* predicted by the Toro model (for *CENA*). It is noted that these ratios are significantly less than that derived from Approaches *A-D*. The apparent anomaly with Approach *E* could be explained by the partial trade-offs of the crustal effects with the effects of a lower stress-drop associated with interplate earthquakes in *WNA*. Consequently, ground motion models developed in *WNA* (i.e. "*WNA source in WNA crust*") predicts significantly lower *PGVs* than predictions based on combining the "*CENA source*"

Table 2. Inferred crustal amplification factors for *PGV's* at 30 *km* distance.

Model (See List Above)	M5	M5.5	M6	M6.5
(A) Gaull [11]	1.64	1.58	1.56	1.58
(B) Toro [3]	1.28	1.54	1.62	1.56
(C) **This study**	**1.60**	**1.60**	**1.60**	**1.60**
(D) Atkinson [17]*	1.59	1.59	1.59	1.59
(E) Sadigh [4] and Toro [3]	1.04	1.12	1.06	1.03

* In interpreting Atkinson [17] recommendations, the period range of interest is taken as between 0.15 secs and 0.65 secs, being the period range related directly to the PGV. The average of value of 1.35 and 1.82 specified for these periods is 1.59.

with "*WNA* crust". Consequently, it is not always conservative to adopt attenuation models developed in high seismic interplate regions for applications in some intraplate regions (such as *SEAus* and the Mexican Gulf region).

4. Path Attenuation Factors (G.b)

The product of the source factor, α (2nd column of Table (1) in Section 2), and the crustal factor $\gamma = 1.6$ (Section 3) provides predictions for the *PGV's* for different regions within Australia at a reference hypocentral distance of 30*km*. Path attenuation factors which extend the predictions for different distances comprise the geometrical factor (*G*) which represents the spatial distribution of energy and the whole path attenuation factor (β) which represents the dissipating of energy along the seismic wave transmission path [24]. The product $G\beta$ which equals to unity for $R = 30km$ by definition, represents the total path attenuation effects of the *PGV*.

For near-field conditions (R<1.5 times the crustal depth) the following relationships may be assumed:

$$G = 30/R \tag{4}$$

based on spherical attenuation.

The *G* factors representing cylindrical attenuation in far-field earthquakes have been summarized in Ref. [9].

The β factor has been developed in Ref. [24] into the form of Eq. (5):

$$\beta(R, Q_0) = Cm\left(\frac{30}{R}\right)^{C1C2R^{\eta}} \tag{5a}$$

where

$$C1 = 0.005 \tag{5b}$$

$$C_2 = 0.043\left(\frac{Qo}{100}\right)^2 - 0.53\left(\frac{Qo}{100}\right) + 1.8 \tag{5c}$$

$$\eta = 0.022\left(\frac{Qo}{100}\right) + 0.8 \tag{5d}$$

$$C_m = 1 - \left(\frac{7.8 - M}{1.8}\right)\left(1 - \left[1.86 - 0.22ln(R)\right]\right) \text{ where}$$

$$C_m \leq 1.0 \tag{5e}$$

The established link between the Quality Factor Q_0 defined at one hertz (a parameter commonly used in seismological studies) and the attenuation factor β, enables valuable local seismological information to be incorporated directly into the modelling. When the *Q* value is uncertain, it is conservative to assume C_m, C_2 and η equals to unity which reduces Eq. (5a) into a much simplified form.

The value of Q_0 has been identified for different parts of Australia (citation to the geophysical literature is provided in the footnote of Table (3)). The corresponding values for *G* and β were then calculated in accordance with Eqs. (4) and (5) respectively for 50*km* and 70*km* distances as listed in Table (3) based on a magnitude 6.5 event.

It is shown in Table (3) that the effects of energy dissipation as represented by the β factor could be neglected at 50*km* and only becomes significant at distances exceeding 70*km*. For distances, <50*km* the attenuation could be represented by assuming $C_m = C_2 = \eta = 1$ in Eq. (5a), see bottom row of Table (3). In comparison, the effect of the geometrical (*G*) factor representing the effect of spatial distribution of energy is far more significant.

Table 3. Path attenuation factors for 50km and 70km distances (G = 0.67*).

Location	Quality Factor Q_0 # (Defined at one Hertz)	β Factors Calculated from Eq.3	
		50km	70km
Western Australia	550	0.98	0.91
Northern and Central Australia	500	0.98	0.90
Area Surrounding Perth	50	0.91	0.77
New South Wales	200	0.94	0.82
Victoria	100	0.92	0.79
Queensland	200	0.94	0.82
Southern Australia	300	0.96	0.86
Predictions Based on $C_m=C_2=\eta=1$	When the Quality Factor is Unknown or Uncertain	0.88	0.74

* The geometrical factor G=0.67 was calculated in accordance with the far-field attenuation relationships presented in Ref. [9] assuming a crustal depth of 30km.

\# The quality factors were based on recommendations by Wilkie [23] and Mitchell [34].

5. Comparison with Historical MMI Data

Instrumental strong motion records are typically very scarce in low seismicity regions like Australia. However, very useful intensity information has been recorded on Iso-seismal maps for earthquakes that have occurred in Australia over the past one hundred years. In this study, *MMI* values were digitized from Isoseismal maps for some nineteen earthquakes exceeding magnitude 5, see Tables (4a) and (4b). In addition, Intensity values associated with *M*5 and

Table 4. Details of historical earthquake events (based on Isoseismal maps[35]).

(a) Southeastern Australia

Earthquake Location	Year	Magnitude (M_w)	Distance (km)	Recorded MMI
New South Wales				
Newcastle	1989	5.6	11-12 30 64 100	VIII VII V IV-V
Picton	1973	5.5	20	VII
Dalton-Gunning	1934	5.6	20 50 100 150	VI V IV-V III-IV
Boolaroo	1925	5	20	VI
Maitland	1868	5.3	20	VI
Victoria				
Wonnangatta	1982	5.4	30 60 90	V-VI IV-V IV
Warrnambool	1903	5.3	10 35 60 100	VII V IV III
South Australia				
Adelaide	1954	6*	20 50 100 200	VIII VI-VII V-VI IV
Robe	1948	5.6	50 100 150	V IV III
Nilpena	1939	5.7	50 100 150 200	VI V-VI IV-V III-IV
Cleve	1911	5.5	20 50 100	VII VI V
Warooka	1902	6	20 50 100 200	VIII VI-VII V-VI IV
Beachport	1897	6.8*	10 30 60 100 200	X VIII VII VI IV-V

* Magnitude adjustments of up to 0.5 units magnitude have been made for conversion from M_L to M_w.

(b) Western and Central Australia

Earthquake Location	Year	Magnitude (M_L)	Distance (km)	Recorded MMI
Western Australia				
Collier Bay	1997	6.3	10 50 100 200	VIII-IX VI V-VI IV-V
Cadoux	1979	6.2	10 40 100 200	IX VI V IV
Meckering	1968	6.9	10 15 24 60 100	IX VIII-IX VII-VIII VI V
Central & Northern Australia				
Uluru	1989	5.6	15 25 51 105	VII VI V IV
Tennant Creek	1988	6.7	10 60 200	IX VI V
Marryat Creek	1986	6	50 100 200	VI V-VI IV

*M*6 earthquakes have also been digitized from family curves that were developed from Intensity records obtained in Queensland. The magnitude-distance (*M-R*) combinations associated with the digitized intensities were then substituted into the *CAM* equations Eqs. (1-5) for the calculation of the *PGV's* which were then converted into *MMI* values using Newmark-Rosenblueth's expression [20]. The residuals of the two sets of *MMI* data ("digitized" and "calculated") were then plotted in Figure (2) to demonstrate the accuracy of *CAM*.

Most of the "*Record-CAM*" residuals were within 0-1 *MMI* units except for a few outliers that were based on very old data, see Figure (2). This range of residual values seems reasonable as it represents the difference in Intensity between an average "rock" or "hard rock" site (from *CAM*) and an "average site" (from Iso-seismal maps). The mean *MMI* residual of 0.5 is translated into an average site multiplying factor of 1.4 (square root of 2) which is consistent with *MMI* residual analysis from other studies [25].

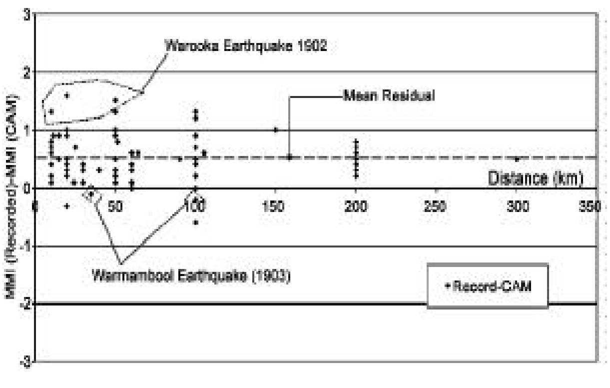

Figure 2. MMI Residuals (Record-CAM).

The standard deviation of the residuals for "*Record-CAM*" is 0.4 *MMI* units as shown in Table (5).

Similar residual plots shown in Figures (3a-3f) (Recorded *MMI*-Predicted *MMI*) are for comparing the accuracies amongst numerous existing earthquake ground motion attenuation models which have been developed by Sadigh [4] and Toro [3] and [26] for "rock" and "hard rock" sites, Gaull [11] for "average sites" and Sarma [27] for "rock and soil" sites. Apart from the model by Sadigh, all the other models were developed for applications in intraplate regions. *MMI* values were calculated from the aforementioned attenuation relationships based on *M-R* combinations shown on the Isoseismal maps. With response spectrum attenuation relationships [3, 4], the *PGV's* (and hence the *MMI's*) were obtained by dividing the predicted maximum response spectral velocity by 1.8. With peak ground acceleration (*PGA*) attenuation relationships [26, 27], the *PGV's* (in *mm/sec*) were obtained by multiplying the predicted *PGA* (in g's) by 750, as described in Ref. [1]. It is noted that the choice for this *PGA*-to-*PGV* conversion factor will affect the mean of the residual values but will not affect the scatters (or standard deviation).

The "mean" of the residuals associated with every attenuation relationship that have been incorporated into the comparison, see Figures (3a-3f), is typically within ±1 *MMI* unit as listed in the 2nd column on Table (5). Thus, the attenuation models considered in this study are generally in reasonable agreement with historical data in terms of overall averages.

However, large scatters were found with some models. *CAM* has been identified with the smallest "standard deviation" of the residuals as listed in the 3rd column on Table (5). The standard deviation is

Table 5. Statistics of the residuals.

Residual	Mean	Standard Deviation
Record-CAM (Figure (2))	**0.5**	**0.40**
Record-Sadigh 1997 [4] (Figure (3a))	1.1	0.70
Record-Gaull 1990 [11] (Figure (3b))	-0.2	0.50
Record-Toro 1997 [3] (Figure (3c))	0.7	0.60
Record-Toro 1987 [26] (Figure (3d))	0	0.60
Record-Sarma 1995 ROCK [27] (Figure (3e))	0.4	1.30
Record-Sarma 1995 SOIL [27] (Figure 3f)	-0.3	1.40

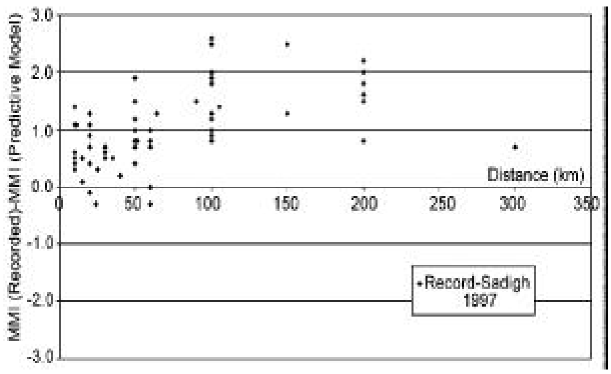

Figure 3a. MMI Residuals (Record-Sadigh 1997 [4]).

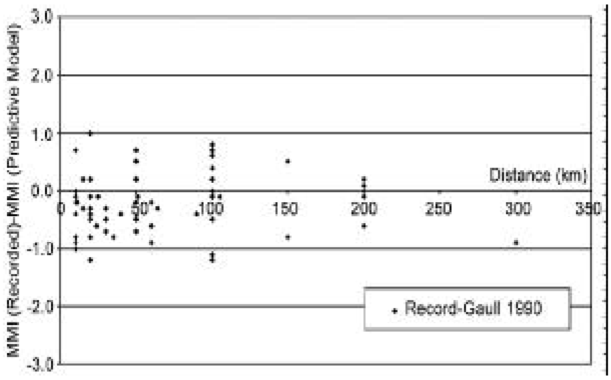

Figure 3b. MMI Residuals (Record-Gaull 1990 [11]).

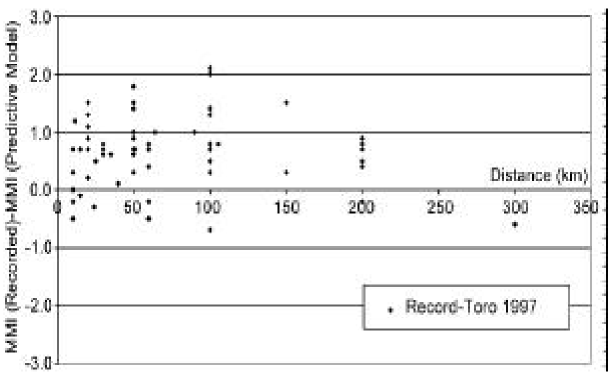

Figure 3c. MMI Residuals (Record-Toro 1997 [3]).

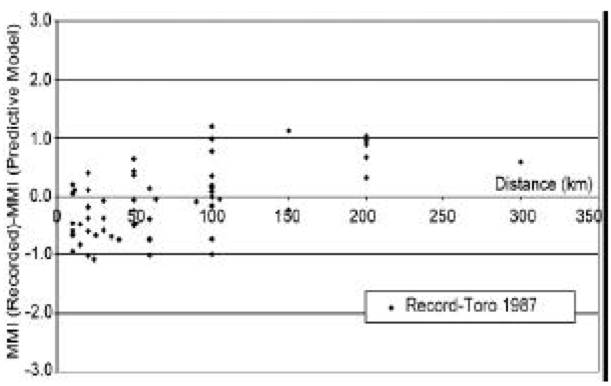

Figure 3d. MMI Residuals (Record-Toro 1987 [26]).

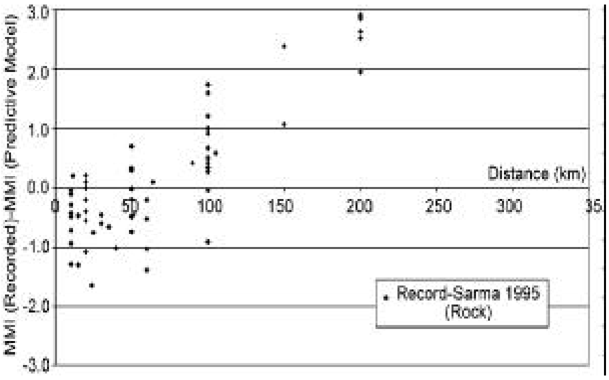

Figure 3e. MMI Residuals (Record-Sarma 1995 Rock [27]).

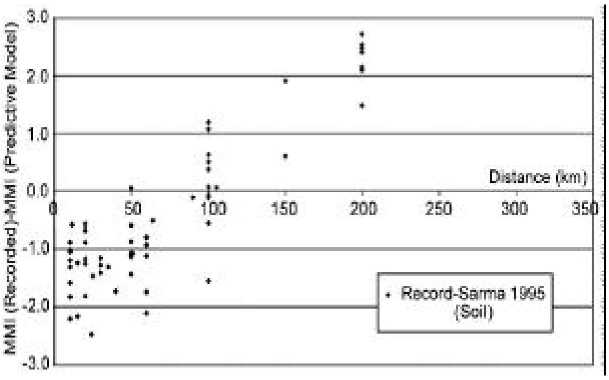

Figure 3f. MMI Residuals (Record-Sarma 1995 Soil [27]).

even slightly lower than that of the attenuation model of Gaull [11] which was developed directly from the Australian database. If a positive shift of 0.5 *MMI* unit (or site factor of 1.4) has been applied to the *CAM* equations to allow for amplifications of the "average site", few residuals would exceed 0.5 *MMI* units. The better performance of *CAM* in terms of the calculated residuals is mainly attributed to the appropriate separation of the source, crustal and path attenuation effects in the modelling as described earlier in the paper. This approach enables geological variations within the continent to be fully accounted for based on local information.

The PGV's and *MMI's* predicted by *CAM* for rock and "average sites" are presented in Figures (4) and (5) respectively (for magnitude 5.5 and 6.5 earthquakes). Separate curves have been used in the figures to represent different crustal conditions and *Q* values. As stated earlier in the paper, curves identified with "hard rock" conditions apply to Western and Central Australia. Regions of "rock" conditions possess Q values of 100 (e.g. Victoria), 200 (e.g. *NSW* and Queensland) or 300 (e.g. South Australia) as listed in Table (3). It is noted that the effect of *Q* is only significant for distances exceeding 100*km*.

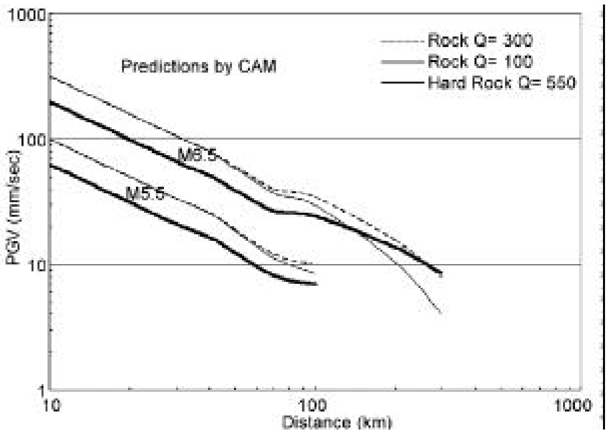

Figure 4. Estimated peak ground velocities on rock sites.

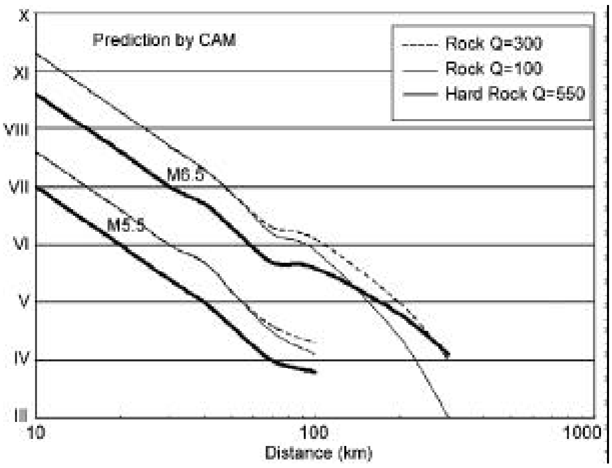

Figure 5. Estimated modified mercalli intensities on average sites.

In the above comparisons, the effects of the source radiation pattern and the associated azimuthal dependence of the earthquake intensity has not been modelled explicitly. Such effects are clearly visible in macro-seismic data for intermediate size events as shown by Kronrod [28].

6. Comparisons with MMI Records from Newcastle Earthquake

Intensity information recorded from the well publicised 1989 Newcastle earthquake (*M*5.6) was more precise than some of the older historical events listed in Table (4) due to proximity to built-up areas and the destructive nature of the Newcastle earthquake [12]. Importantly, *MMI* observed on alluvial sites and rock sites could be distinguished for that event. *MMI* recorded on rock sites was typically around *VI-VII* at an epicentral distance of 15*km*, see Map No. 3 of Ref. [12].

The appropriate *CAM* factors (as described in

Sections 2-4) for this event are listed as follows:

- ❖ Source factor (α) = 19*mm/sec*, Table (1) for *M*5.6 at reference distance of 30*km*.
- ❖ Crustal factor (γ) = 1.6 for New South Wales (Section 3).
- ❖ Geometrical factor G =30/15 = 2 (Eq.(2)).
- ❖ Whole path attenuation factor (β) = 1.0 implying negligible energy dissipation.

The calculated *PGV* on rock sites (being the product: $\alpha.\gamma.G.\beta$) = 60*mm/sec* with an inferred *MMI* = *VI-VII* based on the Newmark-Rosenblueth [20] expression.

It is shown that this calculated *MMI* value for rock sites in the Newcastle event is very consistent with field observations. Further, the higher *MMI* value of *VIII* observed on some soft alluvial sites was also very consistent with a site magnification factor of up to 2 as inferred from the distribution of the *MMI* residuals, see Figure (2).

The *MMIs* recorded outside the Newcastle city have also been plotted as a function of distance in Figure (6) along with predictions by *CAM*. Although the average site conditions surrounding these *MMI* records are uncertain, the comparison seems to be reasonable in view of the recorded *MMI* for “average sites” being less than one *MMI* unit higher than the calculated *MMI* for rock sites, which is again consistent with the general trend shown in Figure (2).

7. Comparisons with Accessible Instrumental Records of Small Events (M4.9-M5.3)

The *MMI* earthquake data has been shown to provide useful trend data to support the use of *CAM* in predicting *PGVs*. A more definitive measure for evaluating the accuracy of *CAM* is to use direct instrumental measurements of earthquake ground

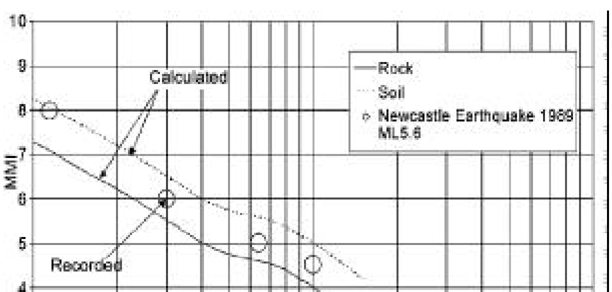

Figure 6. Comparisons of recorded and calculated MMI from the 1989 Newcastle Earthquake.

motions. Directly recorded motions are considered very valuable in view of the lack of strong motion data records in Australia.

Some instrumental ground motion data is available for the 1994 Ellalong earthquake (*M*5.3) where some five seismographs located on rock sites at around 40-50*km* of the epicentre were activated with the recorded *PGV* averaging around 10*mm/sec* which corresponds to *MMI* = *IV-V* [29]. The *PGV* calculated from *CAM* was around 15*mm/sec* which corresponds to *MMI* = *V* (being the product of α = 15*mm/sec*, γ =1.6, G = (30/45) and β = 0.97). The slightly lower recorded *PGV* is believed to be partly due to the effect of the Sydney basin which is known to possess very high energy absorption properties. Such effects have not been accounted for in the generalized predictions by *CAM*. The discrepancy was also partly attributed to variability in the source effects between events of similar magnitude.

The record-*CAM* comparison has also been carried out for the 1996 Thomson Dam Earthquake (*M*5) in Victoria (also known as the “Mount Baw Baw earthquake”) [30]. The recorded *PGV* of 10*mm/sec* for the *M*5 event at around 10*km* distance was grossly lower than the *CAM* predictions of around 55-60*mm/sec* (being the product of α = 12*mm/sec*, γ =1.6, G = (30/10) and β=1). It is recalled that the Ellalong event of similar magnitude (previous paragraph) generated comparable *PGV* at three times the distance (40-50*km*). There is clearly an anomaly associated with the occurrence of the reservoir induced Thomson Dam event. It is suggested [31] that the anomaly could have been contributed, at least partially, by the non-circular radiation pattern generated at the earthquake source.

In contrast to the earthquake events at Newcastle, Ellalong and Thomson Dam (Mount Baw Baw), the Tennant Creek earthquake of 1998 occurred in the inner continental region of Central Australia which is characterised by hard rock conditions similar to *CENA*. The velocity response spectrum recorded from the *M*4.9 aftershock at an epicentral distance of 10*km* is shown to be in reasonable agreement with the predictions by *CAM* as shown in Figure (7).

Comparison of *CAM* with the important work of Somerville [32] on response spectral shape has been presented earlier in Ref. [33] and is not repeated here.

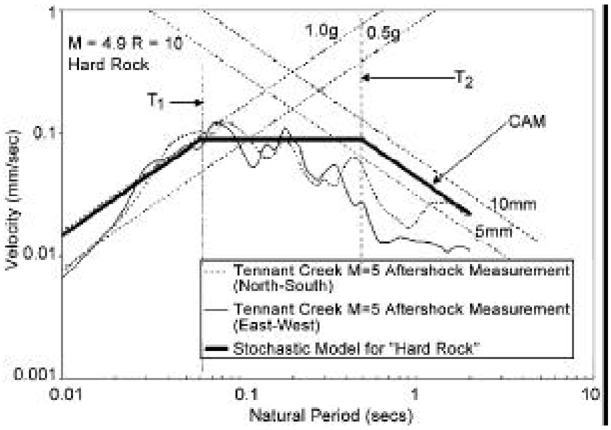

Figure 7. Response spectra for M4.9 Tennant Creek aftershock.

8. Conclusions

- ❖ The *CAM* modelling approach adopted in this study is based on an appropriate separation of the source, crustal and path attenuation effects in the modelling. Each of these effects are represented by separate component factors.
- ❖ The source factors are based on the *PGV's* predicted at the reference distance of 30*km* in hard rock conditions. A few selected existing attenuation models developed for *CENA*, the Scandinavian Peninsular and Western Australia have been used to demonstrate the generality of the source model.
- ❖ The crustal factors have been developed by stochastic simulations of a recently developed seismological model which separate the crustal and path effects in *WNA* earthquakes from the source effects. It was further shown that very consistent predictions for the crustal factor could be made by a different approach wherein the factor is simply taken as the ratio of *PGVs* predicted for adjacent regions with similar tectonic conditions.
- ❖ The path attenuation factors for different regions within Australia have also been developed in accordance with the Quality factor representative of each region using stochastic simulations.
- ❖ In the proposed Component Attenuation Model (*CAM*), the *PGV's* for any given magnitude, distance and crustal condition is predicted by taking the product of the source, crustal and path attenuation factors as outlined in this paper.
- ❖ Very good agreement between both historical Intensity data and instrumental earthquake data with *CAM* has been demonstrated. Analysis of the residuals shows *CAM* as a better predictive tool for Intensities and peak ground velocities than a number of commonly used attenuation models.

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