A Review of GMPEs that Have Been Proposed for Use in South-eastern Australia by Comparison with MMI Data

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Abstract

Several ground motion prediction equations (GMPEs) have been adopted for use in Australia by Geoscience Australia (GA) as presented in its publication known as NSHA 2018. Five such adopted GMPEs have been evaluated with three developed locally and two "third party" GMPEs that were taken from external sources. GMPEs codenamed **A12** and **SGC09** in NSHA 2018 have been included in this evaluation study. The peak ground velocity values so predicted by these GMPEs have been used to infer Modified Mercalli Intensity (**MMI**) values for comparison with data recorded from the historical earthquake events. It is shown that ground motion intensities of some historical earthquakes (that were within 100 km from the epicentre) as inferred from the **A12** and **SGC09** model are lower than what has been recorded from the historical archives. The authors also made their own post-dictions by adapting seismological models that had been developed in Central and Eastern North America. These seismological models have been modified to consider crustal differences between the host and target regions. Ground motion intensities that are based on modifying the considered seismological models are in much better agreement with field observations than the GMPEs that have been adopted by GA previously.

Key words: seismic hazard, ground-motion models, **MMI**, attenuation model

1. Introduction

A Ground Motion Prediction Equations (GMPEs) can be used to define the attenuation behaviour of earthquake ground motions for a region and is expressed as a set of mathematical functions of magnitude and distance from the source (**M-R**) along with other parameters reflecting site conditions and style of faulting. To conduct *probabilistic seismic hazard analysis* (PSHA) for the region one or more GMPE's that are considered to be representative of the seismic wave transmission properties of the region would need to be identified. Modern GMPEs are conventionally developed from field recorded strong motion data. In tectonically active regions such as Western North America (WNA), abundant strong motion data recorded from instruments is used for developing GMPEs. Given that these empirical GMPEs are heavily dependent on field recordings, inter-regional variances can be factored into the modelling to a large extent (Boore et al. 2014, Campbell and Bozorgnia 2014). However, the empirical modelling of GMPEs can produce results that are sensitive to the manner in which the data is processed and analysed (Zafarani et al. 2008).

For tectonically stable regions of low-to-moderate seismicity, recorded strong motion data is typically lacking. Two common modelling approaches have been adopted to overcome the challenge of lack of instrumented strong motion data. The first approach is the use of macro-seismic intensity data that are contained in Isoseismal maps of historical earthquakes. The second approach is stochastic simulations of the seismological model which relies on regional information of various seismological parameters for input into the model. Both approaches when used on their own have shortcomings when applied to a low to moderate seismicity region. This article presents the combined use of both approaches in developing a GMPE for south-eastern Australia and to demonstrate its merits over existing GMPEs.

2. Use of macro-seismic intensity data

South-eastern Australia (SEA), like other low-to-moderate seismicity regions, is subject to challenges over the paucity of strong motion data recorded by instruments. However, very useful macro seismic intensity information expressed in terms of the Modified Mercalli Intensity (**MMI**) has been recorded on Isoseismal maps for earthquakes that occurred in this region for over a hundred of years. This type of data has been used in investigations for studying the attenuation behaviour of earthquake ground motions in Australia (Lam et al. 2003, Tsang et al. 2010) and in many other regions of low to moderate seismicity. The analysis of **MMI** data can result in the development of a GMPE that can be representative of the behaviour of earthquakes in strong motion affected areas without requiring recording instruments to be placed close to the epicentre of the earthquake. For this reason, **MMI** data has much better coverage of strong motion conditions than instrumented data in regions of low to moderate seismicity like Australia. The current GMPEs developed by GA for the modelling of seismic hazard in south-eastern Australia were derived from datasets of small magnitude ($\mathbf{M_W} < 5.4$) earthquake events (Allen et al. 2006, Allen 2012). These datasets can be heavily biased to ground motion behaviour typifying small magnitude earthquakes.

MMI data would need to be converted to ground motion parameters such as peak ground acceleration (PGA) or peak ground velocity (PGV). The simple, and well known, **MMI**-PGV conversion relationship is recommended by Newmark and Rosenblueth (1971), Gaull et al. (1990), and Lam et al. (2003). More rigorous conversion relationships have also been developed more recently (e.g. Atkinson & Kaka 2007). Regression analysis of **MMI** data as obtained from historical archives can therefore be translated into attenuation relationships that are expressed in terms of PGV.

In the absence of detailed spectral properties of a historical earthquake PGV is the preferred parameter to characterise the intensity of the earthquake for reasons outlined by Bommer and Alarcon (2006). First, PGV data can be a good damage potential indicator, because of its reliability and simplicity (Akkar and Ozen 2005). The accuracy of "shake maps" relies on the good correlation between PGV and **MMI** values (Kaka and Atkinson 2004). Second, PGV data can be employed for estimating the risk of damage to buried pipelines because of the good correlation between horizontal PGV material strain values (Todorovska and Trifunac 1996); fragility functions for buried pipelines expressed in terms of PGV can be found in open sources (FEMA 2003). Third, PGV data can also be used for assessing the risks of liquefaction (Trifunac 1995, Kostadinov and Towhata 2002, Orense 2005). Fourth, PGV is one of the three parameters for scaling an elastic response spectrum model for engineering design (Newmark et al. 1973, Newmark and Hall 1982). There are other utilities of PGV (Fitzpatrick 1992, Kappos and Kyrikakis 2000). The seismic action model stipulated by the current Australian standard is based on scaling design PGV values that were derived from PSHA employing GMPEs found on **MMI** data; refer commentary to the 2007 edition of AS1170.4 (Wilson & Lam, 2007).

3. Seismological modelling

Seismological models which are also known as Ground Motion Models (GMMs) define the frequency content of free-field ground motions in the form of a Fourier amplitude spectrum (FAS). In regions where the traditional empirical modelling approach to develop GMPEs is not viable because of the lack of strong motion data, stochastic simulations of the seismological models is a popular viable alternative. Seismological research on this modelling methodology has been conducted for several decades. Details are reported widely in the literature (Atkinson and Boore 1995, Lam et al. 2000a, Boore 2003, Atkinson and Boore 2006, Boore 2009, Boore et al. 2014, Yenier and Atkinson 2014, Yenier and Atkinson 2015). The implementation of stochastic simulations of seismological models often relies on the computer program, like GENQKE (Lam et al. 2000a) and SMSIM (Boore 2003). By assigning random phase angles to the individual sinusoids constituting the acceleration time-histories on the ground surface (Lam et al. 2000a), standard calculation procedures may then be applied to derive the intensity value (e.g. PGA) for any given earthquake scenarios (**M-R** combinations). A set of GMPE for the target regions can then be developed using artificial data obtained from the repeated stochastic simulations covering a range of **M-R** combinations.

Information of the earthquake source, wave travel path, and crustal conditions are key components of the seismological model.

Source factors that have been developed with the notion of a “point source” (including “single-point” and “double-point”) can be regarded as the first generation source model (Brune 1970, Boore 1983, Atkinson and Boore 1995, Atkinson 2004, Atkinson and Boore 2014). In a study undertaken by GA in which data recorded from 1200 ground motion records from 84 earthquakes occurring in western Australia was analysed it was found that the average stress drop for large magnitude events was consistent across different parts of Australia (Allen et al. 2006). It has also been found from a follow up study of south-eastern Australian earthquakes that the average Brune stress drop was in the range 23 - 50 MPa (230- 500 bar) depending on the depth of the source (Allen 2012). To address the effects of near-source saturation that is resulted from the finite dimension of the fault source it has been proposed that the earthquake source be resolved into independent “point sources” (Motazedian and Atkinson 2005, Atkinson and Boore 2006). Alternatively, an equivalent-point source along with a magnitude-dependent pseudo-depth forming part of the geometric spreading function has also been proposed (Yenier and Atkinson 2014). The Specific Barrier Model (SBM) has been developed for mimicking the physical behaviour of the seismic source (Halldorsson and Papageorgiou 2005, Zafarani et al. 2008).

The regional path factor which is used to describe the attenuation behaviour of the seismic wave energy comprises the geometric and anelastic attenuation factors (which are distance-dependent parameters). Meanwhile, the local crustal factor is used to encapsulate the combined effects of upper-crustal amplification and attenuation.

Complexity in the earthquake generation process and the associated uncertainties that are embodied in empirical GMPEs cannot possibly be captured completely by seismological modelling, nor by the stochastic modelling process. To address these intrinsic deficiencies of seismological modelling a new class of (semi-empirical) modelling approaches namely the *Hybrid Empirical Method* (**HEM**) that was first proposed by Campbell (2003) and the *Referenced Empirical Method* (**REM**) have been developed. Details of these more recently developed modelling methodologies have been reported in numerical literature references (Atkinson 2008, Atkinson and Boore 2011, Atkinson and Motazedian 2013, Hassani and Atkinson 2015). In **HEM**, the empirical GMPE from the (relatively data-rich) “host” region is modified by a set of adjustment factors which can be derived from spectral ratios of the stochastically simulated ground motions developed for both the host region and the (data-poor) target region, into a new GMPE for use in the target region (e.g. Pezeshk et al. (2015)). In **REM**, the set of adjustment factors are determined from spectral information that is contained in field recorded data. Thus, it is only viable to implement **REM** if there are adequate recorded data in both regions. Thus, the introduction of **REM** cannot supplant a full stochastic model (e.g. model presented in Atkinson and Boore, 2006) in the development of GMPEs (Atkinson, 2008). Both the stochastic modelling approach and **HEM** can be regarded as viable methods of developing GMPEs for regions of low-to-moderate seismicity.

4. Seismological modelling for south-eastern Australia

The *Component Attenuation Model* (**CAM**) is a form of seismological modelling which has been applied to south-eastern Australia and many other intraplate regions as reported in the literature for the past two decades (e.g. Lam et al, 2000b, 2003, 2004, 2010; Lam and Wilson, 2008; Tang et al, 2017). In **CAM** the spectral properties of the earthquake ground motion are decoupled into several component factors: namely the *source* (α), *path* (β) and *crustal* factor (ɤ) which are used for scaling a design response spectrum/peak ground motions. The decoupling essentially enables ground motions to be predicted by combining the generic source behaviour of earthquakes occurring in (the very well-studied region of) Eastern North America and the path and crustal of a targeted region (like south-eastern Australia) based on information obtained from seismological surveys.

The path factor is much dependent mainly on two factors: (1) the quality of the rock crust in the transmission of seismic shear waves considering the dissipation of energy which is known as anelastic attenuation and (2) the behaviour of geometric spreading of energy. Central to the determination of the crustal factor is the assumed shear wave velocity (SWV) profile. Such information can be obtained using the SPAC survey (Lam et al. 2004). The Shear-wave velocity (SWV) profiles, which are used to determine the local crustal factor, will be obtained by mimicking the profiles obtained by geology-based method (Lam et al. 2004, Roberts et al. 2004, Chandler et al. 2006).

Numerous recommendations for the value of the anelastic attenuation quality factor (Q) the geometric spreading function (G), and the parameter characterising the shear wave velocity profile of the rock crust (V_{S30}) and the attenuation properties of the crustal materials near the earth surface κ_0 (pronounced as "kappa") that have been reported in the literature for Australia are listed in **Table 1**.

In **CAM** (Lam and Wilson 2008) the response spectrum in the velocity controlled region is scaled by the velocity parameter: RSV_{max} whereas the acceleration and displacement controlled regions are defined in accordance with a deterministic value of the corner periods. In the book chapter presenting **CAM** (Lam et al. 2010) the design response spectrum for supporting the displacement-based approach for the design and assessment of structures is scaled jointly by the velocity and displacement parameters. In updated **CAM** (Tang et al. 2017) response spectral values at various predetermined natural period of vibration up to a natural period of 8s is predicted. An algebraic expression for calculation of the upper-crustal modification factor considering regional crustal conditions has also been incorporated.

Table 1. Representative Australian attenuation modes

Model and Reference	**A12** (Allen 2012)	**CAM** (Lam et al. 2010)	**SGC09** (Somerville et al. 2009)	**CAM** (Lam and Wilson 2008)	**L08** (Liang et al. 2008) (Hao and Gaull 2004)	**A07** (Allen et al. 2007)	**A06** (Allen et al. 2006)	**A04** (Allen et al. 2004)	**WG95** (Wilkie and Gibson 1995)
Geometric Spreading G(R)	$\mathbf{R}^{-1.33}$, $\mathbf{R} \leq 90$ $\mathbf{R}^{+032}$, $90 < \mathbf{R} \leq 150$ $\mathbf{R}^{-1.66}$, $\mathbf{R} > 150$	$1/\mathbf{R}$, $\mathbf{R} \leq 1.5\mathbf{D}$ $1/1.5\mathbf{D}$, $1.5\mathbf{D} < \mathbf{R} \leq 2.5\mathbf{D}$ $\mathbf{R}^{0.5}$, $\mathbf{R} > 2.5\mathbf{D}$	-	$1/\mathbf{R}$, $\mathbf{R} \leq 1.5\mathbf{D}$ $1/1.5\mathbf{D}$, $1.5\mathbf{D} < \mathbf{R} \leq 2.5\mathbf{D}$ $\mathbf{R}^{0.5}$, $\mathbf{R} > 2.5\mathbf{D}$	$1/\mathbf{R}$, $\mathbf{R} \leq 1.5\mathbf{D}$ $1/1.5\mathbf{D}$, $1.5\mathbf{D} < \mathbf{R} \leq 2.5\mathbf{D}$ $\mathbf{R}^{0.5}$, $\mathbf{R} > 2.5\mathbf{D}$	$\mathbf{R}^{-1.3}$, $\mathbf{R} \leq 90$ $\mathbf{R}^{+0.1}$, $90 < \mathbf{R} \leq 160$ $\mathbf{R}^{-1.0}$, $\mathbf{R} > 160$	$\mathbf{R}^{-1}$, $\mathbf{R} \leq 80$ km $\mathbf{R}^{-0.5}$, $\mathbf{R} > 80$ km	$\mathbf{R}^{-1}$, $\mathbf{R} \leq 80$ km $\mathbf{R}^{-0.5}$, $\mathbf{R} > 80$ km	-
Anelastic attenuation factor Q(*f*)	min(0, 0.000585-0.015log*f*)	-	-	$160f^{0.56}$	$700f^{0.25}$	$10^{[3.66-1.44logf+0. \; +0.058(log}$	$457f^{0.37}$	$(1.85\mathbf{R}+10\exp(-0.1\mathbf{R})) *f^{(0.96-0.0039\mathbf{R})}$, $\mathbf{R} \leq 150$ $(0.42\mathbf{R}+212.11) *f^{(0.5-0.0003\mathbf{R})}$, $\mathbf{R} > 150$	$20f^{0.5}$, $\mathbf{D} \leq 4$ km $100f^{0.85}$, $\mathbf{D} > 4$ km
V_{S30}	0.82 km/s	-	0.865 km/s	0.6-0.8 km/s	-	-	-	-	-
κ_0	0.006 s	-	0.006s	0.035s	-	-	-	-	-
Applicable range*	$2.0 \leq f \leq 24$ Hz $4.0 \leq \mathbf{M_W} \leq 7.5$ $\mathbf{R} \leq 400$	$5 \leq \mathbf{M_W} \leq 7$ $\mathbf{R} \leq 100$	$5 \leq \mathbf{M_W} \leq 7.5$ $0 \leq \mathbf{R} \leq 500$	$5 \leq \mathbf{M_W} \leq 7$ $\mathbf{R} \leq 100$	$\mathbf{M_L} \leq 6$ $\mathbf{R} \leq 100$	$0.78 \leq f \leq 19.9$ Hz $1.99 \leq \mathbf{M_L} \leq 4.65$	$1.07 \leq f \leq 25.0$ Hz $2.13 \leq \mathbf{M_L} \leq 4.76$	$1.79 \leq f \leq 11.79$ Hz $1.68 \leq \mathbf{M_L} \leq 5.02$	$2 \leq f \leq 20$ Hz
Applicable region	South-eastern Australia	Intraplate regions	Cratonic-Australia	Eastern Australia	Southwest Western Australia	South-eastern Australia	Southwest Western Australia	South-eastern Australia	Victoria

(* When applicable range is not explicitly stated in paper it was inferred from data comparisons, "**D**" is the crustal thickness, km)

5. Comparison with historical MMI data

This article is aimed at supporting the latest version of **CAM** by comparing the modelled PGV values with results inferred from **MMI** data of historical events occurring in south-eastern Australia (SEA). A number of GMPEs including that of **NSHA2018** of GA, the **SGC09** model proposed by Somerville et al. (2009), and **LSK03** model that proposed by (Lam et al. 2003) and **CAM** (Tang et al. 2018) have been incorporated into the comparison study (refer **Table 2**). **A12** (Allen 2012) model does not give PGV predictions; the authors made use of the conversion relationship: PGV = RSV_{max}/1.8 (Lam et al. 2010) to obtain the modelled PGV values.

Table 2. List of GMPEs for comparison analysis

No.	GMPE	Reference
1	**A12**	Allen (2012)
2	**AB06**	Atkinson and Boore (2006)
3	**CY08**	Chiou and Youngs (2008)
4	**SGC09**	Somerville et al. (2009)
5	**LSK03**	Lam et al. (2003)
6	**CAM**	This study *

(Note: **A12**, **SGC09**, **LSK03** are specifically developed for Australian condition; **AB06** and **CY08** are for ENA and WNA respectively; **CAM** used in this study can be adjusted to any intraplate regions, and the details can be found in Tang et al. 2018)

The magnitude ($\mathbf{M_L}$) of the 13 historical earthquakes that have been included in the comparison is larger than 5, and the recorded intensity values were taken from within 200 km of the epicentre (**Figure 1**). The PGV-**MMI** conversion relationship as presented in equation (1) as developed by Atkinson and Kaka (2007) was used to transfer PGV values calculated by **CAM** and other selected GMPEs into **MMI** values contained in the Isoseismal maps for comparison. The same conversion relationship (equation 1) was adopted by a previous study undertaken by GA (Leonard 2015).

$$\mathbf{MMI} = \begin{cases} 4.37 + 1.32 * logPGV + 0.47 - 0.19 * \mathbf{M} + 0.26 * log\mathbf{R} & logPGV \leq 0.48 \\ 3.54 + 3.03 * logPGV + 0.47 - 0.19 * \mathbf{M} + 0.26 * log\mathbf{R} & logPGV > 0.48 \end{cases} \quad (1)$$

where **M** and **R** are moment magnitude and hypocentral distance respectively, and the unit of PGV is cm/s.

Information of the historical events was partly based on compilations by the second co-author and co-workers Lam et al. (2003) and partly on more updated information provided by GA as shown on its website (http://www.ga.gov.au/earthquakes). Details of the individual events can be found in **Table I** of the **Appendix**. Many of the listed events are identified with the local magnitude ($\mathbf{M_L}$) of the earthquake. Thus, conversion to moment magnitude **M** (or $\mathbf{M_W}$) is necessary. A correction study on earthquake magnitude values based on vertical component of the recorded seismograms was first undertaken in the 1990's (Wilkie et al. 1994). More recent studies in preparation for the *2018 National Seismic Hazard Assessment (*NSHA2018*)* by GA for conversion to moment magnitude values have been presented (Allen 2017, Ghasemi and Allen 2017). These latest relationships (of the bi-linear form as defined by equation 2) have been employed in the current study undertaken by the authors of this article for determining the moment magnitude of events that have been recorded.

$$\mathbf{M} = \begin{cases} 2/3\, \mathbf{M_L} + 1.2, & \mathbf{M_L} \leq 4.5 \\ \mathbf{M_L} - 0.3, & \mathbf{M_L} > 4.5 \end{cases} \quad (2)$$

Values of parameters for input into **CAM** are listed in **Table 3**. The shear-wave velocity profile and the corresponding frequency-dependent combined amplification and attenuation factor assumed for south-eastern Australia are shown in **Figure 2(a)** and **Figure 2(b)** respectively.

The overall comparison result is shown in **Figure 3**, and the corresponding overall average residuals (predicted **MMI** – recording **MMI**) are listed in **Table 4**. In **Figure 3**, the *x*-axis is the historical recording **MMI** values on rock site (obtained from the original **MMI** value and the modification factor listed in **Table 3**), and the *y*-axis shows the predicted **MMI** values obtained from various GMPEs. By a rough glance of **Figure 3**, the values of **MMI** predicted by the considered GMPEs are larger than the recorded values in conditions of low intensity of shaking. This trend is gradually reversed as the intensity is increased. The discrepancies listed in **Table 4** might well have reflected the fact that both **SGC09** and **A12** were derived from instrumented records that were of much lower magnitude than that of the historical earthquakes considered in this study. The geometric attenuation factor of $R^{-1.3}$ as adopted by **AB06**, and $R^{-1.33}$ as adopted by **A12,** as opposed to the conventional factor of R^{-1} should also be noted as it is still uncertain if the assumptions made by **AB06** and **A12** can be applied to south-eastern Australia. The fact that **CY08** model was derived principally from recordings of shallow crustal earthquakes in active tectonic regions should also be noted. Predictions by **LSK03** and **CAM** are shown to be in reasonable agreement with the recorded values for **MMI** exceeding V and very conservative in the lower intensity range.

Table 3. Parameters used in **CAM** for SEA

Parameter	Value
Source Shear-wave Velocity (km/s)	3.6
Source Density (g/cm^3)	2.8
Stress Drop (bar)	200
Δ (cm/s)	6.113*
Geometric Attenuation Factor (G) (Atkinson and Boore 1995)	$0 \le \mathbf{R} \le 70, \quad \mathbf{R}^{-1}$ $70 < \mathbf{R} \le 130, \quad \mathbf{R}^{0}$ $130 < \mathbf{R}, \quad \mathbf{R}^{-0.5}$
Anelastic Attenuation Factor (Q_0)	200 (NSW)
(Lam et al. 2003)	100 (VIC)
(Lam et al. 2003)	300 (SA)
V_{S30} (km/s)	0.82 (Lam et al. 2004, Allen 2012)
κ_0 (s)	0.006 (Somerville et al. 2009, Allen 2012)
Modification factor (PGV_S/PGV_R)	1.5 (Standards Australia 2007, Lam and Wilson 2008)

(Note: Δ is determined from the linear interpolation of recordings at **M**6.5**R**30 and **M**5.3**R**30, PGV_S and PGV_R refer to PGV value on soil site and rock site respectively, the value of 1.5 is suggested by the Australian Standard (AS1170.4: 2007) and identified by Lam and Wilson (2008) for site class D with deep or soft soil site)

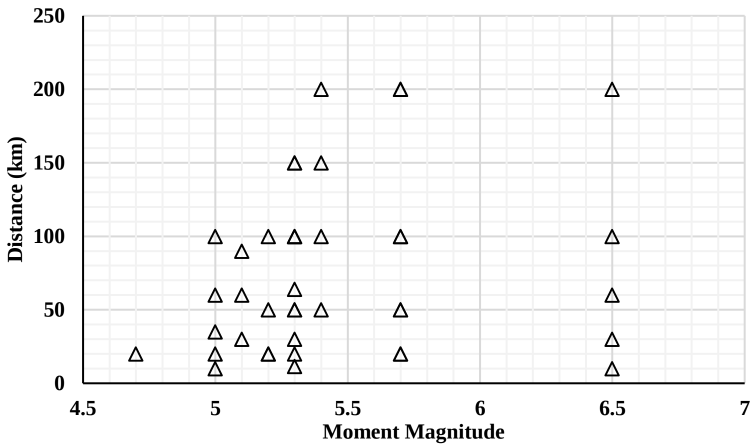
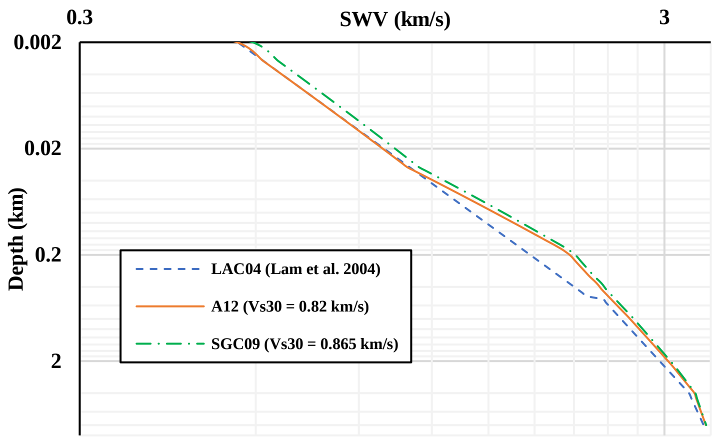
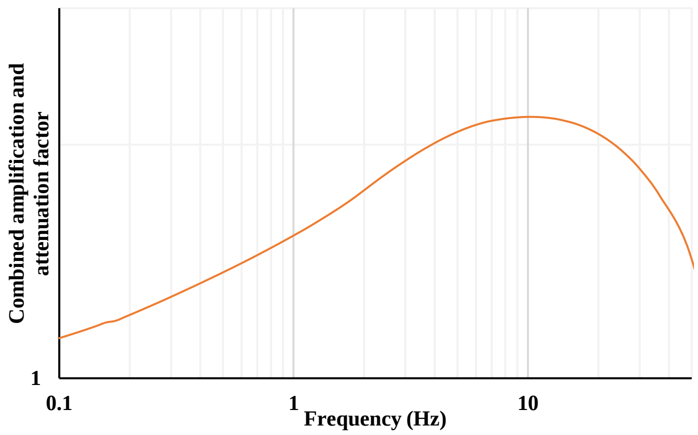


Figure 1. Magnitude-distance combinations in south-eastern Australia (SEA) region

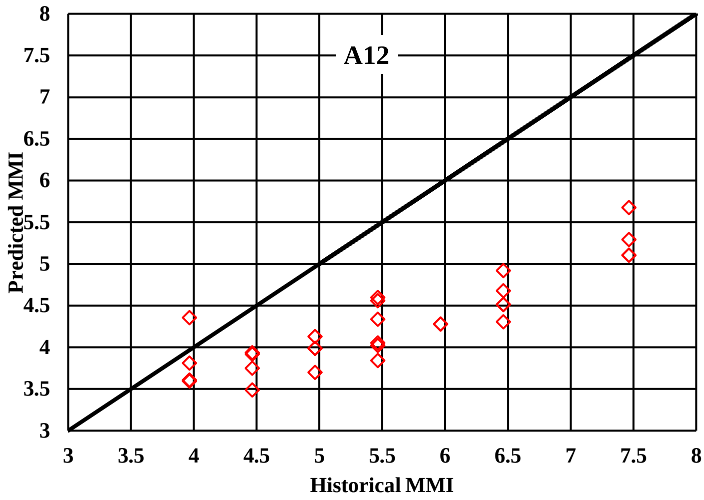


(a) Crustal profiles

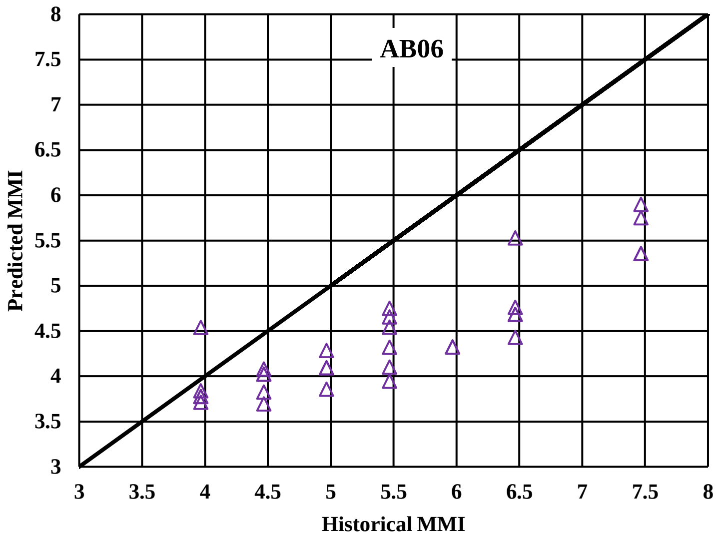


(b) Combined amplification and attenuation factor

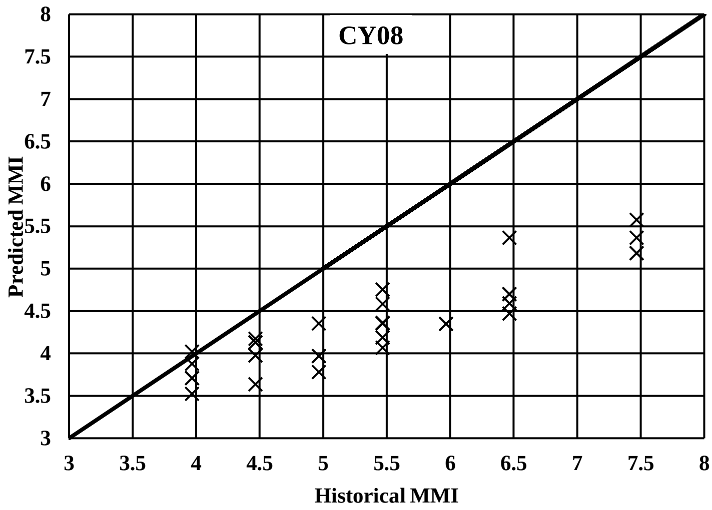
Figure 2. Shear-wave velocity profiles and corresponding frequency-dependent amplification factor for SEA. The profile of **LAC04** was obtained using SPAC and geological-based procedure for Melbourne site condition (Lam et al. 2004), and the profile of **CAM** (this study, V_{S30} = 0.82 km/s) and the profile proposed by **SGC09** (V_{S30} = 0.865 km/s) is obtained from **BJ97** crustal model with the suggested by Allen (2012) and the amplification factor are obtained from *SRI (square-root impedance)* method (Boore and Joyner 1997), κ_0 = 0.006s.



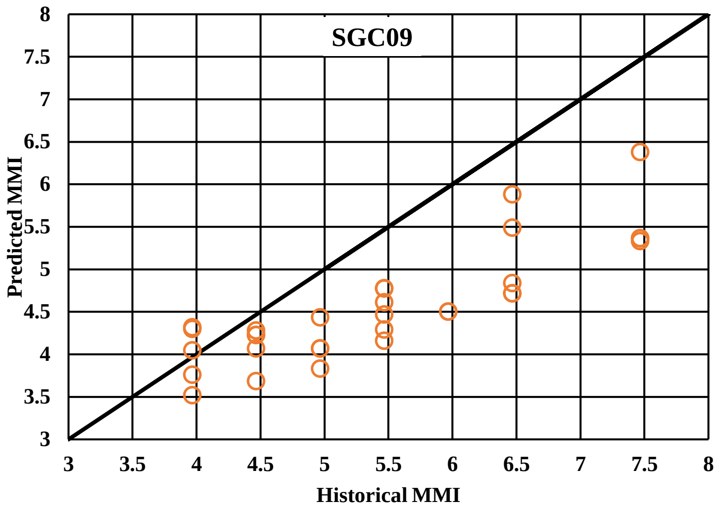
(a) **A12** model



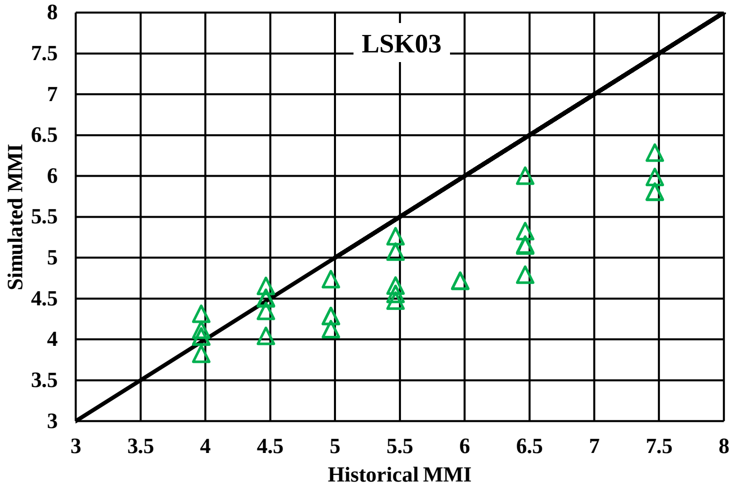
(b) **AB06** model



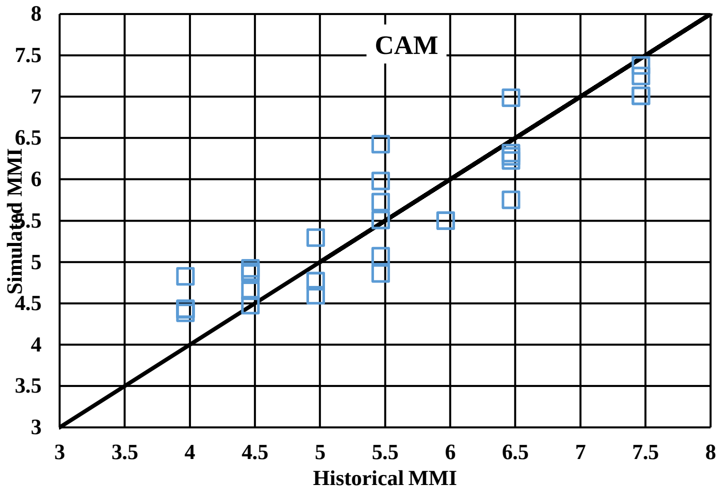
(c) **CY08** model



(d) **SGC09** model



(e) **LSK03** model



(f) **CAM** model

Figure 3. Predicted **MMI** obtained by selected GMPEs and historical recording **MMI**

Table 4. Overall average residuals for selected GMPEs

GMPE	Overall average residuals
A12	-0.65687
AB06	-0.42054
CY08	-0.53663
SGC09	-0.51523
LSK03	-0.30394
CAM	0.008086

6. Conclusion

i. The use of macro-seismic intensity data that are contained in Isoseismal maps for modelling GMPEs (citing early work undertaken for Australia by Gaull and his co-workers) has been reviewed.
ii. The stochastic simulation of the seismological model methodology for developing ground motion models has also been reviewed.
iii. This article is aimed at combining the two modelling techniques for developing a GMPE for south-eastern Australia (**SEA**).
iv. The Component Attenuation Mode (**CAM**) which is essentially a seismological model that is presented in the format of a GMPE is then introduced. Parameters that are for input into the model and are representative of regional conditions for south-eastern Australia have been identified.
v. The GMPEs so derived for using **CAM** were employed for calculating PGV values based on scenarios of historical earthquake events that have occurred in south-eastern Australia in historical times.
vi. The modelled PGV values were then converted to **MMI** values for comparison with information recorded from the field as shown on historical archives. The comparison study has also included values inferred from a few existing GMPEs. The satisfactory performance of the GMPE proposed in this study based on seismological modelling (**CAM**) has been demonstrated.

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Appendix

Table I. Recording **MMI** data in South-eastern Australia (SEA)

No.	Location	Year	ML	Mw	Distance (km)	Recorded MMI
1	Maitland (NSW)	1868	5.3	5	20	6
2	Beachport (SA)	1897	6.8	6.5	10	10
					30	8
					60	7
					100	6
					200	4.5
3	Warooka (SA)	1902	6	5.7	20	8
					50	6.5
					100	5.5
					200	4
4	Warmambool (VIC)	1903	5.3	5	10	7
					35	5
					60	4
					100	3
5	Cleve (SA)	1911	5.5	5.2	20	7
					50	6
					100	5
6	Boolaroo (NSW)	1925	5	4.7	20	6
7	Dalton-Gunning (NSW)	1934	5.6	5.3	20	6
					50	5
					100	4.5
					150	3.5
8	Nilpena (SA)	1939	5.7	5.4	50	6
					100	5.5
					150	4.5
					200	3.5
9	Rube (SA)	1948	5.6	5.3	50	5
					100	4
					150	3
10	Adelaide (SA)	1954	6	5.7	20	8
					50	6.5
					100	5.5
					200	4
11	Picton (NSW)	1973	5.5	5.2	20	7
12	Wonnangatta (VIC)	1982	5.4	5.1	30	5.5
					60	4.5
					90	4
13	Newcastle (NSW)	1989	5.6	5.3	11.5	8
					30	7
					64	5
					100	4.5