

The component attenuation model for low and moderate seismic regions

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ABSTRACT: The Component Attenuation Model (CAM) has been developed over the past five years to model the seismic demand for low and moderate seismic regions. The key objective of this paper is to explain the underlying concept of CAM which is primarily to address problems arising from the paucity of strong motion records. Emphasis is on how to incorporate regional geological and seismological parameters into the modelling. Important features to highlight include the modelling for source effects, long distance attenuation, regional upper crustal effects, and soil resonance with particular reference to velocity and displacement response spectra. CAM is currently used in the assessment of seismic hazard for Australia, Southern and Eastern China, Singapore and Indo-China.

1 INTRODUCTION

In regions of low or moderate seismic activity, strong motion (SM) accelerogram records are generally lacking. Although a fair amount of low amplitude earthquake data has been collected from earthquake tremors, swarms and aftershocks, reliable response spectrum attenuation relationships which represent regional characteristics cannot be developed using such data. The main difficulties are associated with extrapolating trends observed in minor event scenarios to major earthquakes of engineering significance (Gibson 1995).

Response spectrum models codified for design applications in these regions are typically based on well known models developed elsewhere such as the model used by the 1991, or earlier, editions of the Uniform Building Code (UBC 1991) of the United States. When there is a demand for better precision in the estimated seismic hazard for important structures, expert opinion has been sought to adopt more "suitable" attenuation models. However, this is clearly not an entirely satisfactory approach as the conditions of the subject region do not always match that of a data abundant region where representative attenuation models already exist.

In Central and Eastern North America (CENA), problems associated with the lack of SM accelerogram data have been addressed by modelling the earthquake process on a semi-theoretical (and intuitive) framework in conjunction with information derived from analyses of low amplitude ground motion data. Fourier spectra developed from the seismological models for CENA have been transformed into the response spectrum format for direct engineering applications using stochastic simulations or random vibration theory (eg. Atkinson & Boore 1997; Toro *et al* 1997). Refer Lam *et al* (2000a) for a recent review. It should be noted that conditions within intraplate regions could vary significantly. For example, crustal conditions in Australia are highly variable even though the continent is wholly intraplate (Dowrick *et al* 1995). Thus, there are doubts if the developed CENA models in their present form could be adapted to intraplate regions worldwide which are characterised by a diversity of geological and seismological conditions.

From the foregoing arguments, it does not seem viable to use existing attenuation models from Western and Eastern North America (WNA or CENA), or from other well studied areas, as “blue-prints” for the rest of the world.

The Component Attenuation Model (CAM) introduced in this paper is a contribution to the long-term solution for this modelling problem in the global context. In CAM, contributions by the earthquake source and various path effects to the response spectrum are represented by separate component factors (Lam *et al* 2000b). The concept of decoupling the source and path effects is not new as this has been central to the development of the seismological models. CAM is unique in that stochastic simulations have been built into the model which can be used to construct the response spectrum directly (Lam *et al* 2000c). Importantly, CAM is compatible with the performance based design approach in which displacement has been given more emphasis than in the conventional force-based procedure.

CAM provides predictions for the following response spectrum parameters : RSD_{max} , RSV_{max} and RSA_{max} which are the maximum values on the displacement, velocity and acceleration response spectrum respectively. On rock sites, RSD_{max} is defined at a period of 5secs (modifications are required of the model to cater for structures possessing a higher natural period). On flexible soil sites experiencing resonance, RSD_{max} is taken at the period of resonance. In both cases, RSV_{max} controls the gradient of the rising part of the bi-linear displacement response spectrum or the hyperbolic (falling) part of the flat-hyperbolic acceleration response spectrum. Design response spectra of different formats including the recently accepted ADRS format can be constructed conveniently using these three predicted response spectrum parameters (Lam & Wilson 2001).

In the rest of this paper, individual component factors in CAM: namely the source factor (α), the geometrical and whole path attenuation factors (G and β) the upper crustal factor (γ_{UC}) and site amplification factors are summarised and discussed under separate headings to address the effects of the source and wave transmission mechanisms. The CAM parameter Δ (which can be RSD_{max} , RSV_{max} or RSA_{max}) is expressed generically by the following expression:

$$\Delta = \alpha(M,d).G(R,D) \beta(Q,R,M). \gamma_{UC} (V_{300}, \kappa). S \quad (1)$$

where M is the moment magnitude, R is site-source distance, d is depth of centroid of the rupture surface, D is depth to Moho, Q is Quality Factor, V_{300} is the shear wave velocity at a depth of 300m, and κ is the parameter defining attenuation in the upper crust. (Full details of the site factor, S , in the CAM framework can be found in Lam *et al*(2001) and Chandler *et al* (2002)).

Eq.1 represents the latest expression of CAM which features new parameters not presented in earlier publications. Particular emphasis is given throughout the paper on how to incorporate regional geological and seismological conditions into the modelling.

2 SOURCE FACTORS

Modelling regional “source” effects based purely on observations requires capturing crucial information of seismic waves generated by major ruptures. This is a challenge to most intraplate regions where earthquakes of engineering significance typically occur very infrequently and in unexpected locations. The source characteristics of CENA has been modelled by Atkinson (1993) based on a database of some 100 intraplate earthquake records collected by a major seismometry network operating in CENA together with tele-seismometry records of major world events. In addition, theoretical constraints associated with the definition of the moment magnitude have been used to define very low frequency properties. In view of the costs for developing similar source models independently, the Atkinson model for CENA is tentatively taken as the generic model for all intraplate regions where earthquakes are typified by high stress drop and reverse (thrust) faulting. It is assumed at this stage of the model development that only crustal properties controlling the path effects vary whilst the average source properties are uniform. This major assumption is being continuously tested as CAM is compared with field observations on an international scale. Comparisons to-date are generally very supportive of this assumption (Lam *et al* 2000c, Koo 2001, Chandler & Lam 2002,

Balendra *et al* 2002, Lam *et al* 2002).

The generic source mode of Atkinson has been incorporated into CAM by stochastic simulations and response spectrum calculations as presented in Lam *et al* (2000b), and is expressed as follows:

$$\alpha(M) = a_0^* (a_1 + a_2(M-5)^{a_3}) \quad \text{bracketed term is unity at } M=6 \quad (2a)$$

Table 1 Source factor coefficients of Eq.2a

Parameter	a_0^*	a_1	a_2	a_3
$RSD_{\max}(\text{mm})$	10	0.20	0.80	2.3
$RSV_{\max}(\text{mm/sec})$	70	0.35	0.65	1.8

* Note : a_0 has only been introduced in this publication as a new notation

Eq.2a and Table 1 are based on results from stochastic simulations assuming hard rock conditions and a reference distance of 30km. Whilst RSD_{\max} and RSV_{\max} have been defined very precisely, it is recommended that RSA_{\max} be predicted simply in accordance with a pre-determined corner period (T_1) which defines the transition between the acceleration and velocity controlled regions of the acceleration response spectrum. T_1 in the order of 0.05-0.10secs can be inferred from stochastic simulations for hard rock conditions (Lam *et al* 2000b). $T_1 = 0.1$ secs is considered appropriate for hard rock conditions for most practical applications since most infrastructure has a fundamental period higher than this value. More precise predictions for RSA_{\max} do not seem to be justified in view of the uncertainties and site-to-site variabilities associated with low period (high frequency) responses.

The amplitude of waves generated from the source of the earthquake is proportional to the shear wave velocity (V_s) of the surrounding crust raised to a power of 3 according to wave theory. Eq.2a assumes that fault rupture is at a depth $d > 12$ km approximately where V_s averages around 3.8km/sec. At a shallower depth $d = 8$ km or 4km, V_s is estimated to average at 3.55km/sec or 3.45km/sec respectively based on the generic shear wave velocity profiles of Boore & Joyner (1997). The so called ‘‘mid-crustal’’ amplification factor which allows for this ‘‘depth effect’’ of the source is accordingly 1.25 or 1.35.

Eq.2a can be re-written in accordance with the scaling relationship described above to incorporate ‘‘d’’ as the modelling parameter:

$$\alpha(M,d) = a_0 (a_1 + a_2(M-5)^{a_3}) \cdot (1.48 - 0.03d) \quad (\text{for } 4 < d < 8) \quad (2b)$$

In situations where d is uncertain, assuming a mid-crustal factor of 1.3 (corresponding to $d = 5 \sim 7$ km) seems to be reasonably conservative. For most moderate and large magnitude shallow earthquakes ($M \geq 6$) the centroid of the ruptured surface is constrained to a minimum depth due to the finite dimension of the rupture. For example, d is unlikely to be considerably less than 5km for a M6 earthquake which has a rupture dimension in the order of 100 km² even if the rupture reaches the earth surface. Thus,

$$\alpha(M) = a_0 (a_1 + a_2(M-5)^{a_3}) \cdot (1.3) \quad (\text{for } M \geq 6 \text{ shallow crustal earthquakes}) \quad (2c)$$

The source factor of CAM at this stage of the model development is restricted to typical intraplate crustal earthquakes. There is plenty of scope to extend CAM for modelling earthquakes in other seismo-tectonic settings (eg. subduction earthquakes).

3 GEOMETRICAL AND ANELASTIC WHOLE PATH ATTENUATION FACTORS

For near-field earthquakes ($R < 50$ km), the Geometrical factor (G) and the Anelastic Whole Path Attenuation Factor (β), both normalised to unity at 30km distance, is given by Eq.3 (Lam *et al* 2000b).

$$G(R) = 30/R \quad (\text{for } R \leq 50\text{km}) \quad (3a)$$

$$\beta(R) = (30/R)^{C_1 R} \quad (\text{for } R \leq 50\text{km}) \quad (3b)$$

where $C_1 = 0.003, 0.005$ and 0.015 for RSD_{\max} , RSV_{\max} and RSA_{\max} respectively.

At this distance range, regional differences are not shown to result in any significant overall effect on the attenuation of the seismic waves. For a short transmission path, energy dissipation is generally very limited and hence regional parameters have not been included into the expression. As the wave transmission path exceeds 100km, regional parameters such as the depth to the Moho discontinuity (D) and Quality Factor (Q) becomes significant.

Low amplitude seismometry records may contain potentially useful information of the wave travel path regardless of the engineering significance of the earthquake itself. For example, the attenuation of low amplitude seismic waves with distance (spectral-ratio method) and time (Coda Q method) is commonly measured using seismometers following an earthquake tremor (Wilkie & Gibson 1995). The Quality Factor (Q) could then be determined from these studies to define the regional wave transmission quality of the earth's crust. Whilst the measurement seems relatively straightforward, results are typically interpreted only in terms of a filter function in the Fourier spectral format. Importantly, there has been no widely recognised, and direct, link between Q and the potential earthquake hazard in engineering terms (other than by repetitive stochastic simulations using specialised software).

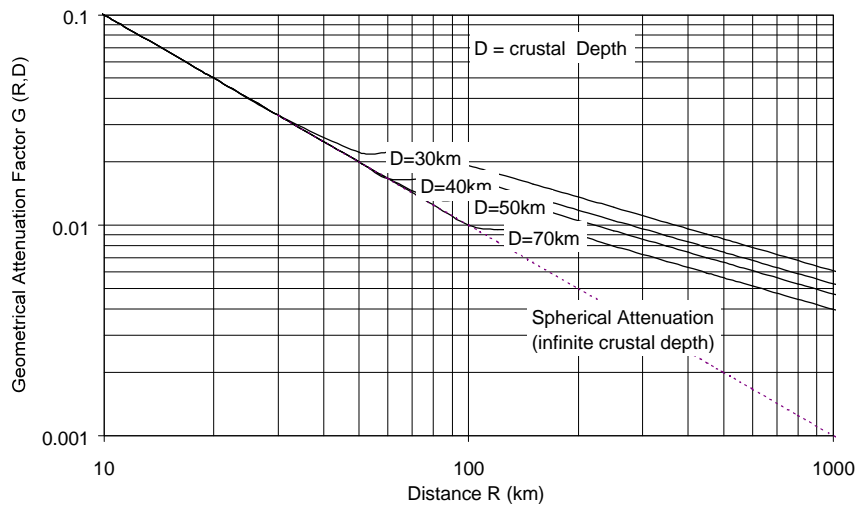


Figure 1: Geometrical attenuation factor G (R,D) for both RSV_{max} and RSD_{max}

The G factor in Eq.3a has been modified in accordance with the tri-linear attenuation relationship of Atkinson & Mereu (1992). Eq.3b has also been further developed into a far more elaborate form to provide the link between Q and the response spectrum parameters (Chandler & Lam 2002). The developed attenuation relationships are presented herein graphically (Figures 1 & 2).

4 UPPER CRUSTAL FACTORS

Upward propagating seismic waves can be modified rapidly by the upper (say 4km) layers of the earth's crust due partly to the shear wave velocity gradient. The seismic waves could also be affected significantly by attenuation mechanisms which are represented collectively by the well known *Kappa* parameter (Atkinson & Silva 1997; Abercrombie 1997; Boore & Joyner 1997). These path effects as described can be difficult to track if measurements are only taken from the earth's surface. When the path effects and the source effects are both uncertain, it is clearly difficult to separate these effects based merely on information provided by earthquake records. A viable alternative to estimate the upper crustal effects is by studying crustal properties using information obtained from borehole records and from seismological sources.

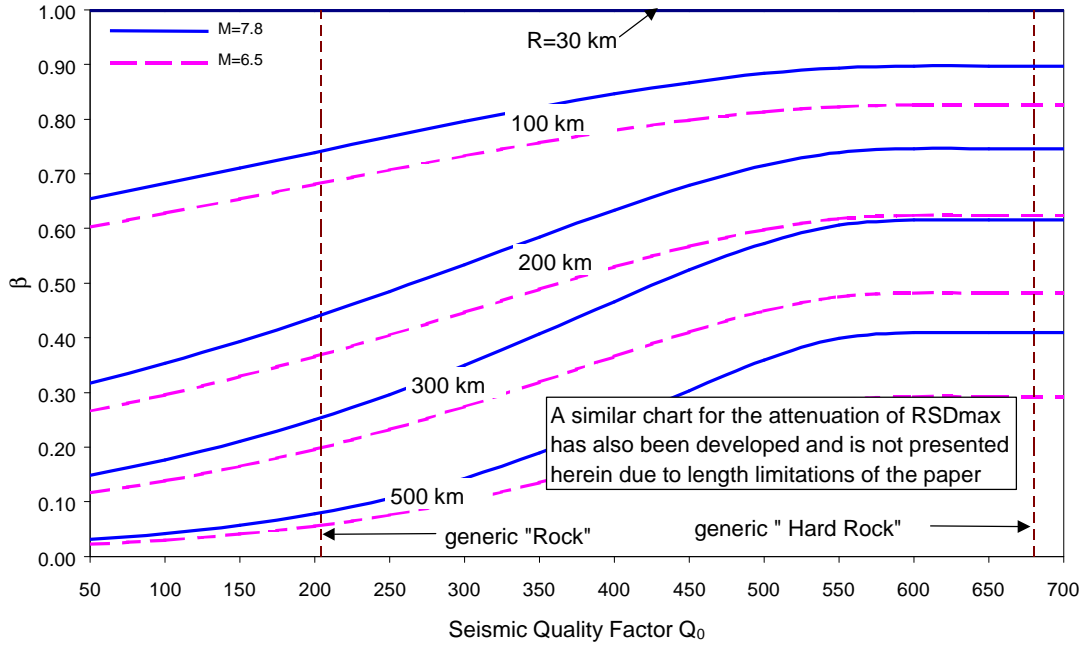


Figure 2: Normalised anelastic whole path attenuation factor $\beta(R,Q,M)$ for RSV_{max} after Chandler & Lam (2002)

Generic crustal shear wave velocity (SWV) profiles have been developed by Boore & Joyner (1997) for the Western and Eastern parts of North America (WNA and CENA) using a large database of downhole travel time survey records together with P and S-waves velocity data obtained from seismological refraction experiments and monitoring programs. The proposed "quarter wave length approximation" rule was applied to determine the filter function based on the modelled SWV profiles. Stochastic simulations were then used to represent the crustal effects in the form of the velocity response spectrum as shown in Figure 3 for the earthquake scenario of M6 at 30km distance on rock sites. The response spectral velocity amplification is shown to occur at the period range of 0.2-0.6secs. Wave components in this period range are controlled by properties of the earth crust at a depth range of between 100-400m according to the quarter-wave length approximation rule. For this reason, the SWV gradient associated with upper crustal effects is defined by the SWV estimated at a reference depth of 300m (V_{300}) in the CAM framework. For example, the V_{300} values for generic "Rock" and generic "Hard Rock" profiles are 2000m/sec and 3000m/sec respectively (Figure 4). Determining V_{300} requires drilling holes in rock, and boreholes exceeding 100m are rare and very expensive to drill. Downhole travel time survey is also rarely undertaken in regions of low and moderate seismicity. At the moment, V_{300} can only be estimated by fitting curves based on measurements at shallow depths. Importantly, inexpensive micro-tremor monitoring methods involving only measurement on the ground surface are currently under development to survey shear wave velocity profiles down to depths reaching hundreds of metres (eg. Asten *et al* 2002a&b).

Another important parameter to determine is $Kappa$ which can be estimated from Q values close to the earth surface based on Coda waves recorded from earthquake tremors at very close range (Wilkie & Gibson 1995). $Kappa$ is estimated to be in the range 0.03-0.05secs for WNA (Atkinson & Silva 1997) but very low values (<0.01secs) have been inferred from data collected in Eastern China. Individual graphs presented in Figure 3 are associated with $kappa$ values ranging between 0.01 and 0.05secs. The effect of $Kappa$ is clearly important but its significance diminishes rapidly with increasing natural period. Similar trends have also been observed in the analysis for a M7 scenario (details not shown).

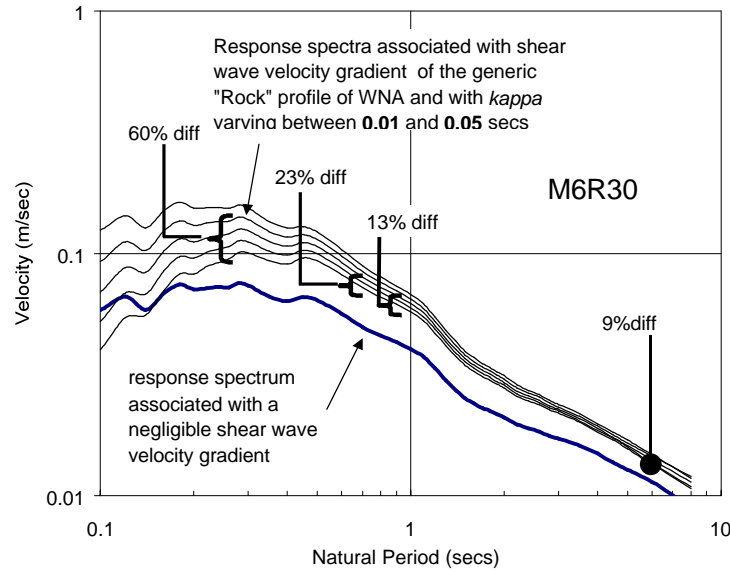


Figure 3 Response Spectra Showing Upper Crustal Modifications

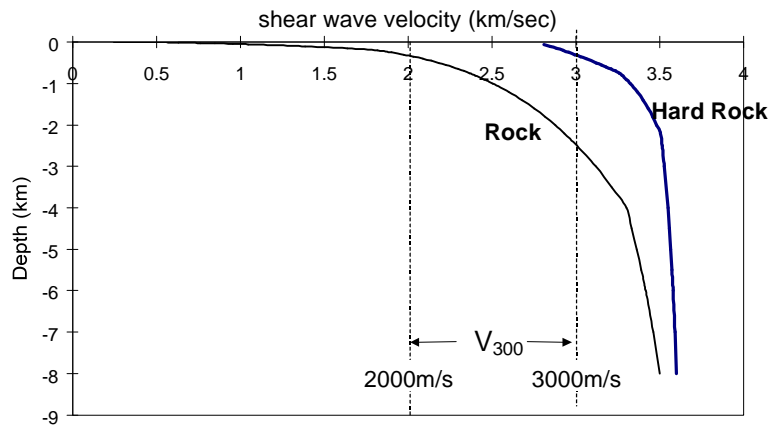


Figure 4 Shear Wave Velocity Profiles of the Generic Crustal Models

Estimated values of the corresponding upper crustal factor $\gamma(V_{300}, \kappa)$ as introduced in Eq.1 are listed in Table 2 below for the case of the generic “Rock” profile in which $V_{300}=2000\text{m/sec}$. The upper crustal factor for the generic “Hard Rock” profile, with $V_{300}=3000\text{m/sec}$, is very small and may be neglected.

Table 2 Upper-Crustal Factors $\gamma_{UC}(V_{300}, \kappa)$ for $V_{300}=2000\text{m/sec}$

Response Parameters	Kappa values				
	0.01	0.02	0.03	0.04	0.05
RSD _{max}	1.25	1.25	1.20	1.15	1.15
RSV _{max}	1.85	1.65	1.50	1.35	1.20

The upper crustal factor (γ_{UC}) quoted in some earlier publications of CAM was in the order of 1.20-1.25 which was based on a κ value of 0.05secs recommended for the high seismic region of WNA. Recent studies leading to the listing in Table 2 have modelled the increase in γ_{UC} with decreasing κ which are expected in certain regions of low and moderate seismicity. However, the higher crustal amplification seems to be limited only to the velocity controlled period range and is not sustained at higher periods. Thus, κ does not seem to have pre-dominant engineering significance in the context of displacement demand which is related directly to structural drift and

stability.

Overall, the upper crust tends to amplify RSD_{max} and RSV_{max} and attenuate RSA_{max} . It is recommended in Lam *et al* (2000c) that the corner period of the acceleration response spectrum(T_1) be varied from 0.1sec (for M5) to 0.3secs (for M7) to account for the upper crustal attenuation in generic "Rock" (in comparison with $T_1=0.1$ secs for generic "Hard Rock" as described in Section 2).

5 MODELLING SITE AMPLIFICATION

The effects of soil resonance on soil sites is an important design consideration for structures. Moreover, the effects of site resonance are accentuated for a non-ductile construction which has little energy absorption capacities. For this reason, modelling the effects of site resonance is central to CAM. In CAM, the response spectrum representing the effects of site resonance is constructed in accordance with the amplified response at the fundamental site period (T_s) at which point the structure is subject to the highest drift demand. The effects of resonance are therefore best presented in the displacement response spectrum format as shown in Figure 5. This form of response spectrum construction is distinguished from most contemporary site amplification models which do not parameterise site period explicitly. The "site factor" (S) as shown in Figure 5 is dependent on factors including the soil SWV, hysteretic and radiation damping properties and frequency content of the bedrock excitation in relation to the site period. Research is continuing to study amplification associated with resonance. The S factor can be simplified as follows based on studies undertaken to date (Lam *et al* 2001; Chandler *et al* 2002) :

$$S \sim 6\lambda \text{ where } \lambda = 0.8 + 0.0001(V_{bedrock} - 1000) \geq 0.8 \quad (4)$$

The site factor as defined by Eq.4 is clearly significantly higher than most current code provisions which are typically based on averaging results associated with soil profiles of different site periods. It should be noted that the effect of resonance has been smeared by this averaging of results. This averaging approach seems appropriate in situations where the site period cannot be ascertained accurately. In the authors' opinion, the preferred approach for the future is to develop and use inexpensive and effective monitoring techniques extensively to provide reliable estimates for the site period.

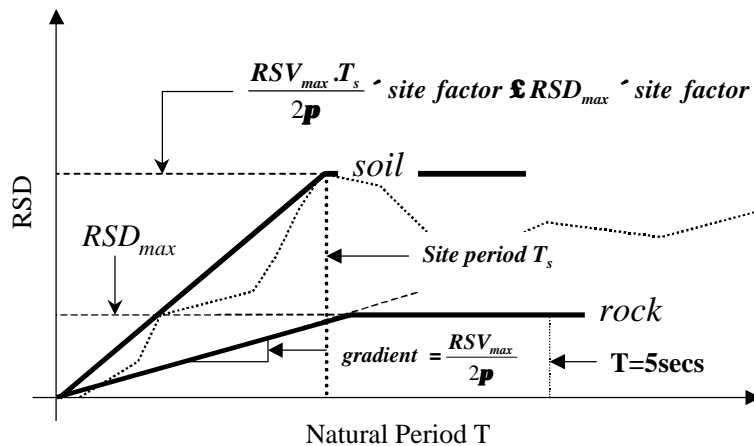


Figure 5 Effects of resonance on actual (dotted line) and idealised (solid lines) Displacement Response Spectra

6 CLOSING REMARKS

This paper presents CAM as a framework for predicting the overall response spectrum properties associated with typical intraplate earthquake scenarios. The incorporation of regional geological and seismological information such as magnitude, distance, SWV profiles, Q and $Kappa$ into the prediction enables a diversity of conditions to be modelled under one generic framework. In regions lacking representative earthquake data, a collective and generic approach to modelling such as CAM is

clearly more advantageous than developing regional attenuation models in isolation. The underlying philosophy of CAM, which allows new information to be incorporated into the model, is therefore more dynamic and open than the conventional approach of developing an attenuation model from a closed dataset of earthquake records.

The emphasis of CAM on the displacement response spectrum and the associated RSD_{max} and RSV_{max} parameters is consistent with the recent emphasis on displacement demand in relation to satisfying life-safety and damage performance objectives. CAM provides an important transparent link between the two response spectrum parameters and seismological parameters such as moment magnitude, distance, Q , SWV profile (V_{300}), $Kappa$ and soil parameters as summarised in the paper. The multi-disciplinary facets of CAM ensure that future development of the model is aligned with up-to-date engineering objectives.

7 ACKNOWLEDGEMENTS

The Component Attenuation Model (CAM) is a key research outcome produced by a major earthquake engineering research program undertaken at the University of Melbourne and supported by the Australian Research Council. The important contributions by Prof. Adrian Chandler of Hong Kong University to the development of CAM are specifically acknowledged.

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