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NEW PERSPECTIVES IN DEVELOPING A GMPE FOR LOW TO MODERATE SEISMICITY OF AUSTRALIA USING A HYBRID APPROACH

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Abstract

Ground motion prediction equations (GMPEs) are fundamental tools in conducting both deterministic and probabilistic seismic hazard assessments. These equations are developed to predict the intensity of ground shaking for a given earthquake, particularly the combination of magnitude and source-site distance. GMPEs are furthermore central in developing earthquake loading codes used for the design of large engineered structures. A major revision of Australia's National Seismic Hazard Assessment is currently underway. It is therefore timely in developing a new hybrid based approach to GMPE, particularly important for Australia that experiences low to moderate seismicity and lacks vast amounts of strong motion records required in an empirical approach. A key aspect of any GMPE is the attenuation behaviour.

Attenuation behaviour of ground shaking due to an earthquake is a complicated interaction between rupture propagation, direction and energy release, as well as material it passes through. These basic properties can be modelled to form a GMPE for a given region, mechanism and method of modelling. Typically, such attenuation factors can be classed into regional (properties of seismic waves generated at source), local (extent of amplification and attenuation) and site (filtering mechanics of the bedrock layers) factors.

In low to moderate seismic regions, most GMPEs use any available data, but also heavily rely on stochastic approaches to generate sufficient data for modelling. In Australia three existing GMPEs have been developed; the Liang model [1] specifically for south-western Western Australia; Somerville models [2], one for Cratonic Australia and the other for Non-Cratonic Australia; and Allen model [3] for south-eastern Australia. These models use a stochastic approach and therefore lack empirical data.

Another approach applied in Australia is the Component Attenuation Model (CAM). CAM is a framework by which a generalised attenuation model is derived from stochastic data of seismological properties rather than recorded earthquake data. This model comprises a series of component factors that represent effects of the source, wave travel path and material it passes through. The CAM technique has been successfully compared with real earthquake data from PEER strong-motion databases, as well as pilot case studies in parts of Australia and Southeast Asia.

The purpose of this paper is to model the GMPEs using a hybrid GMPE approach (investigated by Campbell [4]) as well as CAM approach, then compare Australian GMPEs and PEER-NGA models with available Australian recorded data. Discussion focusses on the models with better comparisons to Australian data and explores the underlying assumptions or requirements used in each case. Analysis shows that the attenuation is over estimated by the models in the 10 – 100 km range and the 5% damped acceleration spectra are inconsistent in the 0.3, 0.5 and 1second periods. As this range of distance and period of structures are highly crucial for major Australian cities there is a requirement to produce an improved GMPE model for Australia.

Keywords: Ground Motion Prediction Equation; GMPE; CAM; seismic hazard; attenuation modelling

1. Introduction

Ground motion prediction equations (GMPE) are fundamental tools in conducting both deterministic and probabilistic seismic hazard assessments (DSHA or PSHA). These equations are developed to predict the intensity of ground shaking for a given earthquake, particularly the combination of magnitude and source-site distance. GMPEs are furthermore central in developing earthquake loading codes used for the design of large engineered structures. A major revision of Australia's National Seismic Hazard Assessment (NSHA) is currently underway. It is therefore timely in developing a new hybrid based approach to GMPE, particularly important for Australia, that experiences low-seismicity and lacks vast amounts of large strong motion records required in an empirical approach.

In low-seismic regions, developing a GMPE will require use of any available strong motion recorded data, and will subsequently heavily rely on stochastic approaches to generate sufficient data for modelling regression. In Australia, where there is a lack of well documented large magnitude earthquakes recorded by multiple seismic recorders at varying distances from the epicenter, it is therefore problematic in adopting a traditional or empirical approach. Recently, three GMPEs have been developed using available Australian data as well as stochastically simulated data, but these have their limitations as a result of this approach.

Another approach already applied in Australia is the Component Attenuation Model (CAM). CAM is a framework by which a generalized attenuation model is derived from stochastic data of seismological properties rather than recorded earthquake data. The purpose of this paper is to compare the available Australian GMPEs and PEER-NGA models with available Australian recorded data and to discuss how the models align with actual earthquake recordings, with reference to other existing studies. As each GMPE has its own assumptions and data sources applied, there is a requirement to produce an improved GMPE model for Australia. Advantages of a hybrid approach, using both GMPE and CAM to formulate an alternative and new model for Australia will be crucial to furthering knowledge in this field. This paper will therefore explore progress to date and how such improvements will also assist upcoming revisions on earthquake loading codes following the NSHA project completion.

2. Seismic Hazard Assessments

2.1 Deterministic and Probabilistic Seismic Hazard Assessments

Two methods of conducting a Seismic Hazard Assessment (SHA) include the Deterministic SHA (DSHA) and the Probabilistic SHA (PSHA) and are only described contextually here. A DSHA is a simpler process used in tectonically active regions that are well defined and is used to determine the maximum credible earthquake motion at a site. However, this method does not account for uncertainties particularly well and is not usable in low to moderate seismic regions. Whereas the PSHA is better suited to accounting for uncertainties and probabilities of an earthquake's occurrence. The purpose of the PSHA approach is to conduct either a site-specific study or a seismic hazard map of a large region, state or nation. Some nations have developed their own seismic hazard maps particularly for assisting in preparing earthquake loading codes, whilst other nations borrow or use another similar nation's hazard map given tectonic and seismic similarities.

The methodology adopted originally proposed by Cornell [5] is often modified using revised versions, most commonly the Cornell-McGuire [6] method. Three components required for a PSHA and include:

- Defining the seismotectonic source zones in spatial terms whereby uniform seismicity is assumed to occur within (these can be irregular shaped areas, grid application, linear sources particularly for active faults and subduction trenches),
- Modelling the earthquake recurrence with respect to earthquake magnitude (Gutenberg-Richter small to large magnitude relations or "b-value"), and
- Selection of appropriate GMPEs for the tectonic regime (accounting for aleatory variability by inclusion of as many relevant models as available).

2.2 GMPE Component for SHA

Once the source model is defined and the earthquake recurrence parameters are determined, the choice of selecting most appropriate GMPEs for use in the SHA is vital. The selection of GMPEs should be broad enough to capture sufficient epistemic uncertainty, especially in a logic-tree framework approach to the PSHA. Note that each GMPE will account for aleatory variability within their developed model. Several authors have described a criteria list by way of an inclusion or exclusion principle [7,8,9,10].

The GMPE (formerly "attenuation function" and more recently "ground motion model" or GMM) is essentially a tool used in equation form to "predict ground motion" at a given location based on an earthquake of known magnitude at another location. Typically, in active regions such as California or Japan, real earthquake recordings will be modelled using a regression method. However, in low to moderate seismic regions, such as Australia, simulated data are generated using either a stochastic approach [11] or Green's Function method [12].

3. GMPEs Developed for Australia

Available data for the intraplate low to moderate seismic regions of Australia is limited, and thus locally developed GMPEs rely heavily on stochastic approaches to generate sufficient data for modelling regression. Table 1 lists three current GMPEs developed for Australia, these include the 'Liang08' model specifically for south-western Western Australia; the 'Sea09' models, one for Non-Cratonic Australia ('Sea09 Non-Cr') and one for Yilgarn or Cratonic Australia ('Sea09 Y-Cr'); and the 'A12' model for south-eastern Australia. These have all used a stochastic approach and therefore lack empirical data typically used by high-seismic regions. Table 1 lists all the parameters incorporated and the comparisons between each model in its data collection, analysis and subsequent development.

Table 1 – Current Australian GMPE parameters, modified from [13]

<table>
<tr><th>GMPE</th><th>Region</th><th>H & E</th><th>M_{min}</th><th>M_{max}</th><th>M_{scale}</th><th>R_{min}</th><th>R_{max}</th><th>R_{scale}</th><th>S</th><th>T_s</th><th>T_{min}</th><th>T_{max}</th><th>R</th><th>M</th></tr>
<tr><td>Liang08</td><td>SW West Aust</td><td>2 earthquakes in SW WA, with stochastic simulations</td><td>4.0</td><td>7.0</td><td>M_L</td><td>50</td><td>200</td><td>R_{epi}</td><td>CENA</td><td>31, PGA, PGV</td><td>0.05</td><td>30</td><td>2M</td><td>T</td></tr>
<tr><td>Sea09 Non-Cr</td><td>Non-Cratonic Aust</td><td rowspan="2">300 stochastic point-source simulations reflecting parametric variability at various distances and magnitudes</td><td rowspan="2">5.0</td><td rowspan="2">7.5</td><td rowspan="2">M_W</td><td rowspan="2">0</td><td rowspan="2">500</td><td rowspan="2">R_{jb}</td><td rowspan="2">1-rock V_{S30} = 865 m/s</td><td rowspan="2">22, PGA, PGV</td><td rowspan="2">0.01</td><td rowspan="2">10</td><td rowspan="2">1M</td><td rowspan="2">T</td></tr>
<tr><td>Sea09 Y-Cr</td><td>Yilgarn-Cratonic Aust</td></tr>
<tr><td>A12</td><td>SE Aust</td><td>56,000 stochastic simulations at 44 unique distances, logarithmically spaced 1-422 km</td><td>4.0</td><td>7.5</td><td>M_W</td><td>0</td><td>400</td><td>R_{rup}</td><td>1-rock V_{S30} = 820 m/s</td><td>18, PGA, PGV</td><td>0.01</td><td>4</td><td>2M</td><td>T</td></tr>
</table>

Parameters in table are: H- number of horizontal records; E- number of earthquakes; R- distance; S- number of different site conditions; T_S- number of periods which attenuation is derived; T_{min}- Minimum period which attenuation is derived; T_{max}- Maximum period which attenuation is derived R- regression method used; M- source mechanism; 1M- Maximum likelihood one-stage regression; 2M-Maximum likelihood two-stage regression; T- Thrust mechanism.

3.1 Hybrid GMPE Approach

In 2003, Campbell proposed a hybrid empirical method that makes use of the ratio of stochastic (theoretical) ground motions in order to compare and use empirical ground motion relations developed for region A, to be used for region B [4]. In the 2003 study, data and empirical relations from western North America (a high-seismic region) were used for eastern North America (a low-seismic region).

Campbell identifies three factors that make such a hybrid empirical method a useful substitute to traditional stochastic methods [4]. Firstly, using well constrained strong motion recordings at multiple magnitude and distance ranges is important for engineering considerations. Secondly, using the relative differences of ground motions between the original and study regions to derive adjustment factors can be helpful. And thirdly, but most importantly, it will estimate aleatory variability and epistemic uncertainty within the derived GMPE more clearly. However, there are limitations to this approach, as applying a hybrid empirical method still requires a large collection of quality data for both the original and study regions. Another potential limitation may be if both regions have very different source spectral shapes, however some studies have shown that this may not be as important as initially thought [14]. A more significant potential limitation is this hybrid approach can only reliably be used for ground motions up to distances of 70 to 100 kilometres.

4. Component Attenuation Model

The Component Attenuation Model (CAM) is a theoretical model that utilises real earthquake data to determine the values required in the attenuation parameters, as opposed to requiring this data (including simulated data) for determining trends by regression analysis techniques [15]. In this approach there is less required ground motion data required, thus also strengthening the approach with less epistemic uncertainties to consider than the PSHA and GMPE traditional approach. It is based on the original work of Brune [16] in classical wave theory of ground motion simulations and has been expanded upon by Boore [17]. This is referred to as the seismological model [15,18,19] that is used for constraining frequency properties of earthquake scenarios for various regions, including low to moderate seismic regions where strong motion data is often lacking. Such pilot studies have been prepared for Australia [20], eastern China [21], Hong Kong [22], South China [23], Tehran [24], and Singapore [25].

The form of the base equation, given in Eq. (1), with variables also explained. Note that the parameters α, β and G form the component factors of the CAM approach. Variables listed in the equation where M is moment magnitude, R is site-source distance and d is depth of centroid of the rupture surface, V_{s300} is shear wave velocity at a depth of 300 metres and *kappa* is the parameter defining attenuation in upper crust.

$$\Delta = \alpha(M,d).\beta(Q,R,M).G(R,d).\gamma_{uc}(V_{s300}, \mathit{kappa}).S \tag{1}$$

Where: Δ = RSD_{max}, RSV_{max} or RSA_{max} (maximum values on displacement, velocity and acceleration response spectrum respectively)

α = source factor where reference prediction is based on R = 30 km on hard rock

β = predicted modification by energy absorption along travel path

G = predicted modification by geometrical spreading

γ_{uc} = predicted upper crustal factor

S = site amplification factors

This approach has been compared to earlier GMPEs in the work of Lam [15] and has been found to estimate a higher V_{max} due to the assumed high stress drop properties incorporated into the model. The results of three earlier earthquakes fit the CAM peak ground velocity estimates reasonably well for Melbourne and should be therefore investigated with more recent and well documented earthquakes.

5. Recent Australian Earthquakes

Previous studies comparing Australian GMPEs and non-Australian GMPEs (including the PEER-NGA) models with available Australian recorded data have included an accumulation of data particularly from south-eastern Australia. In 2001, through qualitative assessments of at least 15 earthquakes between M_L 3.4 to 5.1 were compared to Esteva & Rosenblueth [26], Sadigh [27] and Toro [28] models and found that the Sadigh GMPE was most similar to south-eastern Australian conditions [29]. The most recent version of the Australian Earthquake Hazard Map included two sets of Australian data with more recent GMPEs for western and eastern regions [30]. This study also heavily relied on small to moderate earthquakes at similar distances with M_W 4.1 to 4.6 up to 200 kilometres and M_W 4.0 to 5.3 up to 400 kilometres for western and eastern Australian data respectively. This study concluded the best performing GMPEs across all periods for western Australia are Atkinson and Boore [31], Allen [3] and Chiou and Youngs [32], whilst for eastern Australia these are Atkinson and Boore [31] and Allen [3]. It also considered a theoretical M_W 8.5 offshore earthquake, closest to the plate boundary north of Australia whereby the AUS6 seismotectonic model connects to an existing ASIA1 model [33]. A combination of subduction zone, cratonic and non-cratonic GMPEs were considered appropriate in order to capture sufficient epistemic uncertainties, however gave very large differences at 500 kilometres distance.

A dense temporary network deployed by The University of Melbourne (supplementing long-term seismic networks of the Seismology Research Centre and Geoscience Australia) following the subsequent M_L 5.4 19 June 2012 Moe earthquake (shown in Figure 1) recorded almost 500 aftershocks, the largest being M_L 4.4 20 July 2012. The GCMT solution was used in determining the focal mechanism of the Moe mainshock. This event was recorded as being an oblique thrust event along a series of active faults within the Strzelecki Ranges [34]. The seismic stations as owned and operated by various bodies are shown in Figure 1 together with the location and focal mechanism of the ML5.4 19 June 2012 Moe earthquake. This wealth of data was subsequently compared qualitatively with the NGA-West2 GMPEs released in 2014, as well as Australian GMPEs and determined that the Abrahamson [35] GMPE gave the closest ground motion estimates for the mainshock on soil sites, whilst the Chiou and Youngs [36] GMPE gave best estimates for the same event on rock sites. Further research on V_{S30} values for these sites would be required to confirm this.

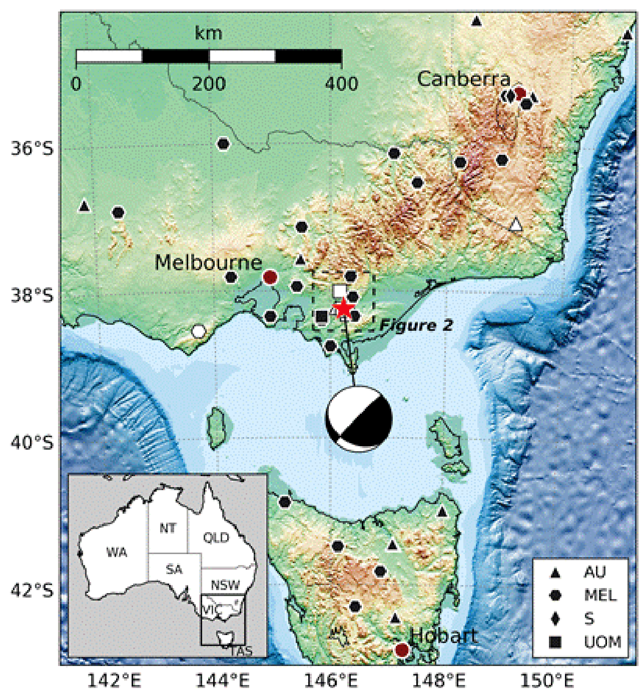

Fig. 1 – Focal mechanism & location of the M_L 5.4 (M_W 5.15) 19 June 2012 earthquake with respect to seismic stations that recorded the event. Station owners/operators listed as AU: Geoscience Australia; MEL: Seismology Research Centre; S: Seismographs in Schools; and UOM: University of Melbourne, from [37]

The most thorough investigation to date using recorded earthquakes in south-eastern Australia was compiled during development of the Allen [3] GMPE, with 75 earthquakes ranging from M_W 2.8 to 5.4, but did not include the 2012 Moe mainshock event. In review of the Moe event it is concluded that the data fits the A12 [3] GMPE well with recordings at two stations available at the time.

Since this was prepared, further research currently underway to incorporate this information more succinctly and comprehensively, have shown initial recordings at multiple stations at various magnitude and distances is shown in Figure 2 and 3 [37]. Figure 2 represents 5% damped pseudo response as spectral acceleration versus period for nine seismic stations at various distances that recorded the 2012 Moe mainshock event comparing at least eight GMPEs including the ‘A12’ GMPE. Four cratonic GMPEs include the Toro ‘T02’ [38]; Campbell ‘C03’ [4]; Atkinson and Boore ‘AB06’ NEHRP B/C boundary [31]; and Pezeshk ‘Pea11’ [39] models; whilst for active shallow crustal GMPEs include the Allen ‘A12’ [3]; Boore ‘Bea14’ [40]; Somerville ‘Sea09’ Non-Cratonic [2]; and Yennier and Atkinson ‘YA15’ [41] models are all plotted for the Moe mainshock event. These are listed in greater detail in the caption but show the non-cratonic GMPEs, especially ‘A12’ GMPE as fitting the data reasonably well at various distances, as compared to the cratonic GMPEs. This clearly demonstrates that for the non-cratonic event of Moe in south-eastern Australia, these GMPEs are better suited than other GMPEs for non-similar tectonic regimes.

Figure 3 shows similar information for four periods (0.2, 0.5, 1.0 and 2.0 sec) but for 5% damped pseudo response spectra as spectral acceleration versus distance [37]. The black crosses show stations recording the Moe event on mainland Australia, whilst the grey X’s represent stations recording the same event across the Bass Strait which has been thought to possibly cause amplitude changes under the sea between mainland Australia and Tasmania, this is yet to be verified at this stage.

6. NSHA Project

The multi-faceted project being led by Geoscience Australia is formulating new perspectives to the components that are in-built within PSHA studies. Re-evaluation of a compiled earthquake catalogue from multiple sources requires involved consideration of magnitude determination methods used and cross-correlating these across multiple sources. This is particularly important when considering a cohesive catalogue is consistent over time periods and regions for magnitude conversion units where differences may occur. This data then builds into the development of multiple seismotectonic models that interpret this information to earthquake magnitude recurrence rates. Different researchers have differing approaches, including uniform distributed seismicity in area and fault models, gridded source models as main types. These all have the same outcome, to interpret the seismicity with or without further information, such as that on tectonics, geology and active faulting in order to define the seismicity within these models.

Another major contribution of the NSHA project is on selecting appropriate weightings, not only to these seismotectonic models, but also to the GMPEs that are incorporated in a PSHA. With insufficient GMPEs developed for Australia, incorporating non-local GMPEs is often adopted and will be explored in the project. The contribution that the authors propose is as well as a new seismotectonic model to be developed, it is equally important to propose another GMPE. This will contribute to minimising the aleatory variability of such GMPEs, particularly for Australia and with more emphasis on capturing more geological properties in these, a more robust consideration of such ground motion can be accounted for.

Fitting non-Australian GMPEs to Australian records appears problematic as differences in seismological properties as used in these other models may not be strictly comparable to Australian equivalents and thus requires further research. Adopting Campbell’s mathematical framework for a hybrid empirical method, using a ratio of stochastic or theoretical ground motion estimates for one region in order to build an alternate GMPE for various regions of Australia will form the basis of this alternative GMPE to be developed by the authors. Further considerations of attenuation components may also be fruitful in selecting appropriate values for this purpose.

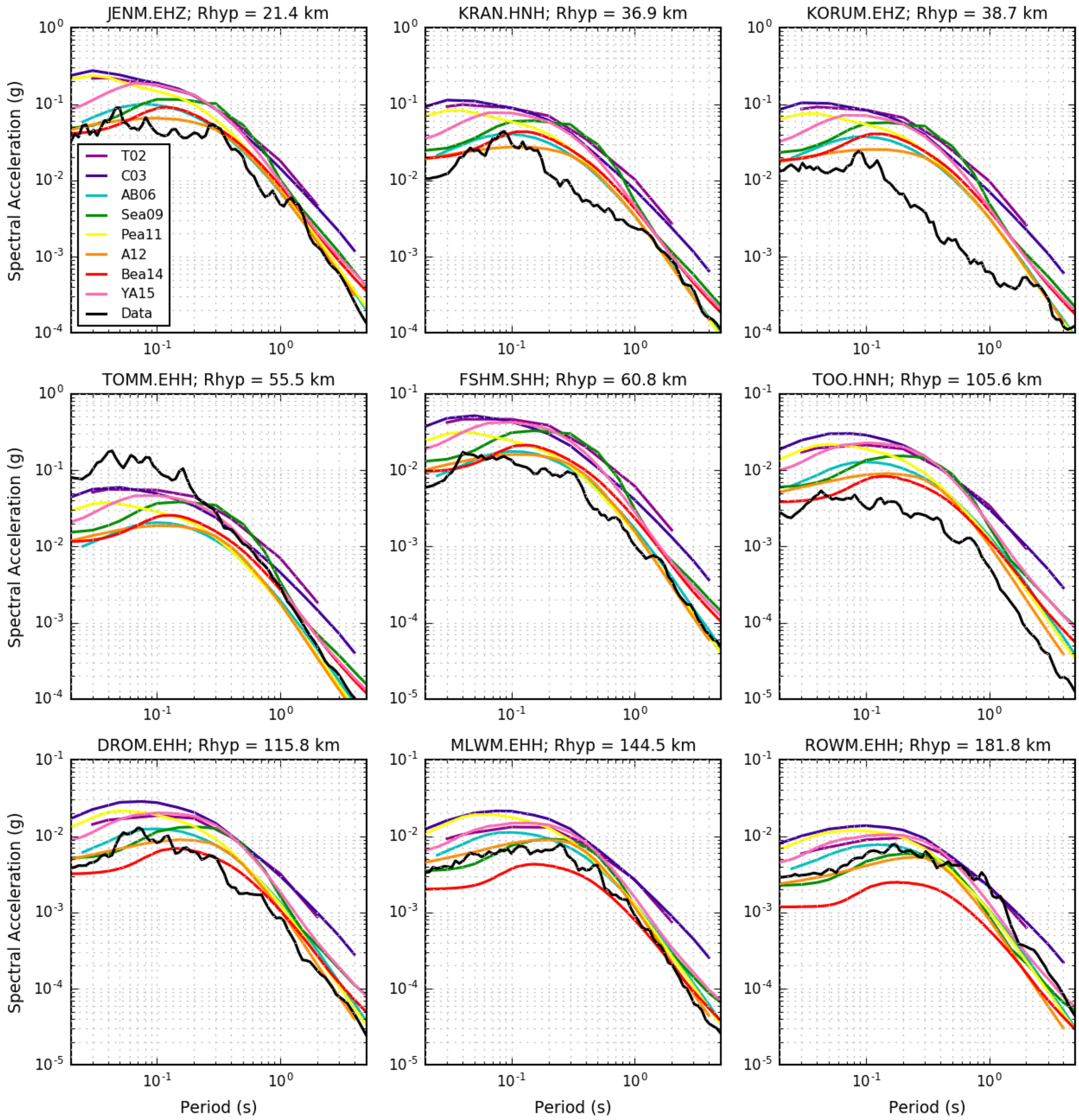

Fig. 2 – Five-percent damped pseudo response for the M_L 5.4 (M_W 5.15) 19 June 2012 earthquake plotted against commonly-used GMPEs for earthquake hazard assessments in Australia: Toro 'T02' [38]; Campbell 'C03' [4]; Atkinson and Boore 'AB06' NEHRP B/C boundary [31]; Somerville Non-Cratonic 'Sea09' [2]; Pezeshk 'Pea11' [39]; Allen 'A12' [3]; Boore 'Bea14' [40]; and Yennier and Atkinson 'YA15' [41]. The subplot titles indicate the station name, channel and Hypocentral distance. The last character of the channel (i.e. the channel orientation) is appended with "H" when the geometric mean of the two horizontal components is used. V_{S30} value of 760 m/s is used for calculation of GMPEs where appropriate, from [37].

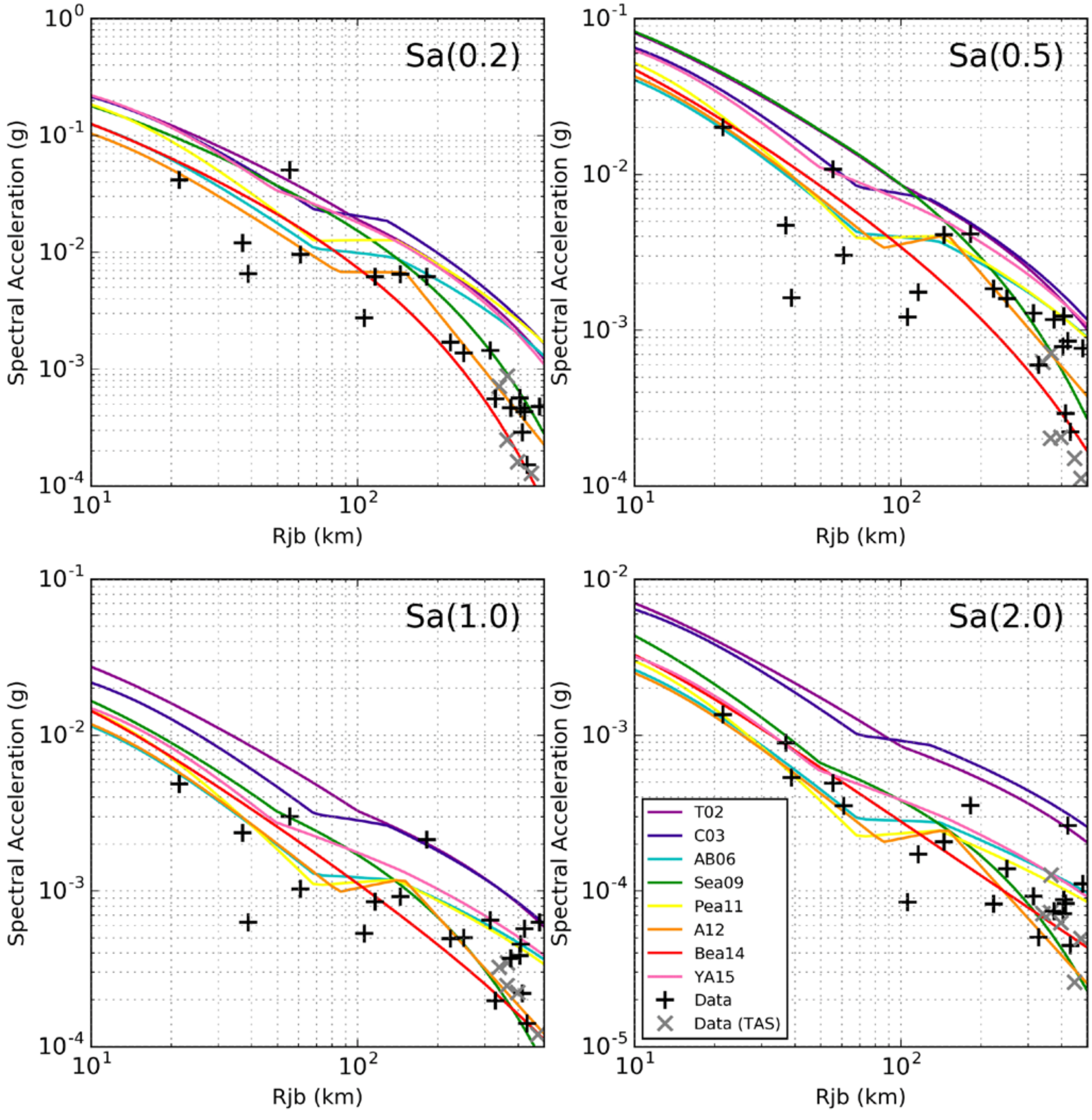

Fig. 3 – Attenuation of 5% damped pseudo response spectra (Sa) for the M_L 5.4 (M_W 5.15) 19 June 2012 earthquake plotted against commonly-used GMPEs for earthquake hazard assessments in Australia for different periods of vibration. Grey symbols represent sites located in Tasmania (refer to Fig. 2 caption), from [37].

6. Discussion

NSHA project aims to review the existing GMPEs, particularly with regard to weightings and applicability which is problematic in low to moderate seismic regions of Australia. The research proposed herein will help to shape future PSHA studies, as well as work in progress on the seismic hazard map for Australia. The key component however to seismic hazard is just as importantly, the input of multiple seismotectonic models, consideration of fault sources, and interpretations of the earthquake catalogue as well, which will also form part of our research towards this nationwide review of seismic hazard in Australia.

The research into alternative strategies for use of GMPE in PSHA studies will include additional models that are aimed at modelling the data more stringently and uniquely than the existing Australian GMPEs (those being stochastic rather than empirical or hybrid approaches). The CAM framework may provide an opportunity (already tested in pilot case studies, mentioned earlier in Australia and south-east Asia) to explore an alternative framework that may bypass some of the complications of PSHA and GMPE developments, adoptions and applications. It is hoped that further work into investigating these tools will aid the earthquake engineering community in making meaningful and applicable contributions to science and engineering fields.

The observed accelerations recorded for the Moe mainshock event show low Peak Ground Accelerations (PGA) varying between approximately 0.001 to 0.2 g. Overall the GMPEs tend to over-estimate acceleration, except at a distance of 55 kilometres, where the acceleration is under-estimated by the GMPEs relative to the Moe event. At natural periods of most interest (0.2, 0.5 and 1.0 seconds) the GMPEs show less variability than at PGA in Figure 2. However, when considering this data in Figure 3 plotted as acceleration versus distance the variability is more evident at longer periods of 1.0 and 2.0 seconds.

The scatter of data in Figure 3 shows there is still much improvements that need to be made to better fit existing GMPEs to actual earthquake recordings in Australia. This is partly difficult given the comparison of only one recorded earthquake in this example, but with more data the linear fits may become more evident. Regardless, it appears (at least for the Moe event) that most of the GMPEs are over-estimating acceleration, particularly at longer periods. The observed recorded data up to 100 kilometres in Figure 3 shows that many of the GMPEs are over-estimating acceleration at these distances and perhaps a re-evaluation at shorter distances is required. Quality factors as path attenuation are particularly important at distances beyond 70 kilometres and will add greater understanding to such over-estimations. Discrepancies may be due to geological properties that either have not been properly captured or there is still much epistemic uncertainty into this aspect. Distance and mid to long period are important aspects that require further investigations.

7. Conclusion

In this paper, ground motion levels particularly for traditional approaches to PSHA and GMPE formulation and usage in practical settings have been presented. Although much work is ongoing with the currently underway NSHA project on defining new seismotectonic models, and how to account for epistemic uncertainties in the selection and weighting of these together with GMPE models, a more recent approach of CAM could hold a validation technique of these principals, but also to provide alternative methods in such low-seismic regions as much of Australia.

There is considerable amount of work required for low to moderate seismic regions, such as Australia. The need is emphasised by the observations presented here in this paper that show the limitations of the existing GMPEs. Primarily these include that observed accelerations are very low. Existing GMPEs over-estimate acceleration at close to mid distance ranges, up to 100 kilometres, especially for natural periods of 0.2 to 0.5 seconds. The non-linearity of rock behaviour provides some evidence that geological properties are not properly captured for Australian rock conditions.

8. Acknowledgements

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