

## **The 2012 Moe Earthquake and Earthquake Attenuation in South Eastern Australia**

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### **ABSTRACT:**

In 2012 the state of Victoria experienced its largest earthquake in thirty years. The epicentre of the  $M_L$  5.4 earthquake is located near the town of Moe, within an area of elevated seismicity called the south-eastern seismic zone. The main event as well as over 200 aftershocks were recorded and located in a coordinated study by the University of Melbourne (UoM), Geoscience Australia (GA) and the Seismology Research Centre. At the time of the largest aftershock (ML 4.4), five instruments were operating within a 20km radius from the epicentre – providing a unique near-source strong motion record. This paper presents the spectral acceleration response results captured from the two events at a range of distances. Estimations of the  $V_{S30}$  parameter have been obtained for the underlying soil structure of some of the recordings stations using available borehole data, soil classification maps, observation of the natural period and using the Horizontal to Vertical Spectral Ratio (HVSR) method. The acceleration response spectra calculated from the ground motions are thus at sites with estimated site-soil properties and these spectra have been compared with estimated values from potentially applicable attenuation models, including the latest NGA-West 2 functions released in 2014. These comparisons indicate the level of compatibility of spectra obtained using the actual data with predictions made using the different attenuation models. The results show a wide range of accuracy with the current attenuation models that are thought to be applicable to the region. This is of particular importance in assisting to select the most suitable attenuation models for future Probabilistic Seismic Hazard Analyses in eastern Australia (Non-Cratonic) and other regions of Australia; the results from this type of hazard analysis are highly dependent on the attenuation model chosen to represent the area of interest.

**Keywords:** Attenuation, Australia, South Eastern, Moe Earthquake, NGA-West 2, GMPE, HVSR, Intraplate

## 1. Introduction

One of the largest earthquakes in thirty years for state of Victoria occurred in 2012 near the town of Moe (Sandiford *et al.*, 2012), within the Gippsland area that is east of Melbourne - renowned to be one of ‘the most seismically active areas in southeastern Australia’ (Brown *et al.*, 2001). The  $M_L$  5.4 main event on the 19<sup>th</sup> June at 20:53 AEST was felt throughout the state, causing minor damage to residential and commercial structures (Allen, 2012). The aftershock sequence included almost 500 recorded events, the largest of which was of  $M_L$  4.4 (Sandiford *et al.*, 2012) on the 20<sup>th</sup> July at 08:39 AEST. An isoseismal map, showing the Modified Mercalli Intensities (MMI), from the main earthquake event is shown in Figure 1(a). Eight recordings of the main earthquake event have been obtained for the analysis, all instrumentation belonging to the University of Melbourne, Environmental Systems & Services Seismology Research Centre and Geoscience Australia. However, due to the initiative by the University of Melbourne to deploy a network of temporary seismometers surrounding the epicentre of the Moe earthquake, five more recordings, in addition to those from the permanent stations were able to capture the largest aftershock. This paper presents some of that data, comparing it to the predictions given by several ground motion models (GMMs) that are thought to be potentially applicable to the region.

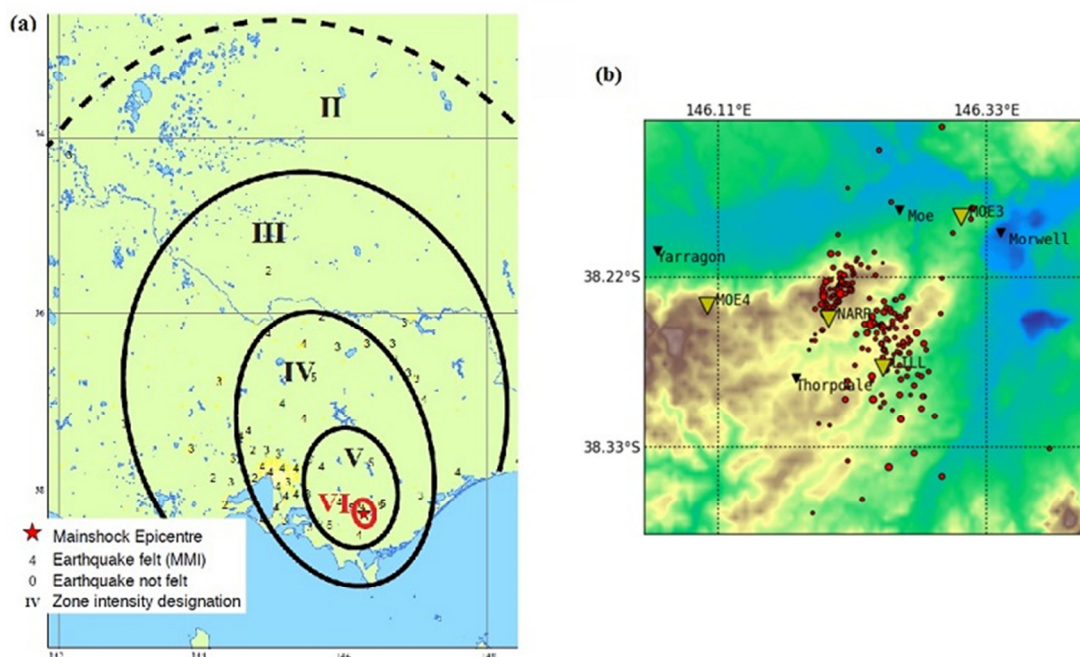


Figure 1 (a) Isoseismal map of the  $M_L$  5.4 Moe earthquake (ES&S, 2014) and (b) aftershocks of the Moe earthquake

## 2. Data

The bulk of the recordings were made with University of Melbourne seismic monitoring instruments, acquired under the Australian Geophysical Observing System (AGOS). The seismographs consisted of Guralp CMG-6TC compact seismometers and CMG-5TC accelerometers. Data was digitally recorded on ES&S Kelunji EchoPro at 250 Hz. Temporary

stations were placed around a mixed network of permanent stations in the UOM and ES&S (private) network. Geoscience Australia also installed five temporary stations within 40 km of the Moe epicenter. Given existing interest in seismicity in South Gippsland, six seismometers were operating within a radius of 50 km at the time of the main event. Earthquake location was performed using the *Hyp* program, part of the Seisan earthquake tools. 5% damped pseudo response Spectral Acceleration were calculated using tools provided by Trevor Allen, formerly at Geoscience Australia. Waveforms were filtered using a 4th order Butterworth filter between 0.2 – 125.0 Hz.

### 3. Estimation of $V_{s30}$ from soil type

In order to compare the attenuation model predictions with the data collected, information about the geology of the individual seismometers sites must be estimated. The shear wave velocity of the top 30 metres ( $V_{s30}$ ) of soil is commonly used as an input parameter for soil amplification of the resulting predicted response by many of recent GMMs, including the Next Generation Attention (NGA) functions. Unfortunately, there is no information on the shear wave velocity of the underlying soil for any of the seismometer sites in question. Therefore, estimations have been made using the Australian Soil Classification maps (ASRIS, 2011), borehole records close to the site (ERD, 2013) and observation of any natural period “peaks” ( $T_{obs}$ ) from acceleration and displacement response results of the site. This information gives us an estimate of the expected ground conditions at each of the sites – where an estimation of the  $V_{s30}$  can be calculated using Equation 1.

**Table 1  $V_{s30}$  values estimated for the seismometer sites, from soil data**

Station	ASRIS classification	Borehole ID	Borehole Description	$T_{obs}$ (s)	$V_{s30}$ (m/s)	$T_{calc}$ (s)
S88U	sodosols	106946	weathered rock, small covering clay	-	498	0.24
KRAN	rudosols	46057	clastic sediment, basaltic rock	0.15	799	0.15
JENM	sodosols/rudosols	310313	sandy clays, weathered rock	0.30	387	0.31
KORUM	rudosols	73361	clastic sediments, weathered rock	0.55	396	0.30
TOMM	rudosols/kandosols	-	-	0.15	783	0.15
CDNM	chromosols	64204	silts, sands, pieces of quartz deep	0.50	250	0.48
DROM	chromosols	69135	clastic sediment, weathered rock	0.32	363	0.33
FSHM	sodosols	100601	unconsolidated sands, deep	0.35	375	0.32
LILL	ferrosols	84258	clays, sands, basaltic rock	0.40	300	0.40
STGU	ferrosols/rudosols/sodosols	84862	unconsolidated clay, deep	0.40	300	0.40
NARR	ferrosols	79828	unconsolidated clay, deep	0.33	359	0.33
HOLS	rudosols		-	0.30	400	0.30
CREM	rudosols	325446	unconsolidated clays	0.25	519	0.23

$$V_{s30} = 30 / (\sum V_{si} h_i) \quad (1)$$

where  $h_i$  is the depth of layer  $i$  and  $V_{si}$  is an estimation of the shear wave velocity of that layer. The shear wave velocity of each layer is estimated from  $V_s$  values that have been used for similar soil conditions in past research, particularly for sands and clays in parts of eastern Australia (Asten *et al.*, 2004; Asten *et al.*, 2005; McPherson & Hall, 2013; Roberts *et al.*, 2004; Wair & DeJong, 2008). The shear wave velocity of each layer can then be edited as such that the calculated natural period of the soil ( $T_{calc}$ ) is close to  $T_{obs}$ , using:

$$T_{calc} = \frac{4H}{V_{s30}} \quad (2)$$

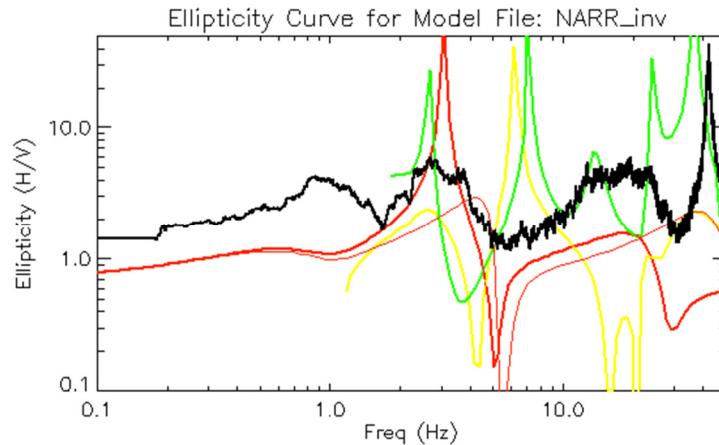
where  $H$  is the depth of soil, taken as 30 metres. Table 1 gives the results of the estimated  $V_{s30}$  for each of the seismometer sites, with indication of the soil classification and the borehole site ID used in estimating the layers.

#### 4. Estimation of $V_{s30}$ using HVSR measurement

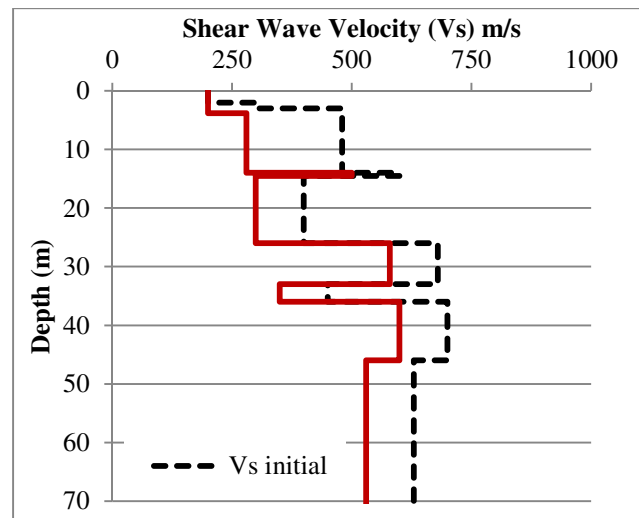
Testing was undertaken by the University of Melbourne to estimate one of the seismometer site's shear wave velocity profile using the Horizontal to Vertical Spectral Ratio (HVSR) method. The method is one of a class of ambient-noise (microtremor) observational methods which measure phase velocities and/or particle-motion shapes of Rayleigh-wave energy as generated by cultural sources (eg. road traffic) and meteorological sources (eg wind on trees). The HVSR method can be employed using single three-component seismometers, and is useful for determining shear-wave site resonances (Lachet & Bard, 1994). Determination of shear-wave velocity profiles is best achieved with a combination of array observations and HVSR measurement (eg Asten *et al.*, 2014, and references therein). In this instance we can use the single-station HVSR data in conjunction with known layer thicknesses and soil types for a selected borehole.

The NARR site was chosen to undertake the investigation, as this was an area that had easy access and was also the closest station to the epicentre in recording the largest of the aftershocks ( $M_L$  4.4). Table 1 shows that the NARR site had a site classification of 'ferrosols', which generally has high clay content as confirmed by the borehole record close to the site. From this, an initial estimate of shear wave velocity ( $V_s$ ) with depth of the soil profile can be made, using generic  $V_s$  values for a range of sands and clays. Using a recording of ambient noise at a single three-component seismometer at the NARR site we obtain the observed HVSR spectrum shown in Figure 2, using methodology outlined in Asten (2006) and Asten *et al.* (2014). It is obvious that the observed HVSR maximum at 3 Hz is significantly lower in frequency than that modelled from the initial estimate of a  $V_s$  profile, but changes to the  $V_s$  profile (retaining layer thicknesses and relative  $V_s$  variation between sand and clay layers) allows estimation of a new  $V_s$  profile which shows a modelled HVSR maximum coincident with that of the observed ambient noise. The initial and revised shear wave velocity profiles are shown in Figure 3, with the spike at a depth of 15 metres

corresponding to a thin layer of softer soil in between layers of harder soil. The  $V_{s30}$  for the revised model is 297 m/s compared with the initial estimate of 359 m/s shown in Table 1.



**Figure 2** Black line: observed HVSr at site NARR. Thin red: modelled HVSr for the fundamental Rayleigh mode for the initial estimate of the  $V_s$  profile (based on layer thicknesses and soil types from the borehole log). Thick red: modelled HVSr for the same mode using a layered earth where  $V_s$  values are decreased in order to obtain coincidence of the observed and modelled HVSr maximum at 3 Hz. Yellow, green lines are modelled HVSr for 1st and second higher modes of the final model; these modes included for reference purposes only.



**Figure 3** Initial and revised shear wave velocity profiles of the NARR site

## 5. Ground Motion Models

Over the past few years there have been some attempts to decide which GMMs, also commonly referred to as Ground Motion Prediction Equations, are applicable to the Australian conditions (Hoult *et al.*, 2013). In stable continental regions such as Australia, the observed ground-motion datasets are not sufficient enough to develop reliable GMMs based on the recorded data alone (Burbidge, 2012). However, there has been some attempt in deriving attenuation functions explicitly for the Australian conditions, including models from Somerville *et al.* (2009) and more recently Allen (2012). Due to the paucity of earthquake

data in Australia, adopting well developed attenuation functions from other regions around the world that has similar geological conditions can also be used for the different Australian regions. For example, GMMs developed in Western North America, such as the Next Generation Attenuation (NGA-West) functions, are considered to be more applicable to eastern Australia (or Non-Cratonic regions) in comparison to the models developed for the eastern parts of North America (Brown & Gibson, 2004). Moreover, there has been a recent update in GMMs for western North America with the release of the NGA-West 2 functions in 2014. The NGA-West 2 functions also have the advantage of estimating the response and attenuation of smaller magnitude earthquake events, and can be used to compare with the  $M_L$  4.4 aftershock records.

Six potentially applicable attenuation functions are used for the purpose of this investigation; Atkinson and Boore (2006) or AB06BC, Chiou and Youngs (2008) or CY08, Somerville *et al.* (2009) Non-Cratonic or SOM09NC, Allen (2012) or ALL12, Chiou and Youngs (2014) or CY14 and Abrahamson *et al.* (2014) or ASK14. All but two of these functions have been used in past seismic hazard studies for Australia and are thought to be applicable to the south eastern Australia region (Burbidge, 2012; Hout, 2014). The other two GMMs come from the recent NGA-West 2 functions, which offer an exciting chance to observe any improvements to their corresponding preceding functions and their applicability to south eastern Australia.

## 6. Attenuation Results

In order to evaluate the selected GMMs and their applicability to the south eastern Australia region, the data is compared with the acceleration response estimated from the attenuation functions at four periods, 0.01s (PGA), 0.1s, 0.5s and 1s. The acceleration response predicted by the different attenuation functions can be plotted versus distance. The captured response of each site and their distance from the epicentre of the event is then superimposed on this same plot. Only the seismometer sites with  $V_{S30}$  values in a range between 350 to 550 m/s have been selected to be compared against the GMMs with a  $V_{S30}$  input of 450 m/s. This provided a good spread of spectral acceleration data over a wide range of distance to compare with. For the GMMs with no  $V_{S30}$  input that have been derived for rock conditions, such as Allen (2012) and Somerville *et al.* (2009), soil amplification factors were applied based on the spectral shape factors given in AS 1170.4 (assumed to be site  $D_e$ , with many of the sites classed as having deep clays). Although the  $M_L$  4.4 earthquake is outside the applicable magnitude range for SOM09NC, it was decided to use the function anyway for comparison with the aftershock data. The comparison of median predictions from the individual GMMs with spectral accelerations from the  $M_L$  5.4 and  $M_L$  4.4 earthquake events versus distance for the different periods are shown in Figures 5 and 6 respectively. Since there were only two recording stations estimated to be on rock ( $V_{S30} > 760$  m/s), data from the  $M_L$  5.3 6<sup>th</sup> August 1994 Ellalong, NSW earthquake (McCue *et al.*, 1995) complimented the Moe earthquake results captured on rock to ultimately compare the GMMs for rock site conditions and for PGA ( $T = 0.01$ s), shown in Figure 4. The GMMs with the closest estimation of acceleration response to the data on soil for each of the distances and each period were found and are

given in Tables 2 and 3 for the main and aftershock events respectively. The results for the most applicable GMMs correlating with the data for rock sites, which included the Ellalong earthquake data, are presented in Table 4.

The relationships of the GMMs with the dataset for the main  $M_L$  5.4 event are poorly constraint in the high period range, shown in Figure 5. This might be a result of a high stress-drop main event, with the majority of the acceleration response content towards the lower end of the period range. Allen and Atkinson (2007) also found evidence of south eastern Australian earthquake events being characterised by near surface high-frequency (low period) attenuation in comparison to the events in eastern North America. Other explanations offered for this poor correlation in the high period range and large scatter of data could be due to directivity of the earthquake and change of frequency content with large distances. The aftershock data seems to correlate better with the GMMs and throughout the period range in Figure 6. The GMMs also provide a good estimation of PGA for the data obtained for south eastern Australia on rock sites and for the two events of similar local magnitude. Tables 2 and 3 illustrate that the two Australian derived GMMs from Allen (2012) and Somerville *et al.* (2009) provide some of the best estimations of attenuation for the  $M_L$  5.2 and  $M_L$  4.2 Moe earthquake events. The eastern North American function from Atkinson and Boore (2006) seems to also provide reasonable estimations for the main event earthquake when comparing to the data collected on soil sites. The more recent western North American function from Abrahamson *et al.* (2014) gave the best attenuation estimates for the main aftershock event when comparing to the data collected on soils sites. Interestingly, another most recent western North American function from Chiou and Youngs (2014) provided the best estimate of attenuation for the data collected on rock sites. Surprisingly, the Chiou and Youngs (2008) NGA attenuation didn't perform as well as some other functions, which has been used in past PSHA studies, along with other NGA functions, in representing the attenuation in eastern Australia (Burbidge, 2012; Gibson & Dimas, 2009; Hoult, 2014).

**Table 2 The four GMMs that were most accurate at predicting the acceleration response from the Moe Earthquake ( $M_L$  5.4)**

	<b>CY08</b>	<b>AB06BC</b>	<b>S09NC</b>	<b>CY14</b>	<b>ASK14</b>	<b>ALL12</b>
Percent Weight	5.0%	25.0%	25.0%	5.0%	0.0%	40.0%

**Table 3 The four GMMs that were most accurate at predicting the acceleration response from the Moe aftershock ( $M_L$  4.4)**

	<b>CY08</b>	<b>AB06BC</b>	<b>S09NC</b>	<b>CY14</b>	<b>ASK14</b>	<b>ALL12</b>
Percent Weight	7.1%	14.3%	17.9%	7.1%	32.1%	21.4%

**Table 4 The four GMMs that were most accurate at predicting the acceleration response on rock from the Moe ( $M_L$  5.4) and Ellalong ( $M_L$  5.3) earthquakes**

	<b>CY08</b>	<b>AB06BC</b>	<b>S09NC</b>	<b>CY14</b>	<b>ASK14</b>	<b>ALL12</b>
Percent Weight	10.5%	0.0%	5.3%	63.2%	5.3%	15.8%

## 7. Conclusion

Data was collected from the main Moe earthquake and the largest aftershock from several recording stations. The soil conditions were estimated by calculating the  $V_{s30}$  using a number of methods. The applicability of the different GMMs in predicting the attenuation of ground motions in south eastern Australia was calculated as a weighted percentage of their performance against the data at a range of periods. The  $M_L$  5.3 Ellalong earthquake data was also used to compliment the data collected for the main Moe earthquake recorded on rock sites. The results showed that there was a range of GMMs that are possibly applicable. The eastern North America function, together with the two Australian derived functions, seemed to be most applicable for predicting the attenuation to the data from the main event, while the western North American function seemed most applicable for the main aftershock data and the main event data compiled from rock sites. There is some evidence to agree with Allen and Atkinson (2007) that the ground motions and attenuation properties of south eastern Australia and eastern North America are very similar at shorter distances. However, there is also some contrasting evidence to suggest that in some instances the western North America functions are more applicable to model the attenuation properties of earthquake events in south eastern Australia. This study has given some basis of which GMMs are applicable to eastern Australia, however more research is recommended to confirm the validity of these GMMs using a much denser dataset. This can be particularly important for hazard studies that utilise Probabilistic Seismic Hazard Analyses (PSHAs), in which there is a high dependency on the type of ground motion models used. It is also necessary to obtain more accurate  $V_{s30}$  values for the seismometer sites in Gippsland, not only to validate the  $V_{s30}$  values used in this research but for analysis of the attenuation of future earthquake events in the Gippsland region.

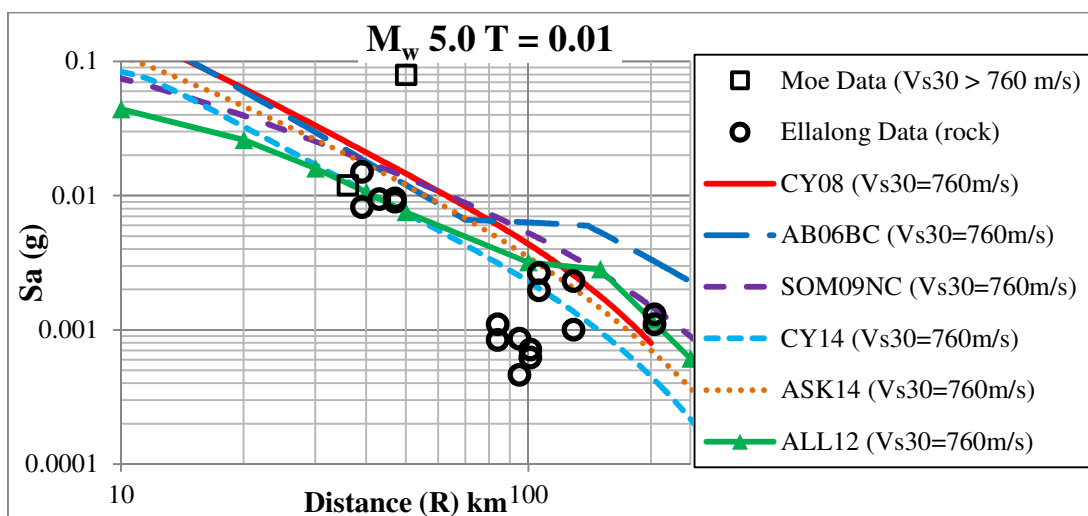


Figure 4 Predictions from the selected GMMs compared to the spectral accelerations from the  $\approx M_w 5.0$  Moe and Ellalong (McCue *et al.*, 1994) events versus distance



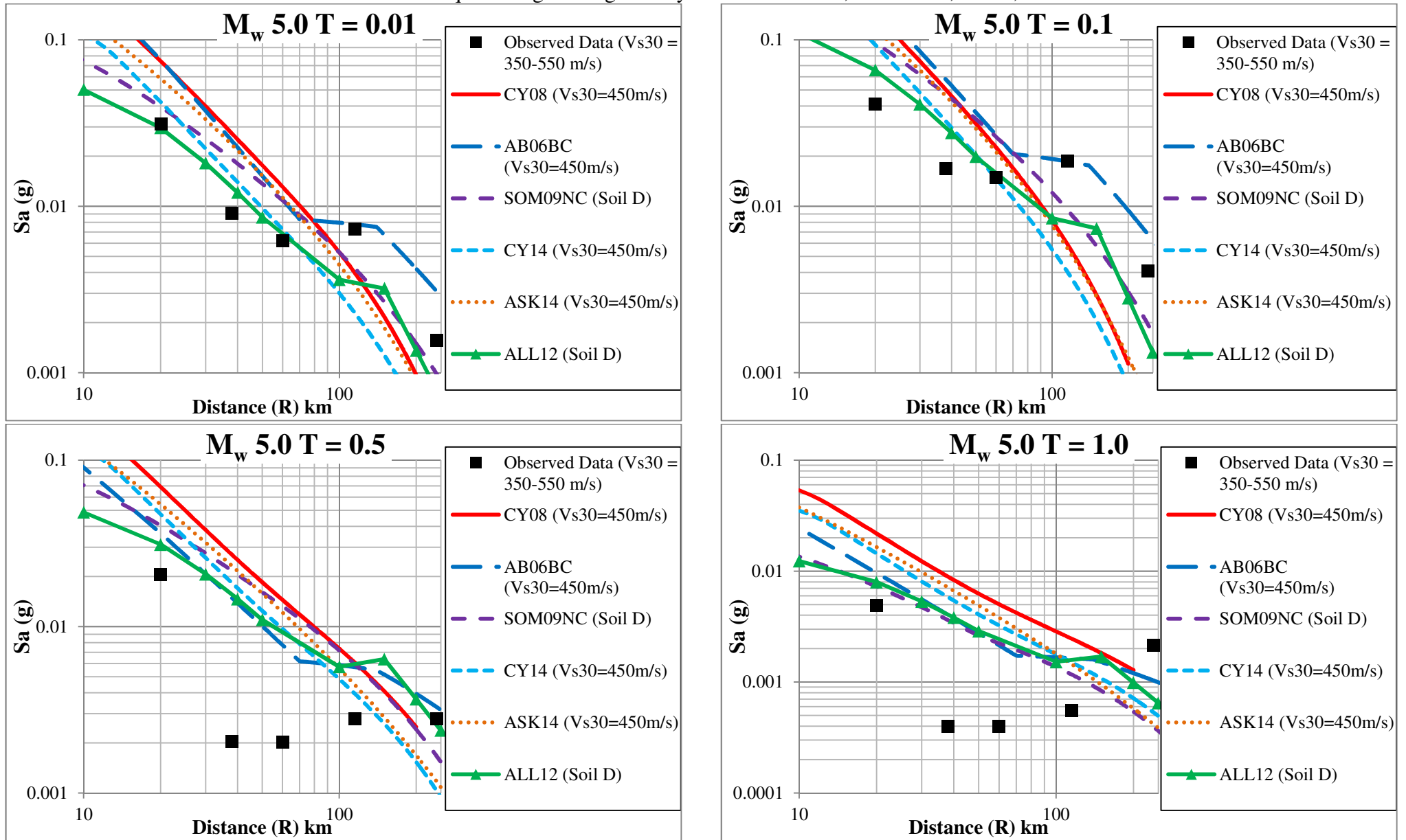


Figure 5(a-d) Predictions from the selected GMMs compared to the spectral accelerations from the  $M_w 5.0$  Moe Earthquake event versus distance

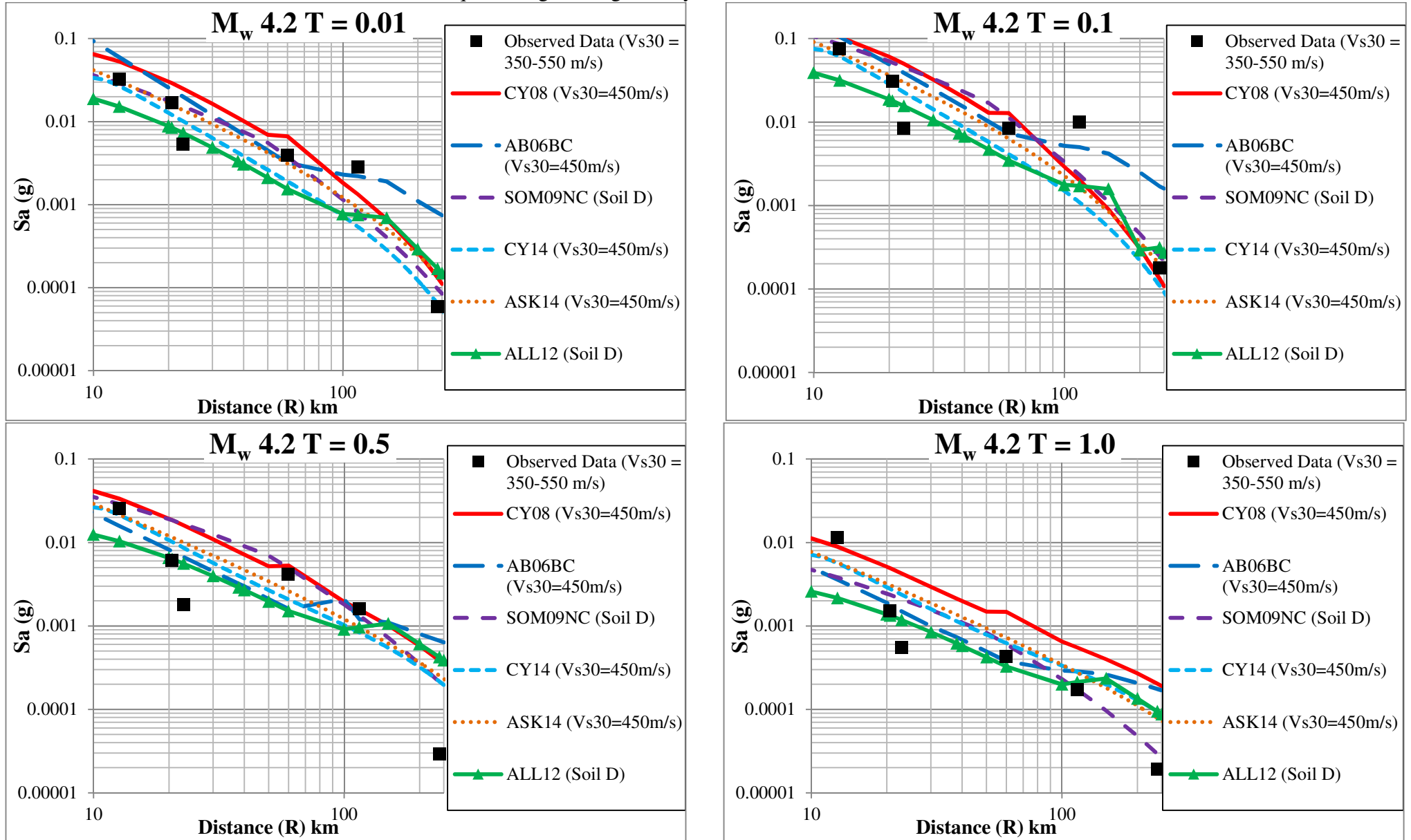


Figure 6(a-d) Predictions from the selected GMMs compared to the spectral accelerations from the  $M_w 4.2$  Moe Aftershock event versus distance

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