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Average response spectra from some Australian earthquakes

T.I. Allen[1], G. Gibson[1,2] & J.P. Cull[1]

[1]*School of Geosciences, Monash University, Melbourne, Australia*

[2]*Seismology Research Centre, Environmental Systems and Services, Melbourne, Australia*

ABSTRACT: Response spectra have been calculated for three moderate magnitude southeastern Australian earthquakes (from MW 4.1 to MW 4.4) with epicentral locations within Palaeozoic terranes. Average 5 per cent damped spectral acceleration and spectral pseudo-velocity are compared with expected results from published attenuation functions using Californian data. Results indicate that for Australian earthquakes, a single-degree-of-freedom system will tend to approach a peak ground acceleration (PGA) or peak ground pseudo-velocity (PGV) at higher frequencies than their Californian counterparts, particularly in the near-field. This can be attributed to the shorter duration and unusually high stress drops typically observed for Australian earthquakes. In the far-field, attenuation of the high frequency content yields equivalent responses for both regions. Moreover, low frequency ground motion is comparable in the near-field, however, at distance the long period motion is lower for Australian events.

More data are required to produce a comprehensive local spectral attenuation function. These results, however, take a constructive step towards the development of Australian response attenuation functions derived entirely from spectral amplitude data. In the absence of quality Australian strong motion recordings from very large earthquakes (necessary to describe engineering design spectra), these data may assist in choosing between published attenuation functions for future earthquake hazard studies.

1 INTRODUCTION

Although Australia is largely considered as being geologically stable, the continent has experienced several moderate to large earthquakes in the recent past that have caused significant damage to local infrastructure (e.g. Meckering, 1968; Tennant Creek, 1988; and Newcastle, 1989). Despite the threat of another large earthquake occurring in a major city, such as in Newcastle, little empirical work has been done to estimate uniform Australian probability spectra functions for engineering design. Previously, this task has been problematical given the deficiency of strong motion recordings from nearby local earthquakes, however, quality data for earthquakes up to local magnitude ML 5.3 are now available.

Uniform probability response spectra used in earthquake hazard studies depend heavily on the spectral representations of ground motion used to compute them. Most published Australian attenuation functions use overseas data, which are derived from larger earthquakes with greater low frequency and long duration motion, rather than the smaller, higher frequency and shorter duration events we observe in Australia. Moreover, some Australian hazard studies still rely on attenuation functions derived from international data alone (e.g. Sadigh et al. 1997; Toro et al. 1997). The Sadigh et al. function, for example, was derived using accelerograms recorded from shallow crustal Californian earthquakes, down to moment magnitude MW 3.8.

The Sadigh et al. (1997) function is the preferred attenuation function to use for eastern Australian hazard assessment because of it provides a well-constrained model for seismic attenuation in continental terranes. Although a convenient substitute for the computation of uniform hazard response spectra, the function does not accurately represent the shorter duration and higher frequency (and consequently, higher stress drop; Allen et al. in press) Australian earthquakes.

In addition, the Sadigh et al. function was derived principally from strong motion data recorded from earthquakes of strike-slip mechanism as a result of nearby plate boundary forces. In contrast, the contemporary stress field of continental Australia is horizontal compression (Hillis and Reynolds, 2000) giving rise to predominantly reverse faulting. Consequently, given the differences between Australian and Californian earthquake mechanisms, coupled with the tectonic setting and the large number of Californian earthquakes relative to Australian events, it is insufficient to rely on these response spectrum attenuation functions in the design of earthquake resistant structures alone. Consequently, stochastic prediction of ground motion and response spectra should be estimated using attenuation functions derived from Australian earthquakes.

This study is to facilitate the development of local Australian spectral attenuation functions. The current paper attempts to reproduce the methods used in Sadigh et al. (1997) to compare the spectral shapes of Australian and Californian earthquakes. Consequently, we only consider earthquakes whose epicentres were located in regions where rocks of Palaeozoic age outcrop. Furthermore, only data from seismographs located at rock sites were used in the study.

2 SEISMIC HAZARD IN AUSTRALIA

Like most intraplate regions, Australian earthquakes tend to be shallow and are typically restricted to a seismogenic zone within the upper 20 km of the crust. Given that the earthquakes are shallow, it is not uncommon for the larger events to be associated with surface rupture. Recent prehistoric fault scarps, some believed to be associated with earthquakes up to, or in excess of moment magnitude M_W 7.0, have been mapped in several localities across the continent (Denham 1988).

Studies of seismic hazard in Australia have previously been limited by the continent’s low levels of seismicity, coupled with a relatively short recording period and sparse seismograph network, especially prior to 1960 (Gibson *et al.* 1981). Because of Australia’s low seismicity and wide distribution of epicentres, empirical predictions of ground motion for large intraplate Australian earthquakes have been difficult.

The first earthquake intensity attenuation relationships developed entirely from Australian earthquake data were those compiled by Gaull *et al.* (1990). Prior to these data, hazard maps were compiled using values derived from international studies. The relationships are based on conversions of Modified Mercalli Intensity, to peak ground acceleration (in m/s^2) and velocity (in mm/s) employing the empirical relations of Gaull (1979) and Newmark & Rosenblueth (1971), respectively. The subsequent hazard maps, combined with modifications from an earthquake engineering draft committee, culminated in the development of the 1991 Earthquake Hazard Map of Australia.

Recent studies by Sinadinovski *et al.* (2000) computed the response spectra for the 1994 M_L 5.3 Ellalong and the 1989 M_L 5.6 Newcastle earthquakes, both located on the eastern margins of central New South Wales, Australia. As no high quality strong motion data were available following the Newcastle earthquake, synthetic seismograms were approximated applying an empirical Green’s Function method (following Hartzell [1978]) to simulate the ground motion from the main shock using the smaller, well recorded aftershocks or sub-events. Employing this method, Sinadinovski *et al.* demonstrated good correlation between the empirical response spectra and the near-field spectra from the synthetic seismograms. They concluded that using Hartzell’s (1978) Green’s Function method to calculate synthetic seismograms gives an acceptable means for representing response spectra for engineering purposes, and can give robust estimates of ground motion for Australian intraplate earthquakes.

3 METHODS AND RESULTS

The fundamental problem in structural dynamics is analysing the response of a structure when subjected to ground motion. Earthquake response spectra specify the maximum dynamic response (i.e. maximum displacement, velocity or acceleration) of a single-degree-of-freedom (SDOF) system in response to an excitation force, such as that due to an earthquake or a blast. The maximum response of the system depends upon the ground motion, and the natural period and intrinsic damping of the structure which characterises the structure's capacity to dissipate ground-generated energy.

Figure 1 gives schematic example of a typical response spectrum for a one-story building subjected to a ground displacement $y_s(t)$. The curve illustrated in Figure 1b gives the maximum displacement of the mass *m* with respect to the displacement at the support anchor point, for any SDOF system. Thus, for a specified excitation force, we need only know the natural frequency of the system to determine the system response (Paz 1997).

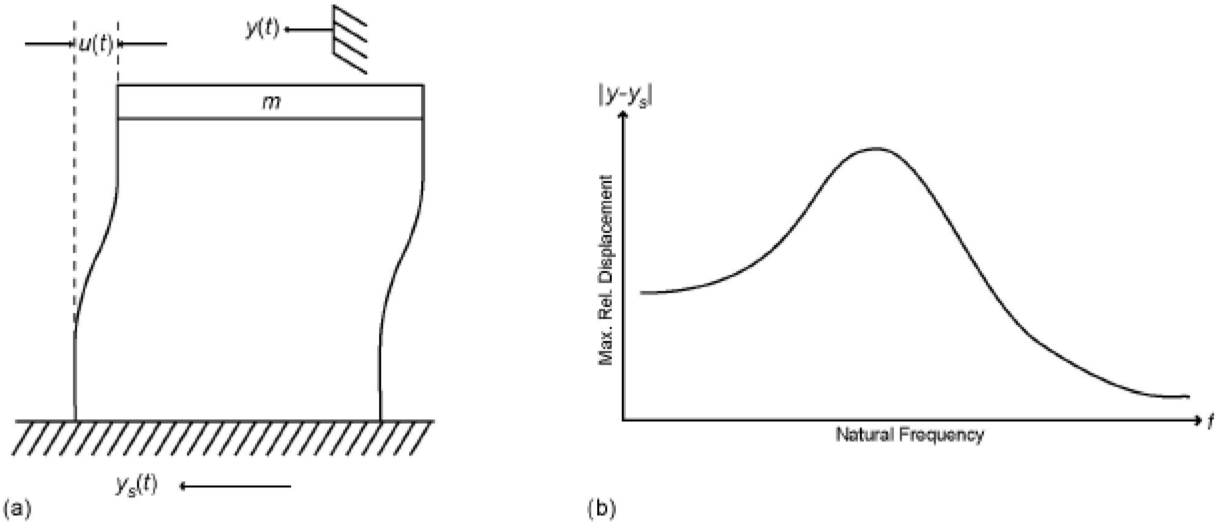

Fig. 1. (a) A schematic diagram of a typical SDOF system, subjected to ground motion ys(t), and (b) its subsequent response spectrum. (After Paz 1997).

Response spectra are typically prepared by calculating the dynamic response of a SDOF system subjected to a ground motion $y_s(t)$ over a range of natural frequencies and damping values x. The resulting motion of the structure is $y(t)$ and the response $u(t)$ is evaluated through numerical integration of an earthquake time series following Duhamel's integral

$$u(t) = -\frac{1}{w_D}\int_0^t \ddot{y}(t)\, e^{-xw(t-t)} \sin w_D (t-t)\, dt \ , \qquad (1)$$

where w is the angular natural frequency and $w_D = w\sqrt{(1-x^2)}$ is the damped natural frequency. The damping ratio is usually small for structural systems (i.e. x << 1); therefore $1-x^2$ 1 and w_D w (Paz 1994). The integral represents a convolution between the input acceleration and the response of the oscillator impulse.

At present, there is no accurate method for estimating the extent of ground motion expected at a particular site from future earthquakes. Therefore, it is sufficient to use a *design response spectrum*, which incorporates the spectra from several earthquakes to estimate an idealised dynamic response. This represents an "average" response spectrum which can subsequently be used for engineering design (Paz 1997).

Three well-recorded, moderate sized earthquakes were chosen for this study. Each was located in rocks of Palaeozoic age to avoid the high attenuation of local travel path conditions, and to subsequently compare with the Sadigh *et al.* (1997) response spectrum attenuation function. Magnitudes for these events ranged from moment magnitude M_W 4.1 to M_W 4.4. M_W and were calculated using the attenuation models of Allen *et al*. (in press) and converted from seismic moment M_0 to M_W following the empirical relation of Hanks and Kanamori (1979)

$$M_W = \frac{2}{3}\log M_0 - 6.0\,, \qquad (2)$$

where M_0 is in N·m. The Hanks and Kanamori (1979) relation was derived principally from large earthquakes.

The local magnitudes M_L were evaluated independently from moment magnitudes, and used the attenuation corrections of Wilkie *et al*. (1994). In the recent studies of Allen *et al.* (in press), the relationship between these two magnitude scales for southeastern Australian earthquakes was empirically evaluated as

$$M_W \approx 0.72\, M_L + 0.74 \qquad (3)$$

for events smaller than M_L 5.0. The earthquakes used in the present study are given in Table 1.

Table 1. Events used for response spectra calculations.

Place	Date	HHMM	Long. (deg)	Lat. (deg)	Depth (km)	M_W	M_L
Thomson Reservoir	1996-09-25	0749	146.422	-37.863	11.4	4.44	4.87
Corryong	1998-07-17	0122	148.005	-36.441	20.3	4.06	4.61
Swan Hill	2001-10-27	0758	143.393	-35.501	9.0	4.16	4.82

Response spectra were calculated employing software developed for this study. The software, eqSource, is capable of calculating spectra for a range of values for intrinsic damping on each component of a triaxial seismograph. Seismograms used in the analysis were digitally recorded on horizontal component seismographs at a rate of 100 samples per second with an anti-alias filter at 25 Hz. Each seismogram was corrected for the effects of instrument response.

Duhamel’s integral was used to calculate spectral acceleration and spectral pseudo-velocity for 100 discrete simple oscillators damped at 5 per cent. Oscillator frequencies were logarithmically distributed from 0.1 to 50.0 Hz. Spectral amplitudes were calculated for each of the two horizontal components of a triaxial seismometer and were subsequently subjected to multiple iterations of smoothing, then plotted for assessment of data quality.

Following Allen *et al.* (2002), the authors have avoided using spectral amplitudes calculated at sites between about 80 to 200 km from the source owing to an apparent increase in ground motion within this range. This occurrence is thought to be the result of critical reflections of *SmS*-waves from the Moho and has been previously well documented by Burger *et al.* (1987), Somerville and Yoshimura (1990), Mori and Helmberger (1996), and others.

Twenty of the 100 calculated frequencies within a bandwidth of engineering interest were selected for regression analyses. Spectral amplitudes were plotted against hypocentral distance and an attenuation relation determined for each frequency. An average response spectrum attenuation function was subsequently derived with these relations for the magnitude range of M_W 4.1 to M_W 4.4 (Fig. 2).

The average response spectra shown in Figure 2 indicate that for southeastern Australian earthquakes, a SDOF system will tend to approach a peak ground acceleration (PGA) or peak ground pseudo-velocity (PGV) at higher frequencies than their Californian counterparts, especially in the near-field. In the far-field, the high frequency content is similar for both regions. Low frequency ground motion is also comparable in the near-field, however, at distance long period motion is lower for Australian events.

Response spectra were also calculated for smaller magnitude earthquakes (from both horizontal and vertical component seismograms) with epicentres distributed in the Palaeozoic terranes of Australia, however, as the Sadigh *et al.* (1997) function is only defined for Californian earthquakes down to about M_W 3.8, these are not discussed in the present paper.

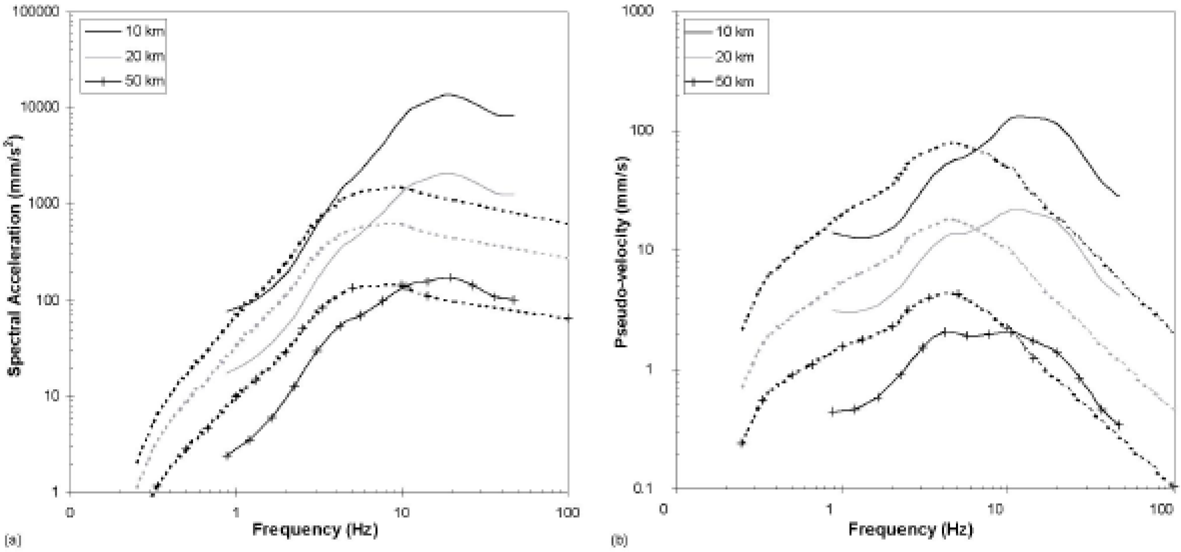

Fig. 2. Average 5% damped (a) acceleration and (b) pseudo-velocity response spectra for M_W 4.1 to M_W 4.4 events with epicentres located in Palaeozoic terranes. Solid lines represent attenuation functions derived from Australian data compared to average response spectra of Sadigh *et al.* (1997; dashed lines) for a Californian earthquake of magnitude M_W 4.25.

4 COMPARISON OF SPECTRA

Average response spectra based on the recorded ground motion of three moderate magnitude intraplate Australian earthquakes suggest that both the PGA and PGV occur at higher frequencies than the ground motion resulting from interplate Californian earthquakes. Indeed, Sinadinovski *et al.* (2000) noted that intraplate earthquakes with relatively low magnitudes can produce large peak accelerations and velocities in the near-field. Enrichment of high frequency motions for intraplate eastern North American earthquakes have also been noted when compared to western North American earthquakes (Boore and Atkinson 1987; Leyendecker *et al.* 1995).

Using stochastic prediction models of ground motion, Boore and Atkinson (1987) demonstrated the sensitivity of ground motion to stress drop, especially for larger earthquakes and higher frequency motions. It has been suggested that stress drop for intraplate earthquakes is higher than for earthquakes with epicentres near plate margins (Hanks and Johnston, 1992; and others). Recently documented stress drops for southeastern Australian earthquakes are consistent with these findings and illustrate higher than average stress drop, even compared to other intraplate regions (Allen *et al.* in press). This could explain the large amplitudes observed for higher frequency ground motion in the near-field. Further from the source, we observe that seismic amplitudes for all frequencies are lower relative to the Californian data, implying that attenuation of seismic energy is more severe in southeastern Australian terrains.

The suggestion of higher than average stress drops for southeastern Australian earthquakes also offers an explanation for the low amplitudes observed in the low frequency bandwidth. It is expected that earthquakes with high stress drop will have more compact source, and therefore produce less low frequency radiation than a low stress drop event with a larger source. This means that seismic moment, and consequently moment magnitude, will be lower for earthquakes of similar PGA and PGV at higher frequencies.

Average response spectra evaluated from international data are often based on moment magnitudes M_W because it provides more robust estimates of an earthquake's size than does local magnitude (e.g. Sadigh *et al.* 1997). However, in practice, M_W is usually only determined for large earthquakes ($M_W > 6.0$) and for smaller events it is assumed that $M_W \approx M_L$. It has been shown by Allen *et al.* (in press) that for Australian earthquakes, these magnitudes are not equivalent at moderate magnitudes and in general follow relation (3), which indicates that both M_W and M_L tend to be comparable around magnitude 2.5, whereas for M_L 4.5, moment magnitude is observed to be about M_W 4.0. This would imply that the substitution of moment magnitudes calculated from Australian data into these published attenuation functions may underestimate the expected ground motion for moderate earthquakes, and consequently the hazard associated with them. Before we can use moment magnitude for ground motion calculations using existing attenuation functions, we must first revise the Hanks and Kanamori (1979) empirical moment magnitude relation to better suit smaller earthquakes and to be more consistent with the local magnitude scale.

Strong ground motion attenuation relationships are usually expressed as smoothly varying functions with distance, however, inhomogeneities in the Earth's structure affects the propagation of seismic waves. Consequently, attenuation functions must become more complex to cater for these inhomogeneities. The higher amplitude ground motion observed in the 80 to 200 km range, thought to be due to critical *SmS*-wave reflections (Allen *et al.* 2002), must therefore be considered in attenuation relations and will be subject to further investigation.

The use of only Australian events with epicentres located in Palaeozoic terranes was a deliberate strategy to compare response spectra to Californian earthquakes to avoid the higher seismic attenuation expected in the younger terranes. Better quality Australian strong motion data does exist for earthquakes located within Mesozoic terranes. Average response spectra for these events will subsequently be calculated and compared to the spectra obtained from the current study for Palaeozoic terranes. It should be noted that earthquakes referred to as occurring in Mesozoic terranes, may have occurred in older rocks beneath the Mesozoic cover. Thus, the category refers to rock ages at the earthquake's epicentre only.

5 CONCLUSIONS

Using Duhamel's numerical integration method, we have calculated response spectra for three well located southeastern Australian earthquakes of moderate magnitude between M_W 4.1 to M_W 4.4. Average 5 per cent damped spectral acceleration and spectral pseudo-velocity have been compared to the attenuation functions presented by Sadigh *et al.* (1997). From these comparisons, it is apparent that both PGA and PGV for Australian tend to occur at higher frequencies than for Californian earthquakes. This is consistent with the enriched high frequency motions observed by Sinadinovski *et al.* (2000) coupled with the unusually high stress drops calculated by Allen *et al.* (in press). This is particularly the apparent in the near-field where the shape of the average response spectra is strongly influenced by the higher frequency, moderate magnitude earthquakes. In contrast, spectral amplitudes in the low frequency range appear to be comparable in the near-field although are lower at distance. Smaller rupture sizes due to high stress drops may explain this behaviour. Consequently, it remains to be seen if these data are characteristic of all Australian earthquakes, or just those with origins in Palaeozoic terranes.

Using these new data recorded from Australian earthquakes, we have taken a constructive step towards the development of Australian response spectrum attenuation functions. It is hoped that these functions, we will be able to provide a re-evaluation of seismic risk in Australia, which should subsequently be used as the basis for revision of the Australian building code. Given that we do not possess quality data from very large earthquakes, we may still have to depend on international data from similar seismotectonic regimes to constrain these functions for larger earthquakes.

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