# The New Response Spectrum Model for Australia

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ABSTRACT: This paper presents an overview of recent research in Australia into seismic activity and ground motion modelling which has culminated in the development of a new response spectrum model for Australia as featured in the new standard for seismic actions. An important element of the research is the prediction of the displacement demand of small-moderate magnitude earthquakes that are characteristics of the intraplate tectonic environment of Australia. The practical implementation of the response spectrum model is illustrated at the end of the paper with the case-study of a lifeline facility. Advancements in seismic demand is complimented by the accurate assessment of the seismic performance of the structure and their sub-assemblages including those with non-ductile behavior.

Keywords: Seismicity, Seismic Hazard, Response Spectrum, Australia, Component Attenuation Model

## 1 BACKGROUND

Whilst earthquakes worldwide predominantly occur along tectonic plate boundaries (interplate regions) destructive earthquakes do occur away from the plate margins and are known as intraplate earthquakes. In the past 100 years, 20 earthquakes of magnitude 6 (M6) or greater have occurred in continental Australia which is wholly within the Indo-Australasian plate. There are on average 2 – 3 earthquakes of M5 or greater occurring every year in Australia (McCue *et al.*, 1995).

The Meckering earthquake of M6.9, occurring in Western Australia in 1968, was the first earthquake event in Australia which caused notable civil engineering damage. This event prompted research into the potential seismic hazard across the whole of Australia culminating in the development of the first earthquake code AS2121 (1979) which was superseded by AS1170.4 (1993). The latter standard has incorporated the seismic hazard map of Australia as reported by Gaull et al (1990).

The Newcastle earthquake of M5.6 in 1989, occurring in New South Wales, caused 11 deaths. Research into the seismic performance behaviour of structures in Australia has since been developed, and "displacement" as the criterion to quantify performance has been central to the research theme. Topics of investigations include seismic activity (seismicity), seismic demand (ground motion) and the performance behaviour of vulnerable items including unreinforced masonry walls, buildings with a soft storey and unrestrained building contents.

The key objective of this paper is to present the outcome of research undertaken by the authors since the mid 1990's in support of the new response spectrum model for Australia. The modelling concept which places emphasis on displacement demand predictions is potentially applicable to other regions of low-moderate seismicity around the globe. The rest of this paper provides an overview of updates on seismicity modelling, attenuation modelling, and response spectrum modelling for rock and soil sites. A case-study illustrating the practical implementation of the developed model on the seismic assessment of a lifeline facility is provided at the end of the paper.

## 2 SEISMIC ACTIVITY MODELLING

### 2.1 *Modelling from historical data*

Early contributors to seismic activity in Australia include researchers from the Australian Geological Survey Organisation (the precursor of Geoscience Australia), Bureau of Mineral Resources and Department of Geology and Mineralogy. Seismically active areas all over Australia were divided into source zones (each of which was assumed to possess a measurable and uniform level of activity). The activity level, which was assumed to remain constant with time, was modelled in accordance with the observed rate of recurrence of earthquake events in the historical database covering a time span of approximately 150 years (Gaull et al, 1990). This activity model when combined with selected attenuation models by the Cornell-McGuire Integration procedure predicts a notional peak ground acceleration (or "Hazard Factor": terminology used in AS 1170.4: 2007) ranging between 0.05g and 0.11g for most parts of Australia for a 10% probability of exceedance (PE) in a design life of 50 years (i.e. return period of 500 years). Normally, this probabilistic seismic hazard approach is used in regions where a great deal is known of the cause of the seismicity and individual fault sources. The noticeable "bull-eyes" contours in the Australian seismic hazard contour maps were the result of the occurrence of isolated historical events. This means that significant changes in the model (additional "bull-eye") have to be made each time a major earthquake event occurs "unexpectedly". There are techniques such as the Kernel Method which has been developed to smear the footprints of isolated historical events (review by Hutchinson et al, 2003). However, the seismic activity model has largely been shaped by observations over a period of around 150 years. The point of contention is that the observed spatial distribution of historical events would not necessarily be indicative of the probabilistic distribution of potential future destructive events.

### 2.2 *Modelling from neo-tectonic data*

Alternative approaches to seismic activity for Australia based on geo-morphological and paleo-seismological analysis was pioneered at the University of Melbourne (Sandiford et al, 2003), followed by contributions from Geoscience Australia. The availability of high resolution Digital Elevation Model (DEM) derived from aerial and satellite images in conjunction with geological data makes it possible for scarps from surface rupturing of pre-historical earthquakes in parts of Australia to be identified (Clarke, 2006; Leonard & Clarke, 2006). DEM information including fault lengths and scarp displacements have been translated into data forming part of the neo-tectonic earthquake catalogue covering a time span of up to approximately one hundred thousand years. It is noted that only large magnitude events (in the order of M7, or larger) have scarps that can be identified following such a long period of exposure. For these reasons, neo-tectonic data so generated from DEM only provides recurrence information in the high magnitude range whilst the conventional historical events catalogue are largely made up of records from low – moderate magnitude (M< 6) events. Leonard & Clark (2006) undertook a study to test the consistency between the very different scales of the two recurrence models. An important finding from the latter study is the significant inconsistencies between the recurrence model of the historical catalogue and that of the neo-tectonic catalogue for the shield regions of Western Australia. The contemporary seismicity level for this part of Australia (based on the catalogue of historical events) is much higher than that projected by the neo-tectonic model (based on data of pre-historical activities). The change in activity level from "pre-historical" to "historical" times follows different trends in different parts of Australia which suggests the interesting phenomenon of activity migration. Limitations of the conventional probabilistic seismic hazard methodology based on historical events have become evident particularly for regions of low – moderate seismicity. The newly developed neo-tectonics catalogue for Australia estimates the maximum magnitude (Mmax) to be in the order of M7.5, whilst Mmax = M7 seems reasonable when considering only the information provided by the database of historical earthquakes.

A hazard factor, or acceleration coefficient, of 0.08g has been stipulated for major capital cities including Canberra, Sydney and Melbourne for a return period of 500 years (0.08g corresponds to a peak ground velocity of 60 mm/sec according to the definitions by the Standard AS 1170.4 since the 1993 edition; further details of the conversion relationship is provided by the footnotes of Figure 1). Infrastructure designed and built over the past 15 years in Australia has been based on this design parameter. Any attempt to make changes is expected to be met with strong resistance irrespective of whether the currently stipulated hazard level is truly representative of the actual seismicity in these cities. Whilst seismic activity modelling must continue to develop, research efforts should be directed at assessing, and comparing, the potential seismic performance of structures and their components.

## 3 ATTENUATION MODELLING

### 3.1 *General*

A common question to ask is how the ground shaking generated by interplate and intraplate earthquakes would differ if the moment magnitude, epicentral distance and site conditions are kept the same. Intraplate earthquakes in Central and Eastern North America (CENA) have been known for a long time to be characterized by the so called "high stress drop" which has been interpreted recently as the result of high velocity fault-slip in the generation of seismic waves at the source of the earthquake (Beresnev & Atkinson, 2002). High slip velocity is considered to be partly attributed to the thrust faulting mechanisms typifying intraplate earthquakes, and in particular Australian earthquakes. However, similar faulting mechanisms are occasionally found with interplate earthquakes (eg. Northridge earthquake). The high stress drop observations are further complicated by variations in the attenuation properties of the earth crust and the magnitude range across different regions. Thus, exactly how much intrinsic difference is between interplate and intraplate earthquakes is still a subject of controversy.

Countries like Australia which has not captured sufficient near-field strong motion data to develop conventional (empirical) attenuation models of its own have the option to adopt the alternative approach of undertaking stochastic simulations of the seismological model which is characterized by the separation of the ground motion model into the "source", "regional" (path) and "local" components (the "local" component is not to be confused with the "site" components which deal with the effects of the surface sediments of the site). The heuristic framework of resolving ground shaking into the "source", "path" and "local" components enables telemetry data recorded by seismometers from long distances to be corrected for the path (and local) effects and hence enable seismic waves radiated from the "source" of the earthquake to be back-calculated. The stochastic seismological methodology was pioneered in the low-moderate seismicity regions of Central and Eastern North America (CENA) where strong motion data was lacking but sufficient telemetry data from the Eastern Canadian Telemetry Network (ECTN) was available to construct viable seismological models for the region (eg. Atkinson, 1993; Atkinson & Boore, 1995 & 1998).

### 3.2 *Hybrid Seismological Model for Australia*

There have been attempts to undertake such a stochastic modelling approach for Australia but the lack of telemetry data means that a seismological model similar to what has been developed in CENA could not be constructed using solely local data. A hybrid seismological (stochastic) modelling approach has been employed wherein the source component of the model is assumed to be generic in nature and hence the source factor of the model is no different to that developed originally for CENA. Central to this hybrid methodology is the assumption that earthquakes from different intraplate regions across the globe are generally consistent in its averaged source properties (Lam et al, 2000a; Lam & Wilson, 2004; Chandler et al, 2006a).

Meanwhile, the path and local components required to complete the seismological model can be inferred from local geological and seismological information (e.g. Lam & Wilson, 2004; Lam et al, 2006). The loss of energy along the wave travel path is very complex. The regional geological conditions in particular have a very important influence on the attenuation properties of the earth crust. In the seismological modelling for CENA, crustal models have been generalized using a broad classification of the earth crust as generic "hard rock" and "rock" (Boore & Joyner, 1997). Crustal conditions in other study areas outside North America might not necessarily be represented by either generic rock classes. In such areas, the shear wave velocity profile should be derived from representative geological or geophysical data obtained locally. In essence, seismological modelling employing the hybrid approach is mainly about deriving "filter" functions representing different parts of the seismic wave transmission paths from the source of the earthquake to the affected sites.

Factors characterizing the filter function of a region will have to be identified to account for the following effects: (i) geometrical spread of energy, (ii) dissipation of energy along the wave transmission path over long distances, (iii) amplification of the upward propagating waves through change in impedance within the upper crust (which is typically about 4 km in depth), and (iv) dissipation of energy in the upper crust. Regional differences in the filter properties explain why the average characteristics of earthquakes can differ considerably between different intraplate regions. The spatial variations of the filtering properties of the earth crusts can be used to explain the significant differences in the attenuation behaviour of earthquakes within Australia even though it is wholly within a tectonic plate. Seismological parameters that are considered to be generally representative of the average conditions in Eastern Australia in view of information collected to-date are summarized in Table 1.

### 3.3 *The Component Attenuation Model and Velocity Demand Predictions*

The seismological parameters listed in Table 1 could be incorporated into stochastic simulations of synthetic accelerograms using program GENQKE (Lam, 1999). Response spectra calculated from the simulated accelerograms were averaged across the accelerogram ensemble. The Component Attenuation Model (CAM) was then developed by curve-fitting the "mean" of the simulated results (ie. based on 50% exceedance). CAM, which was introduced in

Lam et al (2000b & c, 2003) and Lam & Wilson (2004) provides predictions for response spectrum parameters using simple algebraic expressions. The response spectrum parameters: RSAmax, RSVmax and RSDmax are respectively the highest acceleration, velocity and displacement demand of the single-degree-of-freedom systems for 5% damping, and can be used to construct response spectra in different formats. Alternatively, RSVmax in conjunction with the first and second corner periods ($T_1$ and $T_2$) can be used to construct the response spectra. Readers who are not familiar with these parameters and the associated response spectrum model may refer to Figure 1. A detailed presentation of the response spectrum model to practicing professionals can be found in Wilson & Lam (2006).

Equations (1a) & (1b) as presented in below provide approximations to the simulated results for R < 50 km and saves the need to work with the seismological parameters listed in Table 1. Equation (1a) can be used to predict the value of RSVmax on rock sites.

$$RSV_{max} \text{ (mm/sec)} = \alpha_v \cdot G \cdot \beta_v \cdot \gamma \cdot S \qquad (1a)$$

Where $\alpha_v$ is the Source Factor as defined by equation (1b); G is the Geometric Attenuation Factor and is equal to 30/R for R < 50 km (R is hypocentral distance in km); $\beta_v$ is the Anelastic Attenuation Factor which can be taken as $(30/R)^{0.005R}$ for R<50km; $\gamma$ is the combined crustal factor which can be taken as approximately 1.3 in shield regions of Western Australia and 1.6 – 2.0 for Eastern Australia; and S is the site factor (which is the subject matter of Section 5).

$$\alpha_v = 70 \{0.35 + 0.65 (M-5)^{1.8}\} \qquad (1b)$$

where M is the moment magnitude of the earthquake.

Equations (1a) and (1b) enable the peak ground velocity on rock sites to be predicted using the empirical expression of equation (1c); refer Wilson & Lam (2003, 2006).

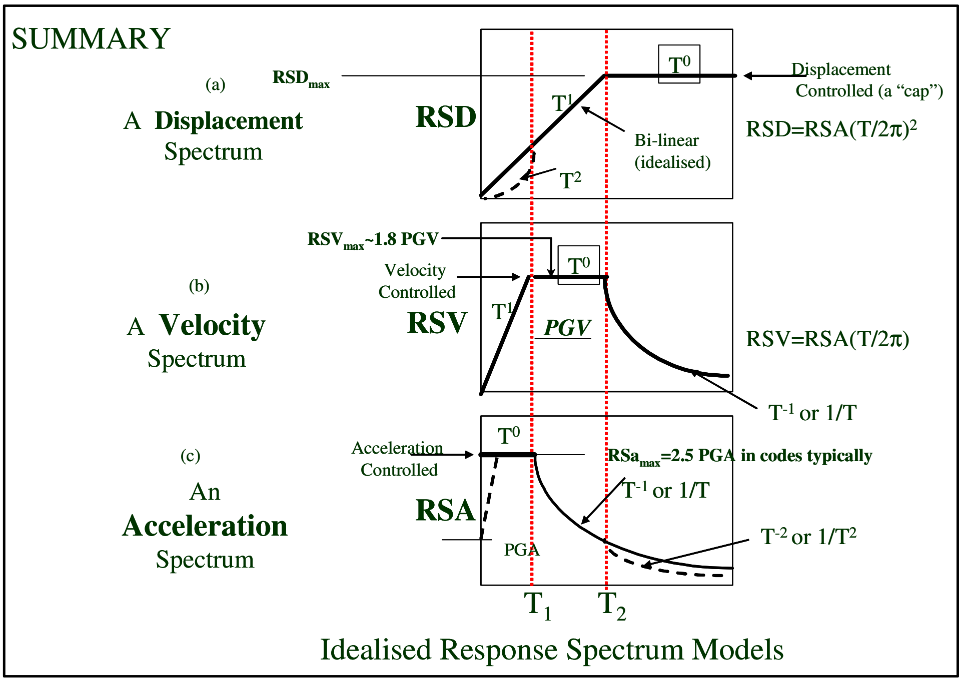
$$PGV = RSV_{max} / 1.8 \qquad (1c)$$

Whilst the whole of Australia has a common (magnitude dependent) source factor, different crustal factors have been assigned to Eastern and Western Australia. It is noted that the CAM expression of (1a) and (1b) are the simplified version of the model which enables response spectrum to be predicted without requiring many input parameters.

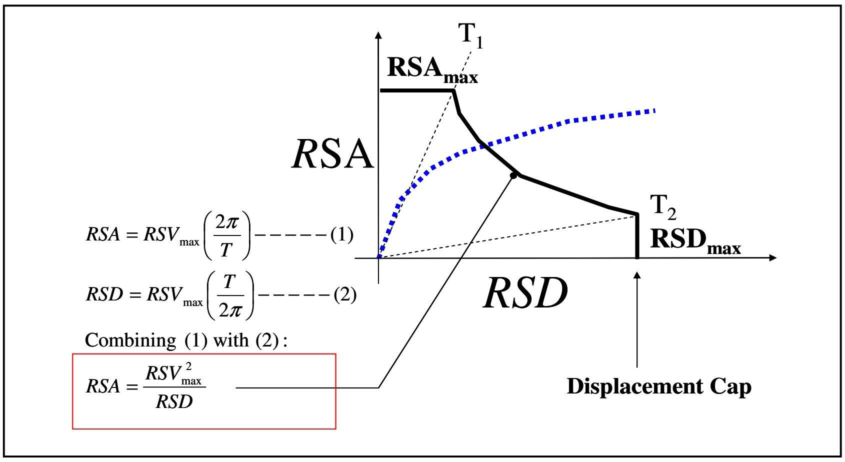
More rigorous representation of the crustal and path effects can be taken into account using a more elaborate procedure in CAM which makes use of shear wave velocity (SWV) information of the earth crust as surveyed by passive seismological monitoring techniques to characterize the attenuation and amplification properties of the wave transmission path (eg. Lam et al, 2006). This version of CAM enables the attenuation properties of specific areas to be modelled with precision and is distinguished from the "broad brush" modelling approach represented by equations (1a)-(1b).

Table 1. Summary of seismological model for Eastern Australia.

| **model or factors** | **recommendations** | **remarks** |
|---|---|---|
| Source model | Spectral source model of Atkin son (1993) developed originally for *Eastern North America*. | The spectral source model of Atkinson (1993) is taken as the *generic source model* for intraplate earthquakes. The generalization of the source model is supported by the calibration studies of Lam *et al* (2003, 2006) for Australia, Chandler *et al* (2006a) for South China, Chandler & Lam (2004) for India, and Sabegh and Lam (submitted) for the Tehran region, Iran. |
| Mid-crust factor | A mid-crust scaling factor, C, of 0.78 was assumed based on crustal density at source = 2700 kg/m$^3$ and shear wave velocity at source = 3500 m/sec. | The assumed shear wave velocity is based on (i) depth of the source which is taken to be in the range : 5 – 8 km and (ii) shear wave velocities as inferred from information presented in CRUST2.0 tiles (refer Lam *et al*, 2006). |
| Quality factor | $Q_o$-Quality factor: 160, exponent: 0.56 | $Q_o$ values ranging between 100 and 300 has been recorded in different parts of Eastern Australia as summarized in Table 3 of Lam *et al* (2003). |
| Shear wave velocity model | Generic " rock" model profile as defined by Boore & Joyner (1997), with shear wave velocity in the order of 600-800 m/sec in the upper 30 m of the crust. | The adoption of the generic "rock" model is likely to result in conservative predictions of upper crustal amplifications in Eastern Australia. |
| *Kappa* factor | *Kappa* factor of 0.035 | This value is based on the lower bound (hence conservative) estimates from the model by Chandler *et al* (2005) for a shear wave velocity of 600 – 800 m/sec at 30m depth. |




(a) Model in the displacement, velocity and acceleration response spectrum format




(b) Model in the form of ADRS diagram

$$\boldsymbol{RSA_{max}} = 3(\boldsymbol{k_p Z})\ \boldsymbol{F_a} \qquad (1)$$

units in g's

$$\boldsymbol{RSV_{max}} = 1.8\ \boldsymbol{PGV\ F_v} \qquad \text{where } \boldsymbol{PGV} = 750\ (\boldsymbol{k_p Z}) \qquad (2)$$

units in mm/sec

$$\boldsymbol{RSD_{max}} = \boldsymbol{RSV_{max}}\ (\boldsymbol{T_2}/2\pi) \qquad \text{where } \boldsymbol{T_2} = 1.5 \text{ secs}$$

units in mm

footnotes:

(1) Factor of "3" (instead of "2.5") is intended to reflect the well known phenomenon of high spectral amplification in the short period range with intraplate earthquakes; $k_p$ is the return period factor and $F_a$ and $F_v$ are site factors (refer Table 3).

(2) The conversion factor of "750" was used by the Standard for back calculating the notional ***pga*** (or hazard factor) from the inferred designed ***PGV*** on rock sites of any given area. This relationship is consistent with a $T_1$ value of ~ 0.3 secs.

Figure 1. Format of the new Response Spectrum Model for Australia (standard provisions).

### 3.4 *Stochastic versus Intensity models*

The approach of mapping macroseismic (Intensity) data taken from post-disaster damage surveys of earthquake affected areas was adopted by Gaull et al (1990) in developing the attenuation models for the whole of Australia. The developed attenuation models were then incorporated into seismic hazard analyses for generation of the probabilistic seismic hazard maps which have been in use in Australia for almost 15 years. Ground motion parameters such as peak ground velocity (PGV), or peak ground acceleration (PGA), can be inferred from Intensity data expressed in the Modified Mercalli Intensity (MMI) scales using empirical relationships. Equations (2a) & (2b) represents one such attenuation model that has been developed for an "average" site in Eastern Australia as presented in Gaull et al (1990).

$$MMI = 1.5M - 3.9 \log R + 3.9 - 0.6 \quad \text{(Eastern Australia)} \quad (2a)$$

$$2^{MMI} = 7/5\ PGV \quad (2b)$$

where *PGV* is expressed in mm/sec.

The main drawback with this approach is uncertainties with the accuracies of the Intensity mapping and that of the inferred ground motions given that Intensity-PGV correlations are dependent on many factors including local design and detailing practices of the built infrastructure. Furthermore, Intensity mapping cannot take into account site effects. Earthquakes of different magnitudes are not necessarily well represented by historical events archived in the Intensity database. Thus, the properties of earthquake ground shaking cannot be characterized accurately by attenuation relationships based solely on Intensity data. An important step in the development of the hybrid seismological (stochastic) model is the correlation of PGV's simulated for rock sites against PGV's inferred from "average" sites from the Modified Mercalli Intensity (MMI) data. The quality of the model was well reflected in the good linear correlations between the two sets of predicted PGV's.

Earlier attenuation studies for the Melbourne area, Australia and the South China Hong Kong area showed that the PGV's of an average site as inferred from Intensity data were consistently 2.0 – 2.2 times higher than the PGV's predicted for rock sites by stochastic simulations (Lam et al, 2006; Chandler et al, 2006a). This inferred amplification factor (from rock site to average site) can be described as a calibration factor since errors arising from different causes as described in the foregoing could have been absorbed into the factor. Notwithstanding, the inferred amplification (calibration) factor of 2.0-2.2 is considered reasonable for the moderate level of ground shaking that is consistent with a seismic coefficient of 0.1g. In essence, predictions by CAM, (as represented by equations (1a)-(1c)), and that by the MMI model of Gaull et al (1990) for Eastern Australia, (as represented by equations (2a)-(2b)), are actually consistent when differences between "generic rock" sites and "average (soil)" sites have been accounted for.

## 4 DISPLACEMENT DEMAND MODELLING

Using equations (1a)-(1c) and equations (2a)-(2b) which provide generally consistent predictions for the PGV's on rock sites, a list of earthquake scenarios expressed in terms of the Magnitude-Distance (M-R) combinations can be calibrated in order that the predicted PGV's on rock sites match with the design PGV of 60 mm/sec (which corresponds to a factor of 0.08g). Such M-R listing for Eastern Australia is shown in Table 2.

Equation (3) is the CAM expression for the prediction of the highest displacement demand up to a natural period of 5 seconds (RSDmax) and is similar in form to equation (1a) for the prediction of RSVmax.

$$RSD_{max}\ (\text{mm}) = \alpha_d \,.\, G \,.\, \beta_d \,.\, \gamma \,.\, S \quad (3)$$

where $\alpha_d$ is the source factor.

Table 2. *M-R* Combinations in Eastern Australia.

| *M* | *R* (km) | $RSD_{max}$ (mm) | | $T_2$ Eq. 3&4a&5 |
|---|---|---|---|---|
| | | Eqs. 3 & 4a | Eqs. 3 & 4b | |
| 5.0 | 10 – 15 | 9 | 5 | 0.5 |
| 5.5 | 20 | 10 | 9 | 0.6 |
| 6.0 | 30 – 35 | 17 | 17 | 1.0 |
| 6.5 | 50 | 22 | 32 | 1.3 |
| 7.0 | 90* | 30* | NA | 1.7 |

* *PGV* and $RSD_{max}$ predicted for *R*> 50 km were calculated not by the presented expressions but using a more elaborate procedure (Lam *et al*., 2000) which is not shown herein.

Two expressions have been developed for the prediction of the value of $\alpha_d$. The first expression (equation 4a) which is of the form similar to equation (1b) was developed by the stochastic simulations of the CENA source model (Lam et al, 2000b). Equation (4b) is based on a theoretical model presented originally in Lam & Chandler (2005). Significant to note is the general consistencies between the two independently developed relationships up to M6.5; but equation (4a) is more realistic than equation (4b) for higher magnitude earthquakes.

$$\alpha_d = 10\ \{0.20 + 0.80\ (M\text{-}5)^{2.3}\} \quad (4a)$$
$$\alpha_d = 10^{\ M\text{-}5} \quad (4b)$$

The path factors of $G$ and $\gamma$ used in equation (3) can be taken to be identical to those used in equation (1a). The *Anelastic Attenuation Factor* $\beta_d$ may be taken as $(30/R)^{0.003R}$ for $R$<50km. Values of $RSD_{max}$ as calculated from equations (3) & (4a-4b) are also shown in Table 2 alongside the listed *M-R* combinations. The "second corner period", $T_2$, of the displacement response spectrum as defined by equation (5) is also shown. Interestingly, the magnitude dependent values of $T_2$ (as shown in Table 2) can be approximated by the simple linear expression of equation (6).

$$T_2 = 2\pi\ (RSD_{max}/RSV_{max}) \quad (5)$$
$$T_2 \sim 0.5 + (M\text{-}5)/2 \qquad \text{for M} \geq 5 \quad (6)$$

Clearly, the displacement demand behaviour of the earthquake is very sensitive to its moment magnitude when PGV is kept constant. The non-linear relationships between the velocity and displacement parameters mean that neither the PGV nor PGA value of the earthquake could be sufficiently indicative of the potential destructiveness of the earthquake.

Thus, an accurate identification of the $T_2$ parameter is critical. In the new Australian Standard for earthquake actions (AS1170.4:2007), the value of $T_2$ is implicitly taken as 1.5 secs based on an upper moment magnitude limit of M7. The use of the response spectrum parameters: RSVmax, RSDmax and $T_2$ in the construction of response spectra for practical engineering applications on rock sites is illustrated in Section 6. The determination of additional parameters for modelling of the site effects is briefly described in Section 5.

## 5 MODELLING OF SITE EFFECTS

The new Australian Standard (AS1170.4, 2007) provides recommendations for site classes and the corresponding site factors as shown in Table 3. The site classification scheme is similar to that proposed initially by NEHRP (published in FEMA273, 1997), and subsequently adopted by the International Building Code (IBC 2006) of the Unites States, except that the site natural period ($T_s$) has been included as a criterion for site classification. Shown along the site factors stipulated by AS1170.4 (2007) are factors stipulated by the IBC (2006) for different intensities of ground shaking.

The alternative (higher tier) approach is to undertake a site-specific spectral analysis of the soil column model. This modelling approach is suited to the seismic assessment (or design) of critical infrastructure or lifeline facilities. Refer to Section 6 for illustration of the application of the response spectrum model by the case-study of a major lifeline facility. The effects of site resonance which can be accentuated by non-ductile behaviour of the structure can be represented more accurately by the site-specific response spectrum as opposed to the standard provisions of Table 3.

Table 3. Site Classification and Site Factors in the new Australian Standard (AS1170.4 : 2007).

| Site Class | Brief Description | AS1170.4 | | IBC ($z$=0.1g) | | IBC ($z$=0.4g) | |
|---|---|---|---|---|---|---|---|
| | | $F_a$ | $F_v$ | $F_a$ | $F_v$ | $F_a$ | $F_v$ |
| A | Strong Rock | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| B | Rock with *SWV* averaging above 360 m/sec | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| C | Shallow soil sites ($T_s$ < 0.6 sec) | 1.25 | 1.4 | 1.2 | 1.7 | 1.0 | 1.4 |
| D | Deep or soft soil sites ($T_s$ > 0.6 sec) | 1.25 | 2.3 | 1.6 | 2.4 | 1.1 | 1.6 |
| E | A special class of sites with very soft soils (SPT < 6) exceeding 10m in thickness | 1.25 | 3.5 | 2.5 | 3.5 | 0.9 | 2.4 |

In the site-specific model, the response spectrum is amplified at the fundamental natural period of the site period ($T_s$) at which point the structure is subject to the highest drift demand. This form of response spectrum construction is distinguished from the usual "site factor" models based on broad classification of the site in contemporary codes of practices. Models developed to-date by the authors and collaborators for the estimation of the site period and site factor can be found in Lam and Wilson (1999), Lam et al (2001), Srikanth (2006) and Tsang et al (2006a & b). It is noted that the calculated site amplification factors (in the order of 3 – 5 typically) which are dependent on the soil SWV, hysteretic and radiation damping properties and frequency content of the bedrock excitations in relation to the site natural period ($T_s$) can be significantly higher than most current code provisions which are based on averaging results from a range of very different site conditions. It is noted, however, that inconservatism in the values of the code specified site amplification factors has been offset by the implicit conservatism of the rock response spectrum models (as demonstrated in the next section).

## 6 CASE-STUDY OF A LIFELINE FACILITY

This section presents the case-study of the construction of the site-specific response spectrum model for a major lifeline facility in Australia. The response spectra are subject to scaling by the Hazard Factor (Z) which is dependent on the design life of the facility and the probability of exceedance (PE) as shown in Table 4. Benchmark Hazard Factors which correspond to 10% PE in a Design Life of 50 years are presented in seismic hazard maps. A value of 0.08g has been stipulated for major centres of population on the eastern seaboard including Sydney, Melbourne and Canberra. A higher Hazard Factor of 0.13g was calculated for the design/assessment of the lifeline facility based on a 5% PE in a Design Life of 100 years.

A 100 year design life and a 5 % probability of exceedance is translated into a design return period of 2000 years according to equation (7).

$$Pr = 1 - \left(1 - \frac{1}{RP}\right)^{DesignLife} \quad (7)$$

where Pr is probability of exceedance; RP is return period.

The stipulated KP factor is accordingly equal to 1.7 in accordance with AS/NZS 1170.0 : 2002. A seismic hazard factor (KpZ) of 0.13g is calculated (where Z = 0.08g has been identified for the benchmark return period of 500 years for the area). The recommended design peak ground velocity (PGV) on rock is accordingly 100 mm/sec according to equation (8) which is consistent with the 1993 and 2007 editions of AS1170.4.

$$PGV(mm/\sec) = 750 K_p Z \quad (8)$$

The notional peak ground velocity (PGV) on rock can be defined as the highest velocity demand on the velocity response spectrum (RSVmax) divided by 1.8 based on the recommendations by Wilson and Lam (2003) and Somerville et al (1998). The earthquake scenarios, as defined by the magnitude-distance (M-R) combinations for Eastern Australia, which are consistent with a PGV in the order of 100 mm/sec are listed below based on the attenuation relationship shown in Figure 2.

The attenuation relationships shown in Figure 2 were derived from stochastic simulations of the hybrid seismological model developed for Eastern Australia as outlined in Section 3. In the seismic assessment of the lifeline facility, the site was divided into four areas: A – D each of which requires a soil column model to represent the subsoil conditions. The subsoil models representing the four areas for input into one-dimensional pseudo non-linear soil dynamic analysis (program SHAKE (Idriss & Sun, 1991) originally written by Schnabel et al, 1972) are summarized in Table 5 based on information provided from the borehole records.

*Standard Penetration Test Count* (*N* values) for individual soil layers were not recorded in most of the boreholes. N values were inferred from qualitative descriptions in the borelogs and classification of the sediment types (Figure 3) based on guidelines presented in Lam & Wilson (1999). The initial dynamic shear moduli *G* were then calculated from the inferred N values based on the well known correlations of *Imai & Tonouchi* (1982) which was cited in Lam & Wilson (1999) as a robust relationship which can be applied to both cohesionless and cohesive soils. The initial shear wave velocities were then calculated from basic wave-theory assuming a soil density of 1.5t/cum – 1.8t/cum, with the exact value depending on stiffness and density of the soil. Fresh or slightly decomposed volcanic crystalline rock, *Basalt*, was modelled as "half-space" with a shear wave velocity of 1000 m/sec in the soil column model used for dynamic analysis. The sound volcanic rock layer, the underlying tertiary sediments (of approx. 20m thick) and the basement rock (*Silurian* mudstone) were all modelled as part of the half-space in the soil dynamic analysis.

Table 4. Design Life, Return Period and Hazard Factor.

| | Design Life (years) | Prob. Of Exceedance | Return Period (years) as per eq. (1) | $K_p$ Factor as per AS/NZS 1170.0:2002 | Hazard Factor (as per AS1170.4 ) |
|---|---|---|---|---|---|
| For common building structures: Design Life of 50 yrs and 10% exceedance | 50 | 10% | 500 | 1.0 | 0.08g (benchmark values as shown on seismic hazard maps and tables in AS1170.4) |
| Design Life of 100 years and 10% exceedance | 100 | 10% | 1000 | 1.3 | 0.10g |
| **Design Life of 100 yrs and 5 % exceedance** | **100** | **5%** | **2000** | **1.7** | **0.13g** |

1. Moment Magnitude $M = 7$ Epicentral distance $R = 45$ km
2. Moment Magnitude $M = 6$ Epicentral distance $R = 20$ km

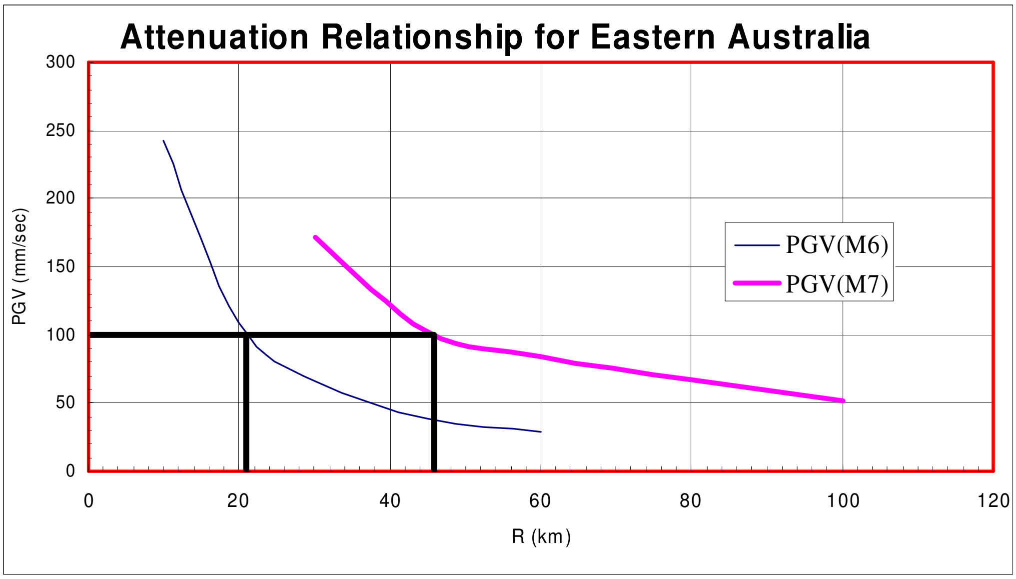
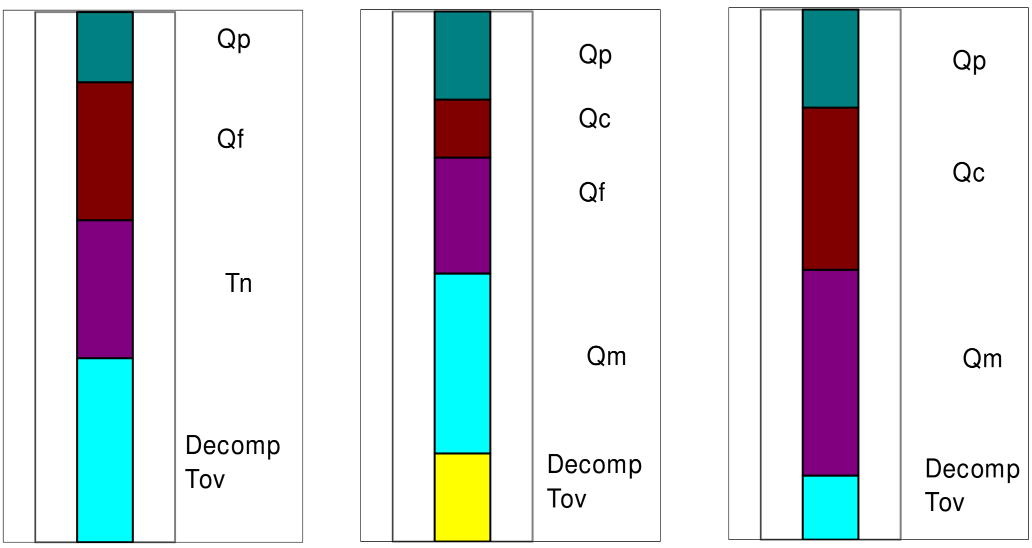



Figure 2. Attenuation Relationship for Eastern Australia.

Table 5. Subsoil Models for Dynamic Analysis.

| | Area A | Area B | Area C | Area D |
|---|---|---|---|---|
| River Alluvials [$Q_p$] | - | surface to 6m<br>$V_s$ = 100 m/sec | Surface to 9m<br>$V_s$ = 100 m/sec | Surface to 9m<br>$V_s$ = 100 m/sec |
| Soft Silty Sand [$Q_c$] | - | - | 9m – 15m<br>$V_s$ = 170 m/sec | 9m – 24m<br>$V_s$ = 170 m/sec |
| Quaternary Silts [$Q_f$] | - | 6m – 18m<br>$V_s$ = 200 m/sec | 15m – 27m<br>$V_s$= 200m/sec | 24m – 43m<br><br>$V_s$ = 180 m/sec |
| Tertiary Sediments [$T_n$ ] (mixture of sands and gravels) | - | 18m – 30m<br><br>$Vs$ = 220 m/sec | 27m – 46m<br><br>$V_s$ = 190 m/sec | |
| Decomposed Basalt [$T_{ov}$] | - | 30m – 46m<br>$V_s$ = 310 m/sec | 46m – 55m<br>$V_s$ = 240 m/sec | 43m – 49m<br>$V_s$ = 280 m/sec |
| Slightly Decomposed Basalt (modelled as half-space) | Half-space<br><br>$V_s$ =1000 m/sec | Half-space<br><br>$V_s$ =1000 m/sec | Half-space<br><br>$V_s$ =1000 m/sec | Half-space<br><br>$V_s$ =1000 m/sec |




(a) Area B (b) Area C (c) Area D

Figure 3. Subsoil models overlying bedrock.

In the soil dynamic analyses, the stiffness degradation relationship of the soil sediments expressed in terms of the ratio of the soil shear modulus $G/G_{max}$ and soil shear strain $\gamma$ is defined by equation (9).

$$\frac{G}{G_{\max}} = \frac{1}{1+\frac{\gamma}{\gamma_r}}$$ where $\gamma_r$ is taken as 0.025 for sand and silts (9)

Similarly, the critical damping ratio $\zeta$ is defined by equation (10).

$$\varsigma = \varsigma_i + \varsigma_{\max}\frac{\gamma}{\gamma+\gamma_r} \qquad (10)$$

where $\zeta_i$ and $\zeta_{max}$ is taken as 0.015 and 0.16 respectively for sand and silts.

The stiffness degradation and damping model as defined above is consistent with recommendations presented in Lam & Wilson (1999) and in the more recent publication by Tsang *et al* (2006b). These models were originally based on the work by Hardin & Drnevich (1972), Seed & Idriss (1970) and Vucetic & Dobry (1991). These analyses were based on a hazard factor ($K_pZ$) of 0.13 g and hence a design *PGV* in the order of 100 mm/sec resulting in a maximum velocity demand ($RSV_{max}$) of about 180 mm/sec for 5 % critical damping on rock sites. Accelerograms consistent with the earthquake scenarios of (i) M7 $R$ = 45 km and (ii) M6 $R$ = 20 km were simulated for rock outcrops in Eastern Australia using program GENQKE (Lam, 1999; Lam *et al* 2000a). Response spectra simulated for the two earthquake scenarios are presented in different formats in Figure 4.

Graphs presented in these figures were based on the ensemble average response spectrum calculated from 18 stochastically simulated accelerograms with random phase-angles. Note, the maximum velocity demand ($RSV_{max}$) as indicated by the averaged response spectrum is in the order of 180 mm/sec and hence in agreement with the targeted intensity of ground shaking on rock.

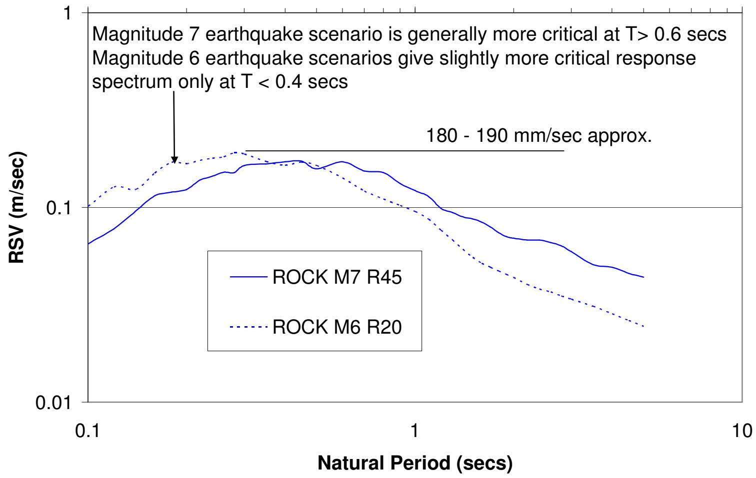
Response spectra stipulated by both the "old" (AS1170.4 : 1993) and "new" (AS 1170.4 : 2007) editions of the Australian standard for "rock" ($S$ = 1 or Class B) sites are also shown in the figures for comparison with the ensemble averaged simulated response spectra calculated from the stochastically simulated accelerograms. Clearly, the design response spectrum stipulated by the "new" (2007) edition of the Standard matches with the simulated response spectra better than that of the "old" (1993) edition. The construction of the response spectrum model stipulated by the new edition of the Standard is based on resolving the response spectrum into the acceleration, velocity and displacement controlled regions as illustrated in Wilson & Lam (2003 and 2006).

Response spectra calculated from a sample of three individual simulated accelerograms and the ensemble average of three, six, twelve and eighteen accelerograms are shown in Figure 5. These figures show the random inter-event variabilities and the increasing robustness of ensemble averages with increasing sample size. It is shown that a sample size of 12 or larger is sufficiently robust.

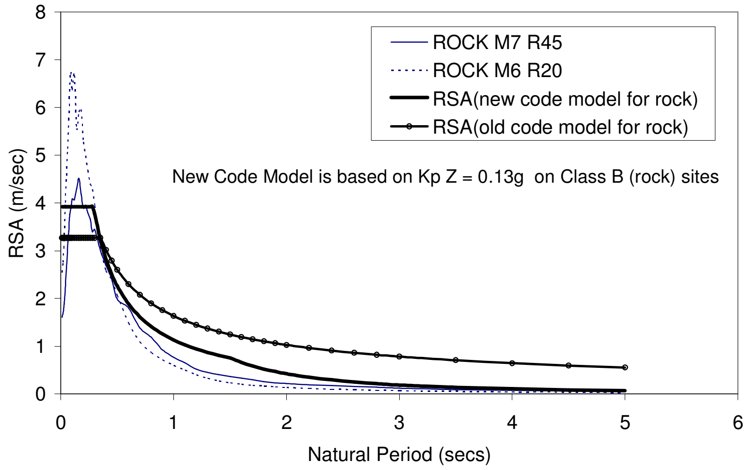
Accelerograms consistent with the earthquake scenarios of (i) M7 R = 45 km and (ii) M6 R = 20 km were simulated for rock outcrops in Eastern Australia for input into the dynamic analyses of the subsoil (soil column) models. Ground motions on rock were generated by program GENQKE (eg. Figure 6). The response spectra for the soil surface for different areas: A-D within the site of the lifeline facility (as calculated by program SHAKE) are presented in Figure 7 (with initial site natural period varying between 1 sec and 1.6 secs).

The response spectra shown in Figure 7 were based on the average response spectra calculated from 12 simulated accelerograms for earthquake scenarios of M7 R = 45 km and (the less critical) the earthquake scenario of M6 R = 20 km calculated by program SHAKE. Response spectra stipulated by the "new" (AS/NZS 1170.4: 2007) editions of the Australian standard with a calibrated site factor of $F_a$ = 1.25 and $F_v$ = 2.6 are also shown in Figure 7 for comparison with the calculated response spectra. Response spectra calculated from a sample of three individual simulated accelerograms and the ensemble average of three, six and twelve are shown in Figure 8 to show random inter-event variabilities and the increasing robustness of ensemble averages with increasing sample size. Clearly, a sample size of 12 is sufficiently large to produce a robust estimate of the averaged response spectrum.

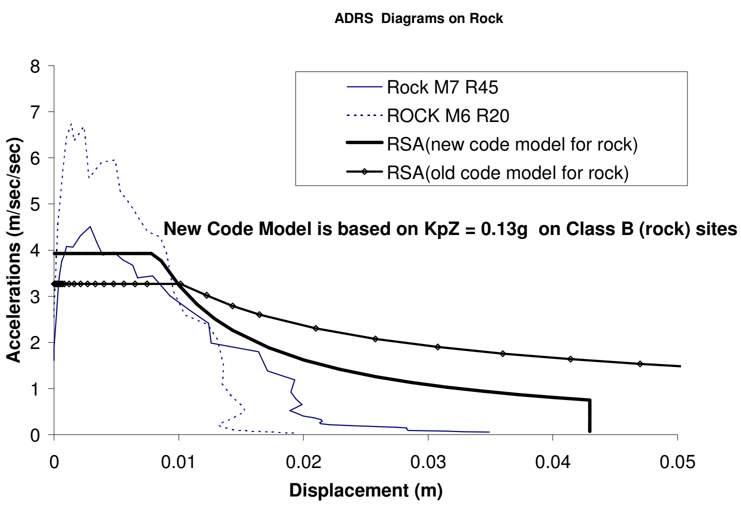
A sample acceleration time-history associated with the earthquake scenario of M7 $R$ = 45 km and M6 $R$=20 km are shown in Figure 9. A tri-linear response spectrum model in the tri-partite (velocity) format for a hazard factor ($K_pZ$) of 0.13g is constructed in Figure 10 to envelope response spectra simulated for the conditions of rock outcrops (Area A) and soft soil conditions (Areas B-D). The tri-linear design response spectrum plotted actually corresponds to that stipulated for a Class D/E site in AS1170.4: 2007 with hazard factor $K_pZ$ = 0.13g and calibrated site coefficient of $F_a$ = 1.25 (for the acceleration controlled region) and $F_v$ = 2.6 (for the velocity and displacement controlled regions). It is recommended that this tri-linear envelope be used to




(a) RSV Spectrum (logarithmic scale)

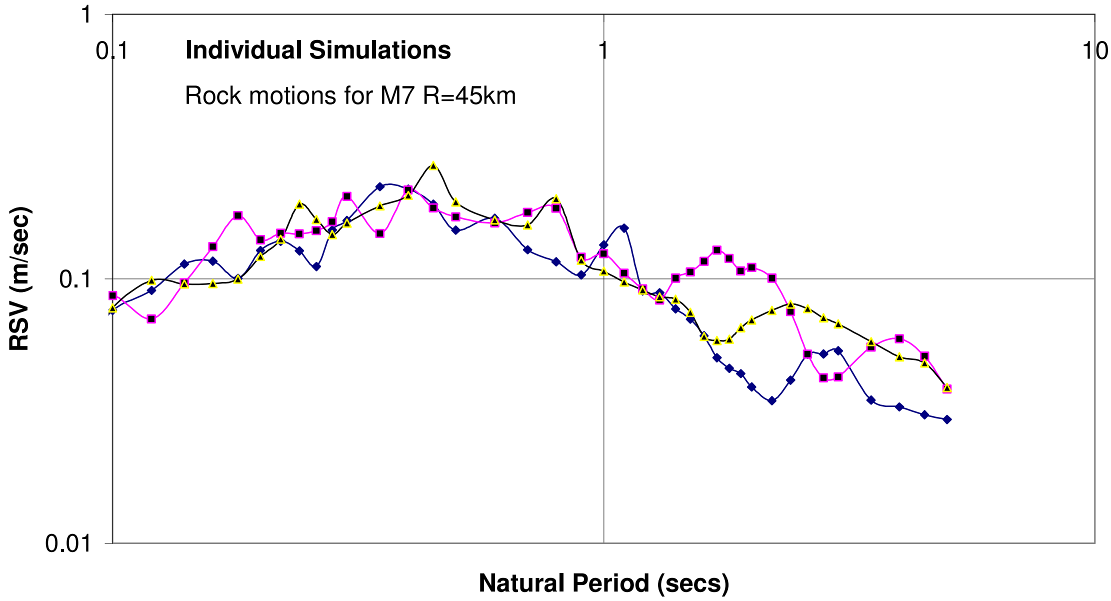



(b) RSA Spectrum

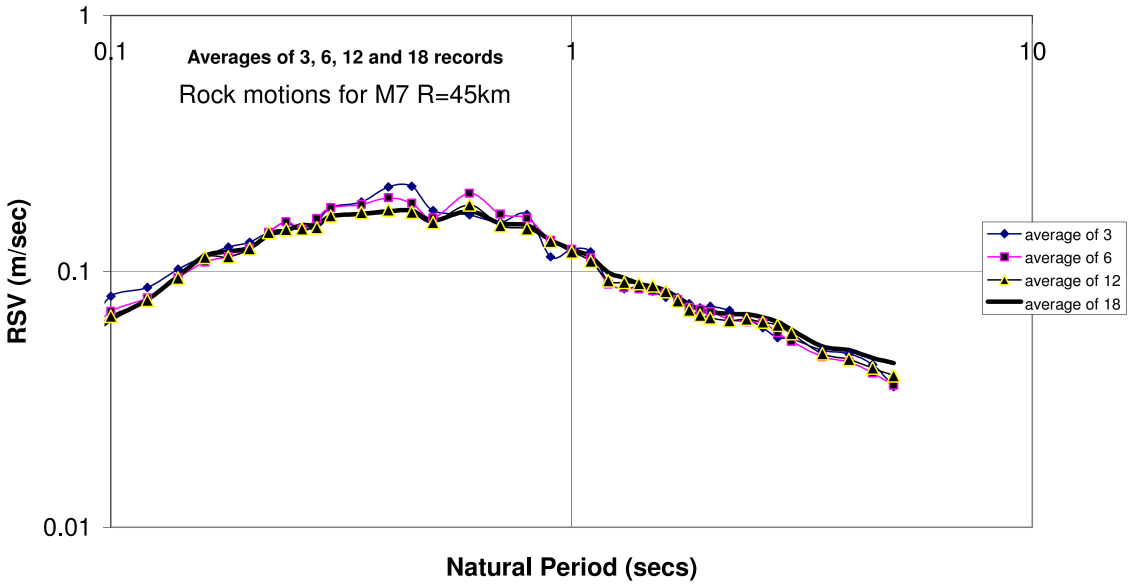



(c) ADRS Diagram

Figure 4. Response spectra simulated for rock outcrops.

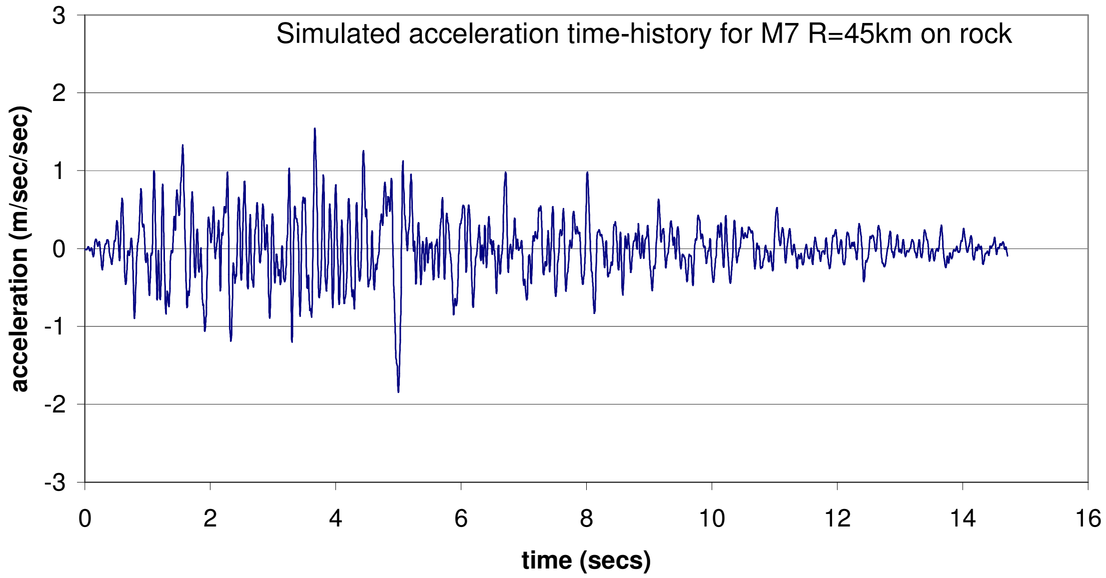



(a) Individual Simulations

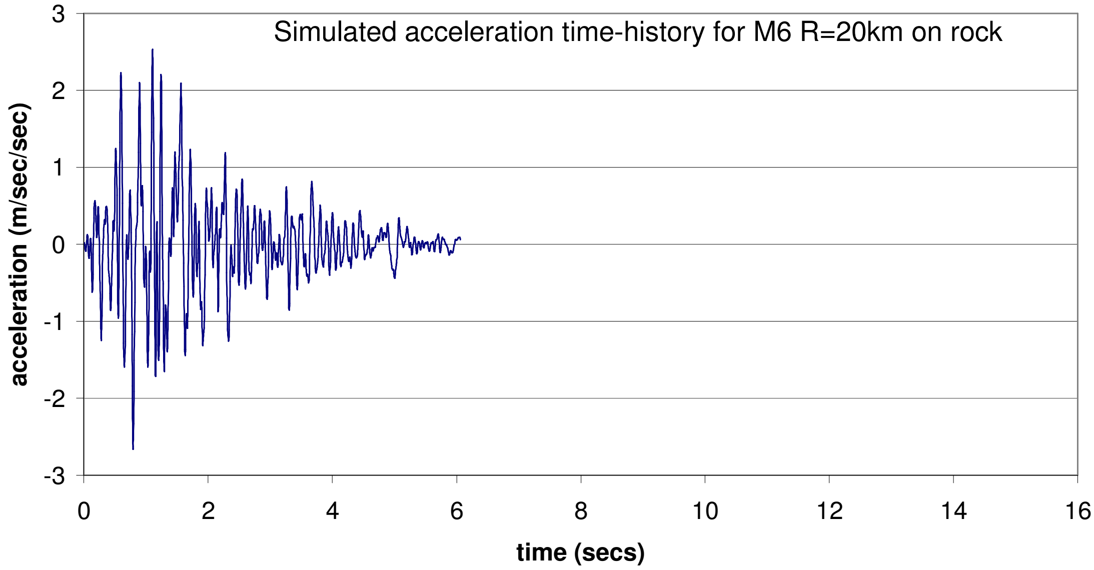



(b) Averages of 3, 6, 12 and 18

Figure 5. Response spectra showing random variabilities.

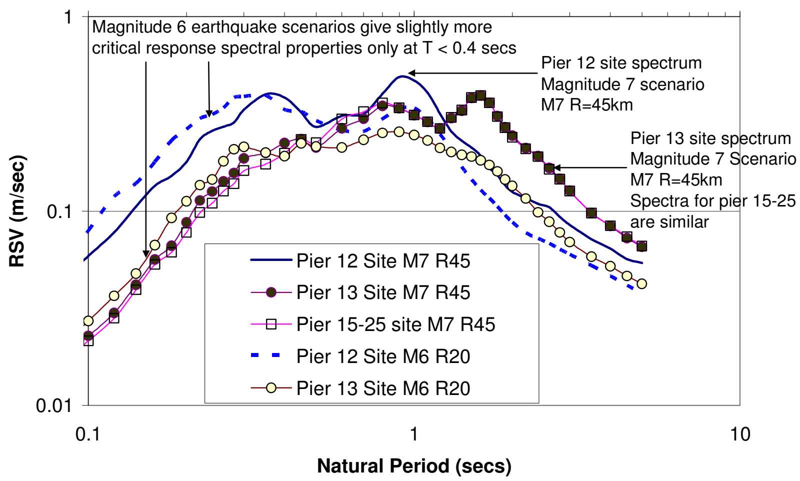



(a) Earthquake scenario of M7 R = 45 km

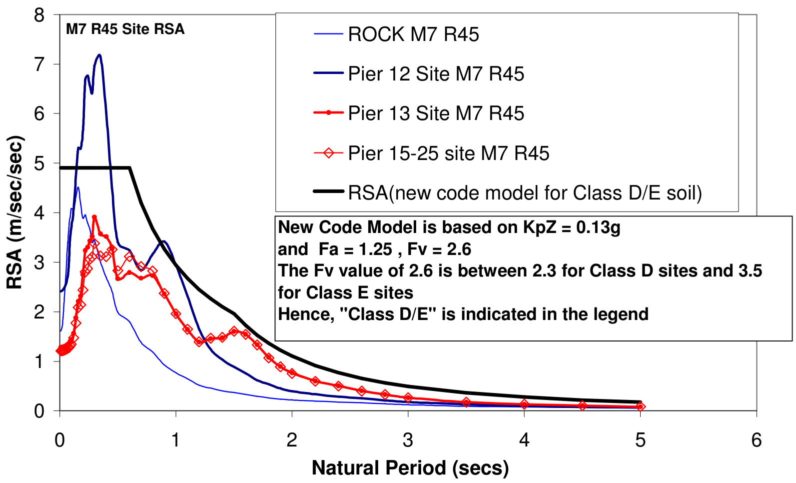



(b) Earthquake scenario of M6 R = 20 km

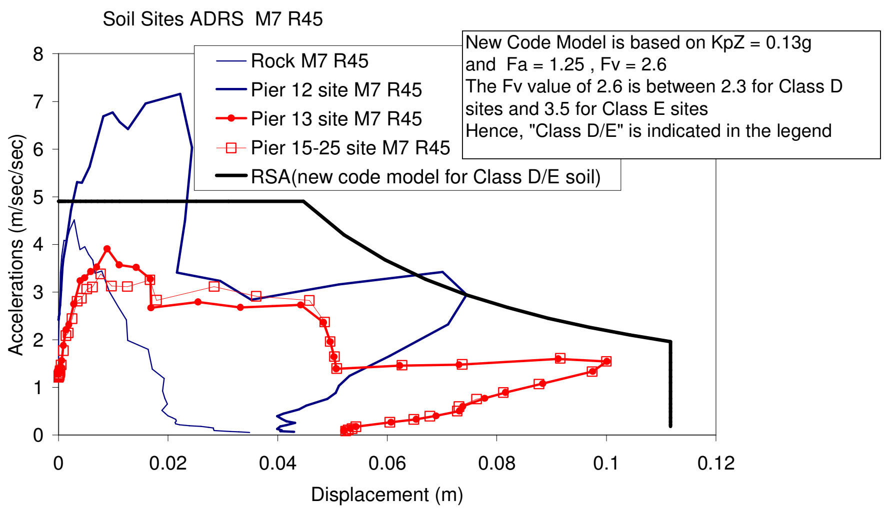
Figure 6. Sample acceleration time-histories on rock.




(a) Velocity Response Spectrum




(b) Acceleration Response Spectrum




(c) Acceleration-Displacement Response Spectrum Diagram

Figure 7. Response spectra simulated for soil surface.

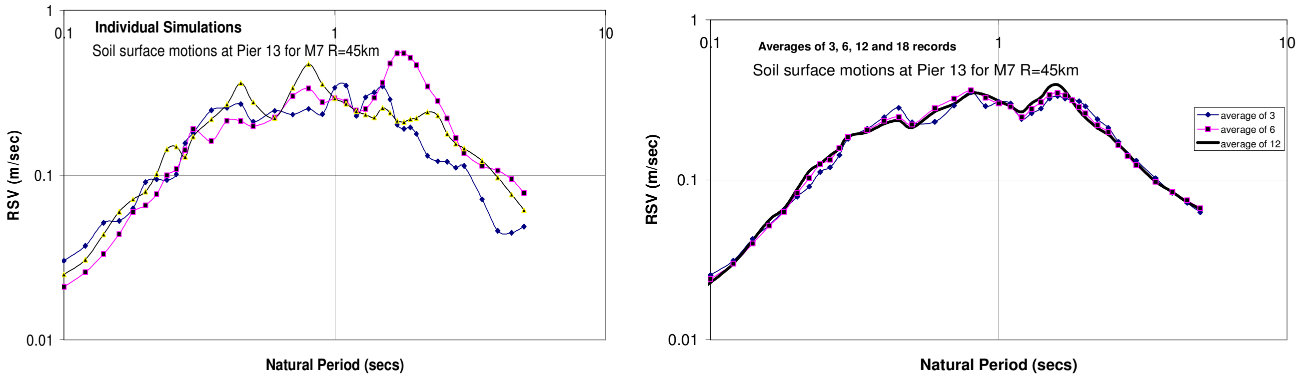
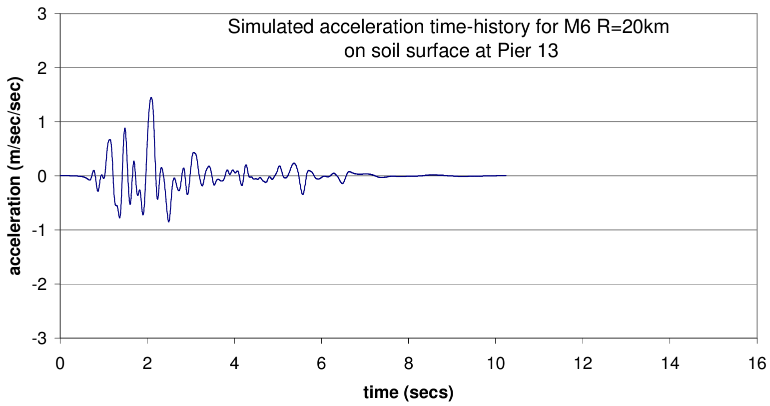
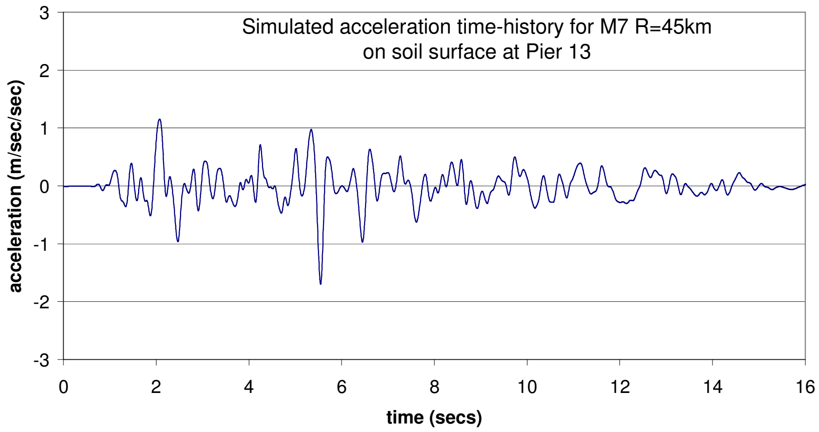



Figure 8 Response spectra showing random variabilities.




(a) Earthquake scenario of M7 R = 45 km




(b) Earthquake scenario of M6 R = 20 km

Figure 9. Sample acceleration time-histories on soil surface.

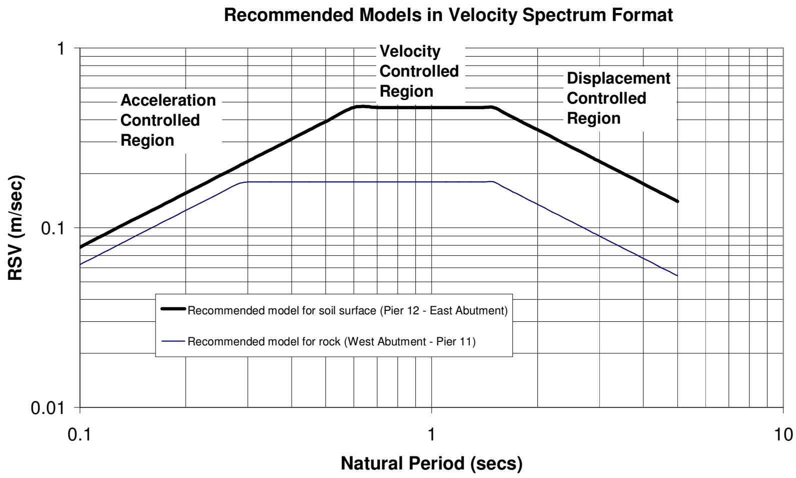
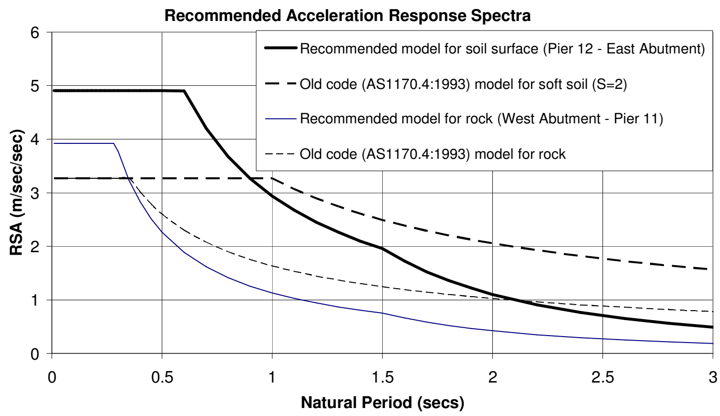
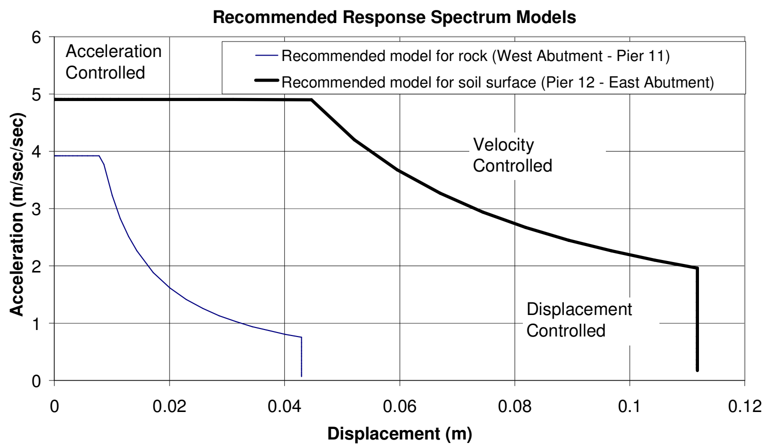



Figure 10. Recommended response spectrum models (based on $K_pZ = 0.13g$)




(a) Acceleration Response Spectrum Format




(b) ADRS Diagram Format

Figure 11. Recommended response spectrum models.

define the response spectrum model for the lifeline facility as illustrated in Figure 11 (acceleration response spectrum and the ADRS diagram format respectively). A sample acceleration time-history associated with each of the projected earthquake scenarios is shown in Figure 6.

## 7 CONCLUSIONS

- Recent development of the neo-tectonic catalogue provides insights into the phenomenon of seismic migration and reveals limitations of the conventional modelling methodology based solely on the catalogue of historical earthquake events.
- The hybrid seismological (stochastic) model has been developed for Eastern Australia and other parts of the continent based on combining the generic source model of intraplate earthquakes with the filtering models of the earth crusts.
- Peak ground velocities derived from the hybrid seismological model and that from Intensity information have been compared. A calibration (site) factor of 2.0 – 2.2 which relates ground shakings predicted for a rock site to that for an average site has been identified.
- The Component Attenuation Model (CAM) enables response spectrum parameters : RSVmax and RSDmax, or corner period $T_2$, to be calculated for a given earthquake scenario using simple algebraic expressions. Response spectra can be constructed for rock sites using these parameters.
- Site classifications and amplification factors similar to the NEHRP recommendations have been stipulated.
- The implementation of the response spectrum model for site-specific applications which allow for the effects of soil resonance has been illustrated by the case-study of a lifeline facility in Australia.

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