

# EARTHQUAKE RESPONSE SPECTRUM MODELS FOR AUSTRALIA

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## **ABSTRACT:**

Response spectrum provisions in the current Australian Earthquake Loading Standard (AS1170.4) were based on recommendations by the 1991 edition of the Uniform Building Code for the United States. Since publication of AS1170.4 in 1993, a number of alternative response spectrum models have been developed in Australia to address local seismic conditions. A normalised velocity response spectrum model was first developed by the Australian Geological Survey Organisation (AGSO) based on the averaging of results obtained from the analyses of strong motion accelerograms collected from worldwide intraplate regions. A generic response spectrum attenuation model, known as the Component Attenuation Model (CAM), has also been developed by the authors at the University of Melbourne based on stochastic simulations of seismological parameters. Design response spectra have been developed for different parts of Australia using CAM, based on locally developed parameters together with generic information. The comparison between the independently developed models (AGSO and CAM) reveal interesting similarities, but also highlights some differences. This paper provides a critical review of the recent design response spectra proposed for rock sites in the new Joint Australian New Zealand Earthquake Loading Standard and makes further recommendations.

## 1. INTRODUCTION

The response spectrum model stipulated in the current Australian Earthquake Loading Standard (AS1170.4: 1993) is based on the 1991 edition of the Uniform Building Code of the United States (UBC91). The flat-hyperbolic ( $\propto T^{-1}$ ) response spectrum shape is based on observations of moderate and large magnitude events in California, and the shape has been modified to provide additional conservatism for long period structures. The drafting of a new joint Australian New Zealand Earthquake Loading Standard (DR00902-00904), denoted herein as "Draft ANZ", provides the opportunity to revise the shape of the normalised design response spectrum. The Australian Geological Survey Organisation (AGSO) undertook a detailed study of 13 accelerograms measured at rock sites from reverse thrust fault events with magnitude ranging from 5.4-6.6 (Somerville, 1998). Records were normalised to a peak ground velocity (PGV) of 50mm/sec. A new normalised design response spectrum (NDRS) model has been proposed for the draft ANZ based on this study.

An alternative NDRS has been recommended based on the stochastic simulations of the seismological model known as the Component Attenuation Model (CAM). CAM is based on the following formulation:

$$Y = \alpha(M).G(R).\beta(R,Q).\gamma_{mc} \cdot \gamma_{uc} \quad (1)$$

where  $Y$  is the maximum response parameter of interest,  $\alpha(M)$  is the source factor,  $G(R)$  is the geometrical factor (geometric damping),  $\beta(R,Q)$  is the anelastic attenuation factor (crustal damping), and  $\gamma_{mc}$  and  $\gamma_{uc}$  are the mid and upper crustal modification factors respectively.

Detailed descriptions of CAM and the associated parameters shown in Eq.1 are provided in Lam (2000a-c). The CAM model was developed from stochastic simulations of the seismological model of Atkinson (1993, 1995, 1997 & 1998). Rigorous seismological validation studies of the seismological model have been carried out as reported in Atkinson (1998). Importantly, predictions based on the CAM model are in good agreement with field measurements obtained from different regions around the world including low seismicity regions in Eastern North America (Lam, 2000c), Australia (Koo, 2000) and Southeast Asia (Lam, 2000d; Bala, 2001).

In this paper, the NDRS proposed for the draft ANZ is compared with that developed from CAM. Based on this comparison, a full range NDRS for rock sites is proposed which is considered to be representative for both small magnitude and large magnitude earthquake events in Australia.

The scope of this paper has been necessarily restricted to the considerations of rock sites due to space limitations. A number of models have been developed for extrapolating soil response spectra from the rock spectrum (Crouse, 1996; Lam 2001). Thus, the establishment of a representative rock response spectrum is of fundamental importance.

## 2. COMPARISON OF NORMALISED DESIGN RESPONSE SPECTRA

Design response spectra in contemporary codes of practice are typically in the form of response spectral acceleration ( $RSA$ ), or seismic design force per unit weight, plotted against the natural period of the structure. A more informative representation frequently used in engineering seismology is to plot the response spectral velocity ( $RSV$ ) in the logarithmic-tripartite format. Response spectra presented in this format clearly indicate three distinct regions of constant (and maximum) response spectral acceleration ( $SA_{max}$ ), velocity ( $SV_{max}$ ) and displacement ( $SD_{max}$ ) as shown in Fig.1. Conveniently, the  $SA_{max}$  and  $SD_{max}$  values can be obtained from the  $SV_{max}$  values with knowledge of the corner periods  $T_1$  and  $T_2$ .

The velocity amplification ratio  $SV_{max}/PGV$  estimated by Newmark-Hall (1982), Somerville (1998) [referred to as the "AGSO" model] and Lam (2000c) [referred to as the "CAM" model] are listed in Table 1. The ratios are generally consistent, with a value of  $SV_{max}$  in the order of twice the  $PGV$  considered representative.

Table 1 Recommended Ratios of  $SV_{max}/PGV$  (based on median estimates)

Model	Newmark-Hall(1982)	Somerville(1998)	Lam(2000c)
$RSV_{max}/PGV$	1.65	1.8	2.0

The corner period  $T_2$  controls the maximum response spectral displacement ( $SD_{max}$ ). Newmark-Hall recommends a conservative value of  $T_2=3$  seconds based on average site conditions in California. The AGSO model recommends a much lower period of  $T_2=0.7$ secs reflecting magnitude 5.4-6.6 events on rock sites in predominantly stable continental regions as shown in Fig.2. The alternative CAM formulation which accounts for the magnitude dependence of  $T_2$  (Eq.1), is in general agreement with the AGSO model at  $M=6$ . Derivation for (Eq.2) can be found in Lam (2000c).

$$T_2 = 0.5 + 0.5 (M-5) \quad (\text{for } M \geq 5) \quad (2)$$

From Eq.2, a magnitude 7 event is associated with  $T_2 = 1.5$ secs which implies a 50% increase in the maximum displacement demand ( $SD_{max}$ ) on a rock site compared with the AGSO model as shown in Fig.3.

The corner period  $T_1$  controls the maximum response spectral acceleration, with  $SA_{max}$  increasing with decreasing values of  $T_1$ . The  $T_1=0.3$ sec period recommended by the AGSO model is generally consistent with that predicted by the CAM model for earthquakes with magnitude in the order of 6-7 for rock sites possessing an average shear wave velocity of about 600-700mm/sec. However, a lower  $T_1$  value in the order of 0.1 sec is possible for very hard rock sites (shear wave velocity exceeding 1000m/sec) and for smaller magnitude events.

### 3. RECOMMENDATIONS FOR NORMALISED DESIGN RESPONSE SPECTRA

A design response spectrum has been developed based on CAM for a peak ground velocity ( $PGV$ ) of 60mm/sec. This corresponds to an acceleration coefficient  $a=0.08g$  in accordance with AS1170.4 (1993) for a 500 year return period event and is therefore representative for many of the major capital cities in Australia such as Melbourne and Sydney. The maximum response spectral velocity ( $SV_{max}$ ) of 120mm is simply twice the  $PGV$  as obtained from Table 1 for CAM. The maximum response spectral displacement ( $SD_{max}$ ) has been determined in accordance with Eq.3, using  $T_2=1.5$ secs.

$$SD_{max} = (T_2/2\pi) SV_{max} = (1.5/2\pi) 120 = 30\text{mm} \quad (3)$$

Similarly, the maximum response spectral acceleration ( $SA_{max}$ ) has been determined in accordance with Eq.4 using  $T_1=0.3$ secs.

$$SA_{max} = (2\pi/T_1) SV_{max} = (2\pi/0.3) 120 = 2500\text{mm/sec}^2 = 0.25g \quad (4)$$

The  $PGA$  is estimated to be in the order of 0.08g, since the maximum response spectral acceleration ( $SA_{max}$ ) is approximately equal to three times the  $PGA$  (refer Table 1). The estimated  $PGA$  value is consistent with the acceleration coefficient of  $a=0.08$  as specified by AS1170.4. The response parameters for the 2500 year return period event can be obtained by scaling the 500 year estimates by a return period factor of 1.9 (DR00902-00904). These CAM parameters have been listed in Table 2 for both return periods as the "recommended" values.

The response parameters nominated in the latest draft for the joint Australian New Zealand Earthquake Loading Standard (DR00902-00904), denoted herein as "Draft ANZ", are listed in Table 2 for  $a=0.08$ . This apparently has been developed from the AGSO empirical model described in Section 2. In addition, the

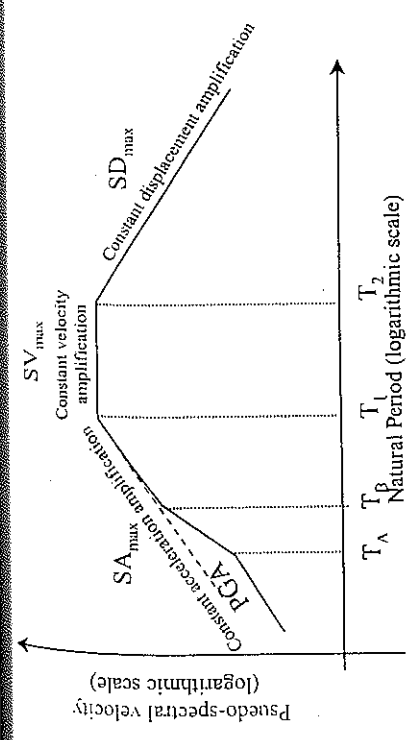


Figure 1 The Tripartite Response Spectrum Model

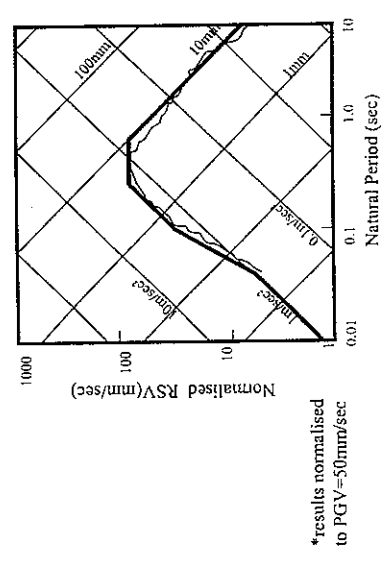


Figure 2 Normalised Response Spectrum Model of AGSO

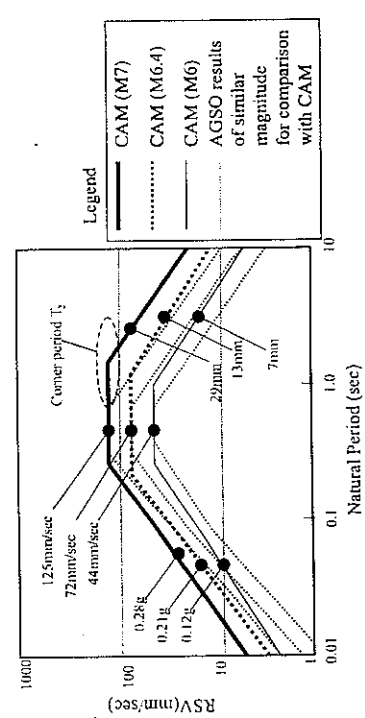
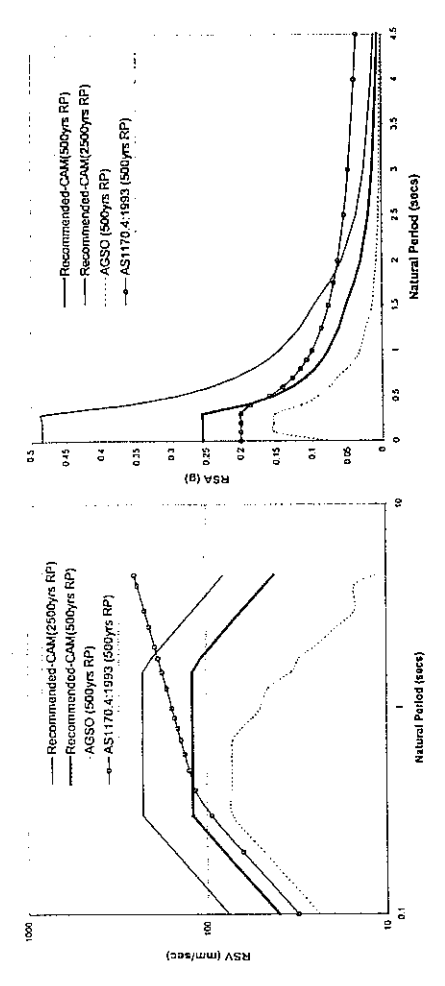
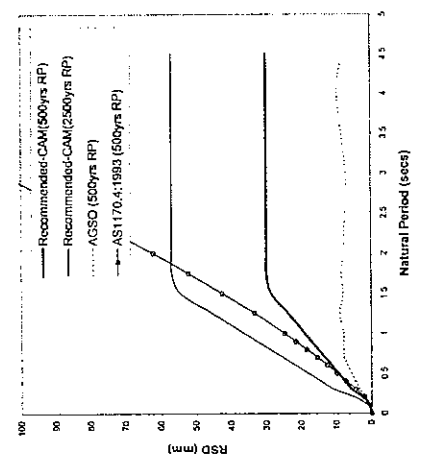


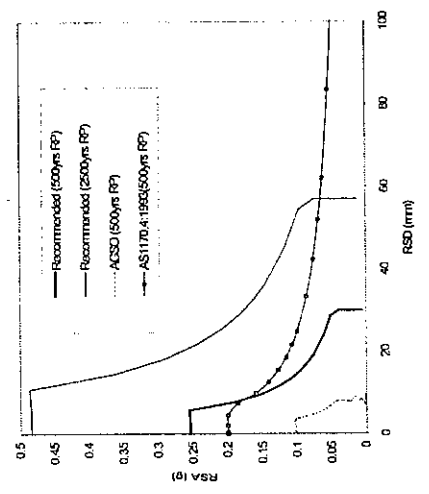
Figure 3 Comparison between the AGSO model and CAM



(a) Velocity Spectrum



(b) Acceleration Spectrum



(c) Displacement Spectrum

(d) Capacity (ADRS) Spectrum

Figure 4 Comparison of Response Spectra (PGV=60mm/sec and a=0.08g for 500 yrs return period)

response parameters stipulated by the current Australian Earthquake Loading Standard (AS1170.4) have also been included in Table 2 for comparative purposes. The AS1170.4 spectrum is considered conservative as the response velocity and response displacement increase indefinitely with increasing natural period, which does not reflect physical reality.

Table 2 Summary of Response Parameters for Rock Sites

Parameter	Recommended 500yrs RP	Recommended 2500yrs RP	Draft ANZ (Class B site) 500yrs RP	AS1170.4 (S=1 site) 500yrs RP
$SA_{max}$	0.25g	0.50g	0.15g	0.20g
$SV_{max}$	120mm/sec	230mm/sec	70mm/sec	Variable
$SD_{max}$	30mm	60mm	8mm	Variable

The response spectra for acceleration, velocity and displacement corresponding to the models shown in Table 2 have been plotted in Figs.4a-4c. The recommended response spectra for 500 year return period is generally consistent with the AS1170.4 spectrum in the low period range. Importantly, the recommended spectrum more accurately represents the displacement demand expected in the higher period range. The Draft ANZ response spectra appear to significantly underestimate the response parameters, particularly the displacement demand in the high period range.

The response spectra can be conveniently represented in ADRS format (acceleration-displacement response spectra) where the displacement demand is plotted against the corresponding acceleration demand for the full range of natural periods ( $0 < T < \infty$ ) as shown in Fig.4d. This ADRS format has gained considerable popularity amongst the international earthquake engineering community as it allows the earthquake demand to be compared directly against the specific force-displacement properties of a structure. Hence in one plot, the performance of a structure in terms of force and displacement can be readily observed. Clearly, the design response spectrum proposed in the Draft ANZ standard appears to significantly underestimate the earthquake demand in terms of both acceleration and displacement as shown in Fig. 4d.

#### 4. CONCLUSIONS

A new normalised design response spectrum is recommended for rock sites in Australia based on a response spectral velocity of twice the peak ground velocity, and corner periods of  $T_1=0.3$ secs and  $T_2=1.5$ secs (based on a magnitude 7 earthquake event). The recommended response spectra for 500 year return period is generally consistent with the AS1170.4 spectrum in the low period range, however, more accurately represents the displacement demand expected in the higher period range. In comparison, the Draft ANZ response spectra appears to be unconservative particularly in the high period range.

#### 5. ACKNOWLEDGEMENTS

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