Generation of Bedrock Response Spectra for Intraplate Regions

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ABSTRACT

The paper describes a generic procedure to model seismic design spectra for both force- and displacement-based applications in regions of low and moderate seismicity. The spectral parameters associated with displacement, velocity and acceleration are determined using a seismological model combined with generic "hard rock" and "rock" crustal models, the latter being based on regional geology and the shear wave velocity gradient of the bedrock formation. The model has been developed within an existing seismological framework in order to study the influence of crustal conditions, along with seismicity, on the spectral parameters that are required for engineering design and structural assessments. Significantly, predictions using the developed model are in good agreement with a range of empirical attenuation predictions for key ground motion and spectral parameters. The predicted spectral parameters are then used in the proposed procedure to construct design response spectra for any given Magnitude-Distance (M-R) combination, the latter being related to the seismicity parameters of the region. The potential of the model is emphasised for low and moderately active seismic areas lacking local strong motion data.

INTRODUCTION : SOURCE MODELLING AND CRUSTAL EFFECTS

Earthquake ground motion predictions for engineering applications rely usually on a two-stage procedure whereby, firstly, an attenuation relationship relates the magnitude M (which is measured typically from very low frequency surface waves) to a much higher frequency parameter such as peak ground acceleration (PGA). Developing a representative attenuation model can be hindered by the typical lack of indigenous strong motion data in regions of low and moderate seismicity. Examples of such regions are Eastern North America (ENA), the Australian continent and several parts of Asia such as South China (including Shanghai and Hong Kong), Singapore and Thailand. Secondly, a design response spectrum model is used with the high frequency parameter to define the spectrum. Thus, ground motion properties have been extrapolated twice in the frequency domain: from the low to high frequency range, and *vice versa*. These extrapolations are notoriously sensitive to errors arising principally from assumptions about the ground motion's frequency properties, which depend on the source parameters, the wave travel path and, where required, the dynamic response behaviour of the soil covering the site. A further development in seismic evaluation and design are displacement-based (DB) approaches, which emphasise the significance of long-period components of ground motion in dictating the inelastic structural drift. Coupled with the more conventional force-based (FB) procedures, both approaches rely heavily on the accuracy of the above extrapolations and hence there is an increasing need for a more direct approach for predicting spectral parameters. The seismological model combined with a generic crustal model, as described here, gives a means to predict all of the key spectral parameters (velocity, displacement and acceleration), based fundamentally on the relationship between the seismic moment and ground displacement.

The proposed response spectrum procedure has been developed from recent studies (Lam et.al. 1998, 1999a, 1999b) on synthetic accelerograms simulated according to a seismological model. This comprehensive model was developed in the U.S. over the last 20 years by Atkinson, Boore and other investigators (see, for example, Boore and Atkinson 1987, Atkinson and Silva 1997). The seismological model expresses the Fourier amplitude spectrum of the earthquake ground motion as a product of a source function and various path modification functions (as presented in Lam et.al. 1999a). Thus, the contributions of the various mechanisms to the resulting ground motions have been separated. The separation of these effects is essential to a rational approach to ground motion modelling, particularly in moderately active (intraplate) seismic regions.

Source effects consider the properties of the seismic shear waves generated at the focus, and permit the use of generic models for "interplate" and "intraplate" regions, defining the fault rupture properties. The latter may be defined using the seismic moment and stress drop, along with a seismic source spectrum model, the shear wave velocity, and a wave spreading model (Lam et.al. 1999b), to give some plausible ground displacement time functions (Beresnev and Atkinson 1997). The peak ground displacement (PGD) predicted from a selected function (the one which is compatible with the omega-squared seismic source spectrum) has been correlated by the authors (Chandler et.al. 1998) with the Moment Magnitude (M) as follows:

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$$\log_{10} PGD \ (mm) = M - \log_{10}R - 3.3 \qquad [1]$$

where R (in km) is the site-source distance. This equation is relatively insensitive to the key earthquake source and ground motion parameters, and confirms the existence of a fundamental log-linear relationship between the moment magnitude and the PGD which in turn dictates the seismic displacement demand on the structure.

In theory, the very long-period threshold limit of the displacement spectrum (allowing the period of the structure to increase indefinitely) is equal to the peak ground displacement, PGD. However, the effective natural period of most structures rarely exceeds 3 to 5 seconds, even if significant yielding has taken place. Hence, using the PGD to define the displacement demand for structures with various natural periods can be overly-conservative. To avoid this, the Effective Peak Ground Displacement (EPGD) has been defined here as the peak displacement of a single degree of freedom oscillator with a critical damping ratio of 5% and a singular effective natural period T_e. The value of T_e has been fairly arbitrarily defined as 5.0 seconds, corresponding to the approximate upper limit of effective structural periods referred to above. The damping ratio of 5% is in agreement with that assumed in seismic codes, although it probably underestimates the effective damping of yielding structural systems and hence introduces a further element of conservatism in the evaluation of displacement demands.

Table 1 compares the PGD obtained from eqn.[1], for a series of realistic M-R combinations, with the EPGD derived from mean response spectral analyses of a large number of synthetic accelerograms simulated in accordance with the latest seismological model (Lam et.al. 1999b). Clearly, the predicted PGD and the computed EPGD (the latter being interpreted as the peak displacement demand on the response spectrum) are very similar up to M=6. However, significant deviations have been found at higher earthquake magnitudes due to the attainment of the threshold limit of spectral displacement demand at a natural period greatly exceeding 5 seconds. Interestingly, this is consistent with the common observation that magnitude scales used in defining large magnitude events should be based upon very long period measurements (> 20 secs).

Table 1. PGD and EPGD Predictions (mm)

M	R (km)	PGD (eqn.[1])	EPGD (Lam et.al. 1999b)
5	10	5	6
5.5	20	8	8
6	30	17	13
6.5	50	32	17
7	70	71	22

The high frequency (acceleration and velocity) components of ground motion are very sensitive to both the details of the source spectrum and the moment magnitude. Generic source spectra have been derived by Atkinson, Boore and co-investigators for both "intraplate" and "interplate" conditions based on a selection of around 1,000 Western North America (WNA) and 100 ENA records (e.g. Atkinson and Boore 1998, Atkinson and Silva 1997). Since predictions of the velocity and acceleration properties are associated with great uncertainties, it is recommended that such predictions be based on the more conservative generic intraplate source model for ground motion modelling in regions of low and moderate seismicity.

A comprehensive review has been given in Lam et.al. 1999a, of crustal effects involving the five principal mechanisms which modify the properties of the seismic shear waves. These comprise: anelastic whole path attenuation, upper crust attenuation, mid-crust amplification, upper crust amplification and geometrical attenuation. Results for certain types of generic rock site can provide useful benchmarks in the prediction of crustal effects. Such generalization of the earth crust properties is founded on the premise that various attenuation and amplification characteristics of the bedrock formation are inter-linked. The two generic crustal models which have been derived are termed the "Hard Rock" and "Rock" models, which are based on the average conditions observed in ENA (Atkinson and Boore 1998) and WNA (Atkinson and Silva 1997), respectively.

As an example of the spectral parameters which may be derived from analyses of synthetic accelerograms simulated in accordance with the two generic crustal models, Table 2 gives values of effective peak ground displacement, velocity and acceleration (EPGD, EPGV, EPGA, respectively) for a particular M-R combination of M = 6, R = 30 km. The generic intraplate source model and spherical attenuation have been assumed.

In Table 2, EPGD is as defined above, EPGV is the ensemble average peak response spectral velocity divided by 2.0 (the factor 2.0 is computed as the average ratio from evaluation of a series of 5% damped response spectra from both synthetic

Table 2. Spectral Parameters for M = 6, R= 30 km

Generic Crustal Model	EPGD (mm)	EPGV (mm/sec)	EPGA (g)	EPGA/EPGV [g/(m/sec)]
Hard Rock Model	13	47	0.23	5.0
Rock Model	21	78	0.17	2.15
Rock/Hard Rock Ratio	1.6	1.7	0.7	0.43

and real earthquake records), and EPGA is the ensemble average peak spectral acceleration divided by 3.0. It is noted that the crustal properties of ordinary rocks have net amplification effects of around 1.6-1.7 compared with the hard rock model, for both displacement and velocity, whilst the rock model also gives a significant reduction of acceleration due to high frequency wave attenuation. Similar effects have been observed for other M-R combinations, except that the amplification and attenuation functions can vary. Hence, in regions where the crustal type is difficult to determine, it is recommended to adopt the generic "Rock" model in predicting EPGD and EPGV and the generic "Hard Rock" model in predicting EPGA. Geometrical attenuation should be considered as a separate effect as it depends on the crustal thickness, as opposed to its geological composition.

RESPONSE SPECTRUM MODELLING

In the procedure proposed herein for response spectrum modelling, the Velocity, Displacement and Acceleration design response spectra are constructed separately as summarised in Figure 1, in accordance with direct predictions of the respective spectral parameters: EPGV, EPGD and EPGA, as defined above.

Velocity Predictions

For Australia, MMI attenuation relationships may be used indirectly to derive empirical predictions of PGV. A direct PGV attenuation relationship has been specified also for rock sites in California (Joyner and Boore 1988). Table 3 summarises results using these relationships, along with predictions (for EPGV) based on the two generic crustal models. The mapping of EPGV's for various M-R combinations has been taken from Lam et.al. 1999b.

The empirical predictions for PGV in California give a reasonably close match to the EPGV's derived using the generic "Rock" crustal model, with particularly close agreement for $M \geq 5.5$ (Table 3). This result is consistent with the known information concerning geological conditions, along with rock types and ages, in this region. These conditions are generally comparable to those of Southeastern Australia, SEA (Lam et.al. 1998), for which the empirical predictions for PGV in Table 3 are, on average, 30% higher than the EPGV from the generic "Rock" crustal model.

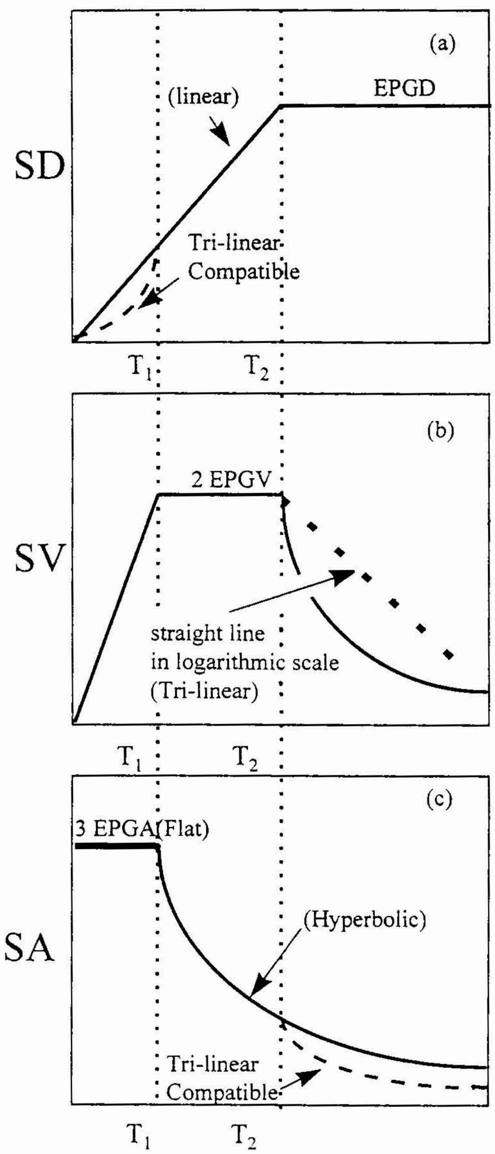

Figure 1. Idealised Displacement, Velocity and Acceleration Design Response Spectra

Table 3. PGV from Empirical Attenuation Relationships, along with EPGV and EPGD based on Generic Models [Units: PGV and EPGV in mm/sec, EPGD in mm]

		Predictions from Empirical Relationships PGV			Predictions based on the Generic Crustal Models			
M	R (km)	WA	SEA	California	Generic Hard Rock		Generic Rock	
					EPGV	EPGD	EPGV	EPGD
5	10	60	118	74	58	9	100	16
5.5	20	55	94	65	42	8	69	14
6	30	63	100	72	50	14	80	22
6.5	50	65	93	69	50	18	73	26
7	70	79	105	76	55	24	72	31

The difference can be explained by the fact that the empirical Australian MMI attenuation relationships employed here (along with an empirical correlation between MMI and PGV) do not relate exclusively to rock conditions, and hence implicitly incorporate the effect of some site amplification for surface soil sites. The observed average factor of 1.3 falls within the range of site amplification factors employed in the Australian earthquake standard, namely between 1.0-2.0, and the value 1.3 corresponds to a stiff soil condition. Hence the average difference of 30% between the predictions appears to be entirely reasonable. In a similar manner, the empirical PGV predictions for Western Australia, WA are, on average, 27% higher than those for EPGV derived from the generic "Hard Rock" model (Table 3). The latter model would appear to match the known geological conditions and rock types in WA (Lam et.al. 1998). Again, the difference may be attributable to the influence of site effects in the PGV empirical model.

The generic crustal model approach may well be the only available option if no reliable empirical relationship for ground velocity predictions exists.

Seismicity modelling

For a given design return period and seismicity parameters defined using the magnitude-recurrence relationship, methods have been derived (Lam et.al. 1999b) for determining an appropriate set of design M-R combinations, assuming uniform seismicity. For example, the M-R combinations shown in Columns 1 & 2 of Table 3 have been generated using a return period of 500 years, for a typical moderately active intraplate seismic region. Such combinations can then be used directly to determine the design EPGV and EPGD (Table 3), based on the seismological model and assumed generic crustal model.

Displacement predictions

Reliable information on earthquake-induced ground displacement is generally difficult to obtain in the near field from normal instrumented recordings due to the relatively poor resolution of accelerometers in the long period range. Validated empirical data on displacement is scarce even in high seismicity regions. However, the situation is expected to improve with the advent of modern instruments which are capable of measuring broad band properties of the recorded strong motions. In low and moderate seismicity areas, a reliable local empirical model to predict displacement demand is unlikely to exist and hence the generic crustal model appears at the present time to be the only option in predicting the EPGD. Using the mapping of EPGD's for the generic "Hard Rock" and "Rock" crustal conditions, as given in Lam et.al. 1999b, the results given in Table 3 have been generated. It is recommended that in the absence of reliable information on the crustal parameters that the "Rock" crustal conditions be conservatively assumed. From the results in Table 3, it is clear that, within a given seismic region, the EPGD is controlled by the larger magnitude event at a longer epicentral distance. Given any pair of EPGV and EPGD predicted for a single M-R combination, a bilinear displacement spectrum can then be constructed in accordance with the procedures outlined above.

Acceleration predictions

It has been shown that the high frequency (acceleration) properties are particularly dependent on the source and crustal conditions. Hence, it is worthwhile to undertake detailed seismological studies of the assumed seismic source region for an accurate and reliable determination of the anelastic attenuation parameters which significantly affect the acceleration properties. A three-tier procedure may be adopted, comprising (i) seismological modelling based on locally derived crustal parameters (such as the Quality Factor Q) to generate artificial accelerograms using a stochastic procedure, (ii) use of A/V ratios (peak ground acceleration/ peak ground velocity) derived from indigenous empirical data combined with ground velocity predictions (Table 3), and (iii) generic assumptions using the crustal model recommended herein.

Comparisons have been made between methods (ii) and (iii). In method (ii), for example, empirical attenuation relationships such as given by Joyner and Boore (1988) have provided sufficient information to derive the average A/V (PGA/PGV) ratios for rock sites in California. These ratios reflect the frequency content of the local ground motions. The results give A/V from 3.5 g/(m/s) for near-field events (R = 10 km) to 1.0 for events in the moderately far-field (R = 70 km). These results agree closely with predictions obtained here using the generic "Rock" crustal model. For the "Hard Rock" model, A/V is predicted to range from about 7 for near field events to 3 in the far field, and such values agree well with intraplate earthquake recordings. The A/V ratios also determine the corner period T_1 (Figure 1), with smaller values corresponding to higher A/V. A lower bound value of T_1 = 0.1 seconds may reasonably be adopted for intraplate regions.

DISCUSSION AND ILLUSTRATION

A distinct advantage of the proposed response spectrum modelling approach over the traditional acceleration-based approach is the direct determination of the response spectral velocity, displacement and accelerations which define the spectral amplitudes over a wide period range. The relatively higher uncertainties associated with the determination of the peak ground acceleration will thereby not be translated into corresponding uncertainties in the specification of the peak spectral velocity and displacement. The application of the procedure may be illustrated by an example, taking seismicity parameters corresponding to a moderately active seismic region with 500-year return period, and assuming a "Hard Rock" crustal classification. The Displacement, Velocity and Acceleration response spectra constructed in accordance with the predicted ground motion parameters (EPGD, EPGV and EPGA) are shown in Figure 2.

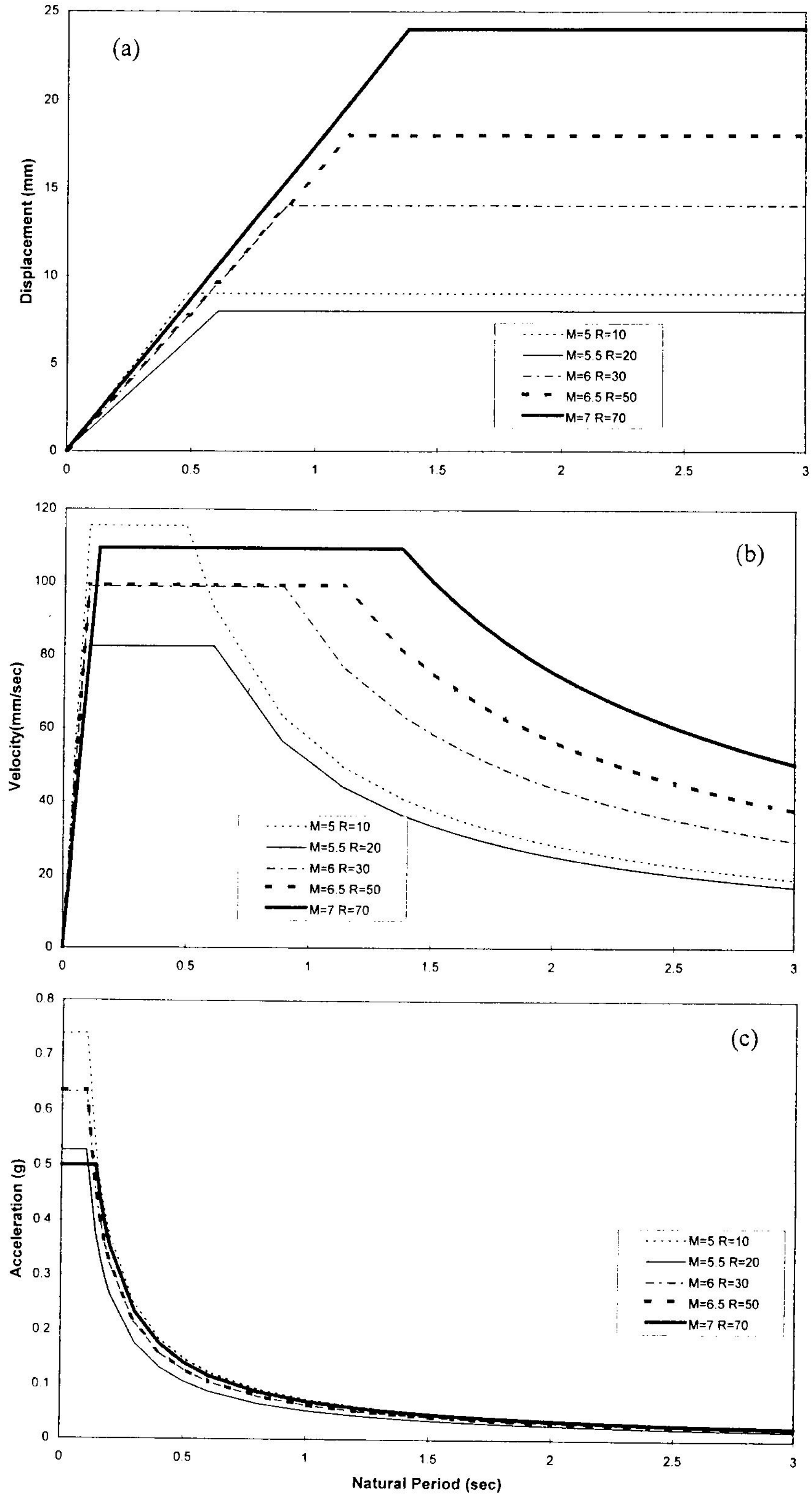

Figure 2. (a) Bilinear displacement spectra, (b) Velocity spectra, and (c) Acceleration spectra, for various M-R combinations

A comparison of the bounding bi-linear displacement spectra with the Australian seismic standard provisions (AS1170.4) applicable to the continental shield ("Hard Rock") region of Perth, WA has been shown in Figure 3. It is clear that the code somewhat underestimates demand in the short period range (by a factor of about 2 in the period range less than 0.2 sec) but is grossly over-conservative for long period systems. Within the period range from about 0.8-1.4 seconds, the code spectrum matches closely the predicted far-field (R = 70 km) displacement spectrum which determines the demand on such systems.

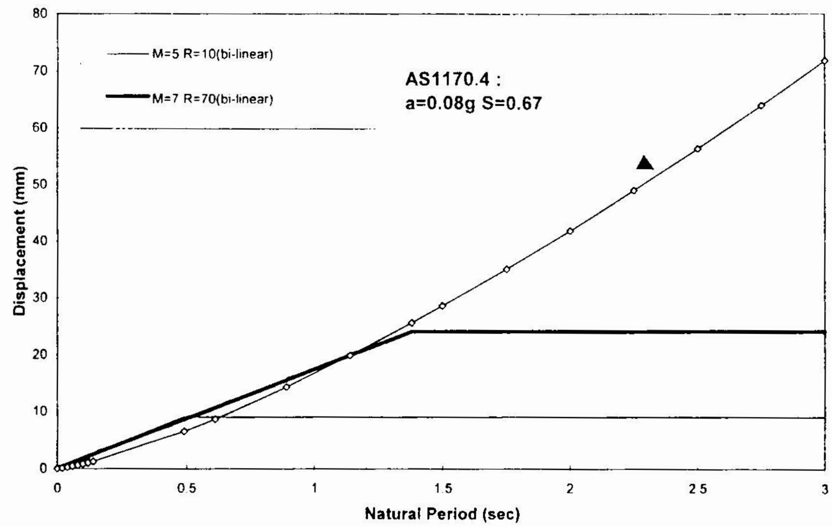

Figure 3. Evaluation of Displacement Response Spectrum Implied by AS1170.4

CONCLUSIONS

1. The concept of the generic source and crustal models have been introduced within the framework of the seismological model. A set of compatible idealised spectra for Displacement, Velocity and Acceleration have been introduced as part of the proposed procedure.
2. The key ground motion and spectral parameters have been modelled for two generic crustal conditions, and predictions have been found to be remarkably consistent with appropriate existing empirical attenuation relationships from various seismic regions.
3. The proposed response spectrum modelling procedure has significant advantages over the conventional acceleration based procedure, as it is less heavily reliant on an individual ground motion parameter estimate (PGA) and evaluates response with broadly consistent levels of reliability across the full spectrum range.

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