Response spectrum modelling for regions lacking earthquake records

A.M. Chandler
Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong Special Administrative Region, China
Email: amchandl@hkucc.hku.hk

N.T.K. Lam, J.L. Wilson and G.L. Hutchinson
Department of Civil & Environmental Engineering, The University of Melbourne, Parkville, Victoria 3052, Australia

ABSTRACT

The design response spectrum is typically the starting point of most codified seismic design and assessment procedures and is predominantly used to prescribe the applied inertia forces induced by earthquake ground motions. In a recent paper, the authors presented and discussed the key properties, limitations, engineering interpretation and modern concepts relating to various types of earthquake design response spectra, including the acceleration, displacement and velocity spectra. The present paper provides a critical evaluation of the various deterministic and probabilistic approaches to response spectrum modelling, including an introduction to the Component Attenuation Model (CAM). The CAM modelling approach was developed recently by the authors, with the express purpose of providing a novel response spectrum modelling technique for regions lacking earthquake records. Traditional approaches for the prediction of earthquake actions using design response spectra rely on accurate hazard models for the region concerned, which in turn depend heavily on the availability of strong ground motion data from the local seismic region, or from analogous regions with similar geological and seismo-tectonic features. In the case of regions with low to moderate levels of seismicity, such data is at best scarce and in many cases unreliable, and this presents unique problems for designers carrying out seismic analysis for new construction or assessing the seismic reliability of existing buildings, bridges and infrastructure. For such regions, novel approaches (such as CAM) which adapt local seismological information for the purpose of earthquake ground motion modelling may be considered. Further key issues including the determination of the Maximum Considered Earthquake, are also addressed in this paper.

KEYWORDS

Seismic design; response spectrum; Component Attenuation Model; moderate seismicity regions

1. Introduction

The properties, limitations, engineering interpretation and modern concepts relating to various types of earthquake design response spectra, including the acceleration, displacement and velocity spectra, have been presented and discussed by the authors in a recent paper [1]. The objectives of the present paper are to provide a critical review of existing deterministic and probabilistic approaches to response spectrum modelling, and to give an overall evaluation of their application to regions of low to moderate seismicity where strong-motion earthquake data is generally lacking and historical data is limited. Firstly, the paper reviews deterministic response spectrum modelling procedures, followed by an assessment of the widely used probabilistic approach. The limitations of a probabilistic approach in regions of low to moderate seismicity and in applications to performance based (PB) design and assessment [2], are highlighted. Next, the concept of the pseudo-deterministic Characteristic Response

Spectrum (CRS) is introduced. The CRS effectively defines the maximum seismic hazard in regions of low to moderate seismicity. Significantly, the CRS reduces an initial probabilistic seismic hazard analysis to a deterministic analysis based mainly on the Maximum Considered Earthquake (MCE) and knowledge of the regional crustal properties. An example application of CAM to determine the CRS for a low seismicity region (consistent with the activity level in southeastern Australia) has been described. Finally, some recommendations for future developments and research directions have been provided in the final section of the paper.

2. The deterministic response spectrum

Earthquake-resistant design for an active seismic region may be governed by one or more "characteristic earthquakes", the parameters of which (magnitude, focal depth, mechanism, fault slip and so forth) can be established for the particular fault source, if the fault is very active and earthquakes have been generated frequently [3]. Such a deterministic modelling approach is ideal in the situation where the site of the design structure is located very close to an active fault. The deterministic response spectrum of the site (termed the CRS above) can be obtained directly by analysing strong motion accelerograms recorded nearby.

Even in high seismicity regions, the above approach has some significant drawbacks, since insufficient representative accelerograms may have been recorded in the vicinity of the site, or earthquakes recorded previously may have been generated from different sources. Alternatively, accelerograms may be generated purely theoretically, in accordance with a certain assumed fault rupture and from wave theory that accounts for the effects of the crustal details along the path between the source and the site, together with the effect of surficial deposits overlying the site [4]. However, such theoretically synthesised accelerograms are rare, since exact details of a future fault rupture cannot be predicted. Furthermore, creating or obtaining representative accelerograms is usually difficult in low to moderate seismicity regions which generally possess a much more diffused seismicity pattern [3],[5],[6],[7] and such regions usually lack any detailed information concerning the potential causative faults along with the key properties of the earth's crust. For such situations, a probabilistic approach to the problem is favoured, as described below.

3. The probabilistic response spectrum

Ground motion parameters such as the peak ground acceleration (PGA) and the peak ground velocity (PGV), as discussed in Ref.[1], can be predicted in probabilistic terms by combining the seismicity information of the source with the attenuation properties of the ground motion parameter, using well-known methods such as Cornell-McGuire integration [8],[9]. Probabilistic design response spectra may be defined in accordance with one or more of such probabilistic ground motion parameters, adopting the procedures described in Ref.[1]. Probabilistic response spectra arise in the various forms described in the following section.

The Normalised Response Spectrum, Dual Parameter Response Spectrum and Multiple Parameter Response Spectrum

The simplest type of probabilistic response spectrum is based on a normalised spectrum and a single probabilistic ground motion parameter that scales the spectrum. Such design response spectra have been widely adopted by earthquake loading standards around the world. A well-known normalised response spectrum model is that developed first in the 1970's by Newmark and Hall [10], by analysing the response spectral shapes from some Californian strong-motion accelerograms, including the widely used 1940 record at El Centro. The normalised response spectrum is first defined for a reference site classification (usually rock or very stiff soil). The response spectrum is then adjusted for other site classifications, according to definitions of the site factor S, defining the ratio of spectral accelerations for soil to that on bedrock, in the medium and long period ranges of the spectrum.

Due to the traditional and almost universal use of force-based (FB) seismic design methods, the PGA has been used as the scaling parameter of the normalised response spectrum. Alternatively, the effective peak ground acceleration (EPGA), based on the average response spectral accelerations in the short period range [11], may be used. In another variation, the acceleration coefficients used by the Australian Earthquake Loading Standard [12] to scale its design response spectrum are actually based on PGV. Similarly, PGV is one of the parameters employed in the Canadian seismic code NBCC 1995 [13], as also discussed below. Despite its widespread use and acceptance as a design tool, such a normalised response spectrum approach has been criticised for not taking into account the significant regional variations in the shape of the response spectrum, for the same site classification. It has been further established that there are many factors other than the site classification that affect the shape of the response spectrum. In other words, the shape of the response spectrum varies even amongst rock sites, and such complex variations cannot easily be modelled in this manner (see Ref.[14] for a more detailed discussion of these points).

The so-called “Intraplate” (non-plate boundary) Response Spectrum (IRS) has been put forward as an alternative method, compared with the standard Newmark-Hall spectrum model, for modelling the observed high frequency properties of earthquake ground motions, particularly in the intraplate region of Eastern North America (ENA) where a small number of actual strong-motion records exist to provide regional data. However, it is by no means proven that all intraplate regions possess sufficiently similar seismo-tectonic and geological properties to justify a global definition of the IRS. An example application is the probabilistic IRS developed for possible application in the Hong Kong region, using a probabilistic seismic hazard analysis (PSHA) approach [15].

Design response spectra may also be defined by Dual Parameters, such as the Uniform Hazard Spectra (UHS) adopted by the International Building Code IBC-2000 [16], which are constructed from the response spectral accelerations (RSA’s) at two key periods in the “short” period and “long” period ranges. The short period range corresponds to periods in the region of 0.2 seconds, and the long period range corresponds to periods of 1.0 second and above. Another such dual-parameter design spectrum is that of NBCC-1995 [13], derived from two ground motion parameters which are coefficients defining the PGA and PGV for the seismic region in which the structure is located. Such spectra have been used to model more accurately the regional dependence of the response spectrum shape.

In the IBC-2000 code [16], the dual seismic coefficients S_S and S_l have been specified separately for each seismic source zone shown on the national seismic hazard maps to define the overall level of hazard at any location within the United States (the subscript "s" and "l" stands for "short" and "long" period respectively). Meanwhile, the coefficients F_a and F_v have been specified to account for the intensity and period dependence of soil modifications at the site (the subscript "a" and "v" stands for the "acceleration" and "velocity" controlled region respectively). Thus, the products F_a S_s and F_v S_l are used to define the response spectrum, RSA(T), within different period ranges based on a set of relationships which can be presented as follows (refer Fig.1):

$$RSA(T) = F_a S_s (0.4+0.6(T/T_o)) \qquad (T < T_o) \qquad (1a)$$
$$RSA(T) = F_a S_s \qquad (T_o < T < T_s) \qquad (1b)$$
$$RSA(T) = F_v S_l / T \qquad (T > T_s) \qquad (1c)$$

where

$T_s = F_v S_l / F_a S_s$ (1d)

$T_o = 0.2\ T_s$ (1e)

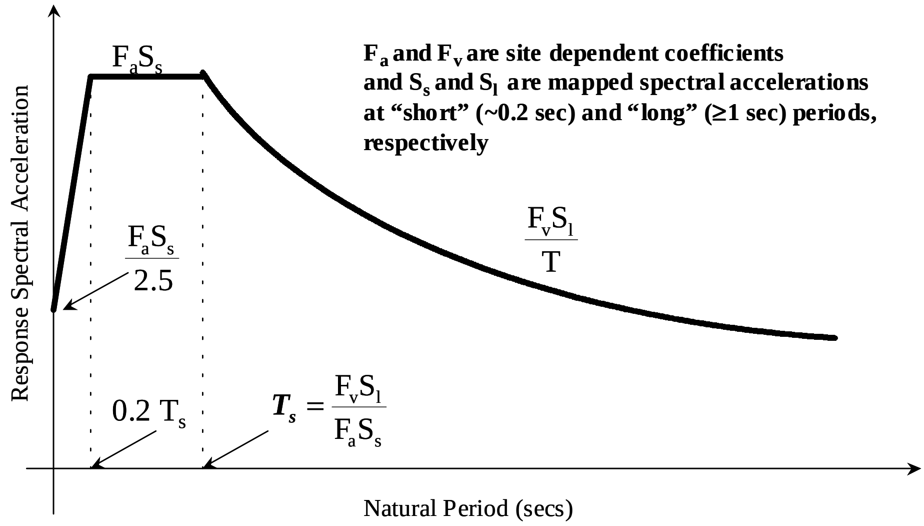

Fig. 1 - Uniform Hazard Spectra for Maximum Considered Earthquakes [IBC 2000]

Clearly, the "flat" (short period) part of the hyperbolic spectrum is defined by $F_a\ S_s$, whereas the "decreasing" (medium and long period) part of the same spectrum is defined by $F_v\ S_l$. Thus, response spectra representing variable frequency contents can be defined by varying T_s, which accounts for both the regional seismicity and the site modification effects. Eqns. (1a)-(1c) define the response spectrum for the so called "Maximum Considered Earthquake" condition, which is based on a 2% probability of exceedance in a design life of 50 years, and is 1.5 times higher than the response spectrum specified for general "Design" condition. In other words, a 2/3 factor should be applied to these equations for normal design applications.

Recognising that the existing approach using dual parameters may involve considerable error in the estimates of spectral acceleration values, methodologies have become available since the early 1990s for deriving the expected values of the spectral acceleration of an elastic single-degree-of-freedom (SDOF) system directly from seismic source zone models and ground motion attenuation relations [17]. Using such methods, the spectral acceleration values are obtained for a range of periods but corresponding to a single probability of exceedance (PE). The plot of such RSA values is a more advanced form of the UHS as defined by the dual parameter approaches of IBC-2000 and NBCC-1995, referred to above. Because the UHS provides a response parameter that is related directly to the design earthquake forces (FB approach), they are preferable to spectra derived indirectly by anchoring to peak ground motion predictions or bounds. It is also noted that a multiple-parameter UHS is expected to form the basis of the earthquake design provisions of the up-dated NBCC-2000 code, to be issued in the near future.

UHS models have been presented in further diverse forms. In the report FEMA-273 [18], dual spectral parameters defining the response spectrum for the reference soil condition are presented directly on seismic hazard contour maps. Spectral parameters corresponding to 10% and 2% PE in a design exposure interval of 50 years (average return periods of about 500 and 2500 years, respectively) are defined using separate hazard maps. Further, the effects of soil amplification for various site classifications (other than the reference soil classification) have been accounted for by the use of dual amplification factors, which are presented in tabular form.

The essential concept of the Dual Parameter response spectrum has recently been further extended by the authors into a comprehensive response spectrum model (CAM model) which combines semi-probabilistic estimates of velocity, displacement and acceleration parameters for a given subject region [14],[19]. Such multiple parameters have enabled a reliable definition of the shape of the design response spectrum across the entire period range of interest for structures. The probabilistic element arises from the definition of regional seismicity parameters, combined with appropriate regional ground motion attenuation functions. The CAM model and its application to regions of low to moderate seismicity, typically lacking earthquake records, will be discussed further in the following section.

Shortcomings of Probabilistic Response Spectra

The major features and potential shortcomings of the probabilistic response spectrum approaches described above, particularly those adopted by seismic codes, are:

- they do not explicitly incorporate the critical parameters (magnitude, distance and crustal properties) which strongly influence the shape of the response spectrum;
- they do not represent the effects of a single earthquake, but instead, are the envelope of the effects of earthquakes of varying magnitudes and distances corresponding to similar PE;
- the response spectrum envelope does not accurately represent the inelastic response behaviour of a structure in a real earthquake, although it appears to be appropriate for elastic design, when only the absolute response spectral level is of interest;
- consequent to all the above comments, spectrum-compatible synthetic accelerograms generated from a probabilistic response spectrum do not realistically represent real accelerograms, and in fact can be extremely misleading and unrepresentative for design purposes [20];
- the amplitudes of critical parts of the design response spectrum (especially in the medium to long period ranges) depend heavily on the accurate specification of large magnitude, long return period events, and in low and moderate seismicity intraplate regions the recurrence intervals of such events have generally been extrapolated from earthquake data associated with much smaller magnitude events [5],[21], leading to large modelling uncertainties.

Some illustration and discussion of the above points now follows:

The probabilistically-derived seismic design response spectrum provisions in codes and standards are not directly indicative of the physical processes which generate and modify earthquake ground motions, and this has led to widespread misconceptions amongst designers concerning how to account for factors influencing the frequency content of ground motions. For example, the response spectral amplitudes in the long period (displacement-controlled) range specified by the UHS developed for the ENA region are generally much lower than for the WNA region, at a given spectral velocity level [22]. This has led many designers, and even some earthquake engineering researchers, to develop thinking that (from anecdotal evidences) intraplate earthquakes in ENA, by their very nature, generate little displacement demand in structures. In fact, from well-known seismological principles [7], the bedrock ground displacement and associated long-period displacement demand generated by an earthquake depend mainly on its moment magnitude (M), regardless of the seismo-tectonic classification of the earthquake. It has been shown by the authors in Ref.'s [14] & [19] along with Ref.'s [5] & [6] that the ratio of effective peak ground velocity to displacement (EPGV/EPGD), is dependent mainly on the Magnitude-Distance (M-R) combination of design earthquake events with specified average return periods. Such events are defined probabilistically, using the regional seismicity parameters. For a given average return period (or PE within a given exposure interval), the moment magnitude of the considered earthquakes in ENA is, not unexpectedly, generally lower than in WNA. Consequently, the (normalised) shape of the response spectrum specified for ENA, and in particular for the Eastern United States, is typified by a relatively low spectral level in the very long period range. Nevertheless, intraplate earthquakes are in fact capable of causing displacement demands comparable to interplate earthquakes of similar magnitude, although regional crustal and path modifications of the ground motions [6],[14] also play a very significant role in determining the localised demands associated with a given event (M-R combination). For these reasons, the shape of UHS varies with the return period (for example, comparing 500 years with 2500 years), and this can appear confusing for designers if the underlying reasons have not been fully understood. These issues have been further discussed in Ref.[23].

In the dual parameter probabilistic response spectrum of IBC-2000, the design RSA's at short and long periods (used in defining the UHS) are not necessarily expected to co-exist in the same earthquake, and hence design of systems which are sensitive to a range of frequencies, based on such spectra, may give artificially conservative results. The same is true of more generalised forms of UHS defined over a range of periods. In a similar context, the EPGA that is critical for design [14] tends to be associated with a small magnitude earthquake event occurring in the near field (small site-source distance, R), whereas the critical effective peak ground displacement EPGD tends to be associated with a large magnitude event in the far field (large R), and hence they rarely co-exist. Yet, the most onerous combinations of the peak ground acceleration, velocity and displacement parameters are typically used to define the probabilistic response spectrum. Further, in situations where the effective natural period of a structure changes significantly during the response to an earthquake, as a result of ductile yielding along with other factors, the gradient of the response spectrum as well as its absolute level governs the inelastic response behaviour. Both quantities must therefore be represented accurately, and this may not be the case in a probabilistic UHS. This deficiency has been partially circumvented through the use of the Load (or Force) Reduction Factor (or R-factor, [1]), or by the use of displacement coefficients that extrapolate the elastic response behaviour to the inelastic response behaviour [24].

There is a global trend in seismic engineering towards Performance Based Design [2],[25], which requires more realistic modelling and a better understanding of the physical processes on the part of the designer. It is considered that the above-cited limitations of the probabilistic response spectrum should be recognised, and solutions to these problems be urgently addressed.

4. Response spectral attenuation functions and CAM

Response spectral attenuation functions (for example, Ref.[21]) express the key response spectrum parameter values (at regular natural period intervals) as functions of M, R, site soil classification and faulting mechanism (such as strike-slip or reverse fault). Such response spectral attenuation functions have often been used in seismic hazard modelling, to develop probabilistic response spectra (based on the standard Cornell-McGuire integration technique [8],[9]). The spectral attenuation functions are used to weight the contributions of various earthquake sources to the site seismic hazard, and are seldom used as end-products in their own right. However, if spectral attenuation functions representing the defined range of natural periods (typically given from 0.1 sec to 2 sec) are used collectively to derive a design response spectrum for any given combination of M, R and site classification, the "collective function" effectively becomes a pseudo-deterministic response spectrum. Such a pseudo-deterministic response spectrum can model only the average effects of the M, R and site classification and does not take into account any particular source or path effects. Thus, strictly speaking, the response spectrum derived from the spectral attenuation function is only partially deterministic (hence the description "pseudo"), to distinguish it from the fully deterministic response spectrum described above.

In a regional context, a number of spectral attenuation models have been developed by empirical studies of strong earthquake ground motions in regions such as Australia, Europe, ENA and WNA (in particular, California), see for example Ref.'s [21],[26]-[28]. It must be emphasised that applications of such attenuation functions are restricted to the region (such as WNA) from which the source data used in deriving the functions were originally obtained, since the important regional source and crustal properties have not been explicitly parameterised in such attenuation models.

The alternative way to obtain earthquake response spectrum prediction across the full period range is from the seismological model, which has been developed in the United States over the last two decades by the work of Atkinson and Boore, along with other investigators [22],[26],[29]-[31]. The Component Attenuation Model (CAM) has been developed recently by the authors, to adapt the seismological model and the associated regional seismological parameters to determine response spectra for direct engineering applications. The response spectral parameter of interest (Δ) (e.g. maximum response spectral velocity) can be determined from CAM using the generic expression of equation (2).

$$\Delta = \alpha(M,F)\, G(R,D)\, \beta(R,Q)\, \gamma(Vs) \tag{2}$$

where,

$\alpha(M,F)$= source factor which is function of the moment magnitude (M) and faulting type (F)

$G(R,D)$= geometric factor which is function of the site-source distance (R) and crustal depth (D).

$\beta(R,Q)$= anelastic attenuation factor which is function of R and the crustal quality factor (Q).

$\gamma(Vs)$ = upper crust factor which is function of the upper crust shear wave velocity profile (Vs).

CAM is particularly suited to applications in seismic regions with low and moderate levels of activity where representative recorded seismic strong motion data is generally lacking. The details of the development of CAM, its applications to different regions (including Australia, Singapore, Vietnam and China), and the associated comparative analysis with empirical models and *ad-hoc* field measurements have been given in Ref.'s [7],[14],[19]&[32-39]. The very good agreement between the predictions of CAM and existing empirical attenuation functions developed in the different regions gives confidence in its use for seismic hazard modelling. The developed model has particular advantages in regions lacking earthquake records. The growing awareness of the need to consider seismic loading effects in such regions has provided the main stimulus for developing CAM. The approach circumvents many of the inherent drawbacks of the more conventional approaches that, for reliable results, rely heavily on the availability of large amounts of regional-specific, strong-motion earthquake data. Since a number of technical papers describing the formulation of CAM and its applications have been published or are in press, the current paper will instead focus on presenting some calculated response spectra for illustration, as in the next section.

5. Design earthquake scenarios and the characteristic response spectrum

CAM effectively defines the displacement, velocity and acceleration response spectra for any given combination of seismological parameters, including the moment magnitude (M) and site-source distance (R) of the earthquake. Thus, CAM can be used as a response spectral attenuation function, forming an integral part of a probabilistic seismic hazard evaluation procedure. CAM can therefore be applied in the context of a deterministic procedure or a probabilistic procedure. In situations where no major potential fault sources have been identified, the seismic activity may be assumed to be distributed evenly over a very large area. A simple relationship developed by Jacob [40] may be applied to obtain the aggregated effects of the distributed seismic hazard at a particular site. This procedure has been adopted by the authors in a series of studies [5],[6],[7],[14],[19],[33]. The relationship is based on the following concept. First, consider a site that is located within a seismic source zone. It is assumed that the boundary of the source zone is sufficiently far away from the site so that its effects on the site seismic hazard can be ignored. Further, the source zone possesses uniform spatial distribution of seismic activity, the level of which can be quantified in terms of the conventional seismicity parameters in the Gutenberg-Richter form ("*a*" and "*b*" [9]; alternatively, parameter "a_5" is used in place of "*a*" [5]). The above two assumptions are not unreasonable in regions of low or moderate seismicity, where source zones are typically very broad and diffused. Such regions usually lack reliable information from which to develop definitive source zone models. It can be established from the foregoing assumptions that at least one earthquake of magnitude ≥M has a 50% probability of occurring within a certain site-source distance (R) from the site, for a given average return period.

It has been shown in Ref.[5] that for any given site-source distance (R) from the site, and for any given level of seismicity (as defined by "a_5" and "*b*") and average return period (T_{RP}), the design moment magnitude (M) may be determined from the following expression:

$$M = 5 + \{ \log_{10} (2\pi R^2 T_{RP}) - 7 + a_5 \} / b \tag{3}$$

where a_5 has been normalised to a time interval of 100 years and a source area of 10^5 km^2.

For example, the design earthquake scenarios expressed in terms of the M-R combinations for T_{RP} = 2500 years (~2% PE in 50 years) and for the low seismicity conditions defined by a_5 =0.5 and b=0.8 (consistent with the general level of seismic activity in southeastern Australia) are given in Table 1. The displacement and acceleration response spectra and the associated response spectrum parameters as determined from CAM for these earthquake scenarios, assuming the generic "Rock" crustal classification, are shown in Figures 2a & 2b and in Table 1, respectively. The M-R combinations shown in Table 1 are consistent with the intuitive expectation that the larger the site-source distance, R, the larger the design earthquake magnitude, M. It is shown that the critical long-period parameters (RSD_{max}) pertain to distant M-R combinations whereas critical short-period parameters (RSA_{max}) pertain to near-field earthquakes. Thus, the displacement response spectrum associated with the largest magnitude spectrum envelope representing this level of seismic activity (Fig. 2a) is the "deterministic" response event being considered.

Importantly, there is an upper limit to the assumed earthquake magnitude that is defined as the Maximum Considered Earthquake (MCE). It is assumed in the example presented herein that the MCE has magnitude M=7. The solution to the seismic hazard problem, although initially defined probabilistically in terms of parameters *a* (or a_5) and *b*, has been presented deterministically.

Table 1 - M-R Combinations and Response Spectrum Parameters for a_5 =0.5 , b=0.8 and T_{RP}=2,500 years

R(km)	M	RSV_{max}(mm/s)	RSD_{max}(mm)	RSA_{max}(g's)
14	5	90	6	0.40
23	5.5	77	7	0.33
36	6.0	84	10	0.30
57	6.5	100	20	0.28
90	7.0 *	114	30	0.27

* M=7.0 represents the Maximum Considered Earthquake

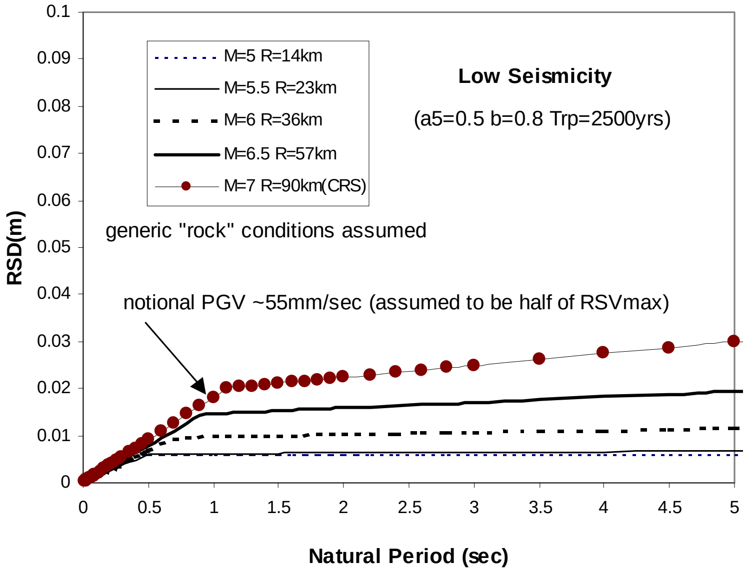

Fig. 2(a) – Displacement Response Spectra obtained from the Component Attenuation Model (CAM) for 2500 years Return Period Design Earthquake Scenarios.

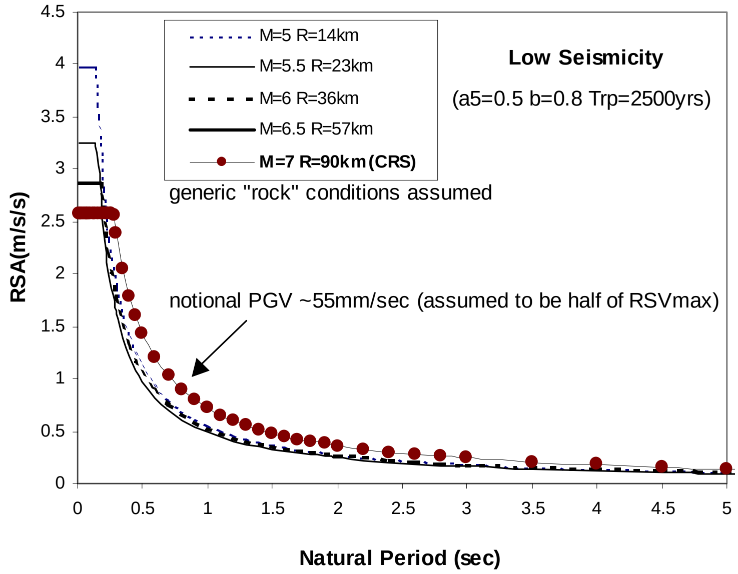

Fig. 2(b) - Acceleration Response Spectra obtained from the Component Attenuation Model (CAM) for 2500 years Return Period Design Earthquake Scenarios.

It should be noted that the CRS modelling concept is founded on the assumption of uniform seismicity over large regions. Thus, the procedure described above should not be applied to determine the effects of distinct, distant major seismic sources that are capable of generating earthquakes of magnitudes significantly exceeding the estimated MCE level in the immediate vicinity of the site.

6. Discussion

It is currently held that the deterministic approach of modelling seismic hazard is more suited to high seismicity regions, where detailed information of the potential fault sources is available from which to simulate earthquake ground motions specific to certain site and source. On the other hand, the probabilistic modelling approach which utilises empirical attenuation functions and Cornell-McGuire integration is generally considered appropriate for low to moderate seismicity regions, where details of potential fault sources are generally insufficient to simulate earthquake ground motions deterministically.

However, this paper has highlighted certain fundamental limitations of the probabilistic response spectrum model. In addition, there are difficulties with applying probabilistic modelling in regions where earthquake data are lacking. For example, the highly extrapolative nature of the process of predicting design-level events with long return periods makes the probabilistic procedure for calculating the average return periods for earthquakes of a given magnitude inappropriate. Significant differences may also exist between the various magnitude recurrence models developed for the same region, due to the different assumptions and interpretation of data. Further, the fundamental lack of strong motion data requires empirical attenuation functions to be adopted from other seismic regions in the modelling process. The combined uncertainties in the extrapolation of magnitude-recurrence models, the adopted "representative" attenuation functions, and the designation of the MCE magnitude present considerable challenges for low to moderate seismicity regions where earthquake data are typically lacking [41].

The dominance of the Characteristic M-R Combination and the associated CRS is a significant research finding (refer previous section). It has been found that the damaging or destructive velocity and displacement components of earthquake ground motions are less sensitive to distance of the wave travel path than accelerations, due to the increased robustness of the transmitted waves. Further, the "wave-guide effect" [42] contributes to further retardation of attenuation at long distances (>100km). Consequently, the assumed spatial distribution of the fault sources in low to moderate seismicity regions has only moderate effects on the design response spectrum. Instead, the assumed Maximum Considered Earthquake (MCE) appears to be the major controlling factor. Thus, a conventional probabilistic seismic hazard analysis (based on the various magnitude recurrence models) may be reduced to a deterministic analysis based mainly on the MCE and knowledge on the regional crustal properties. This has very interesting implications for the future development of seismic hazard evaluation in low and moderate seismicity regions.

The regional crustal structure may be found by established methodologies such as the dispersion analysis of earthquake surface waves, as described previously. However, the determination of the MCE is not as straightforward. A useful review of methods for determining the MCE for a given seismic region was given by Reiter [9]. This is an issue of current concern in engineering seismology and represents a parameter with high uncertainty in any seismic hazard analysis, especially in low to moderate seismicity regions. Some discussion on this point was given in Ref.[23].

The modelling of uncertainties has traditionally formed an essential element in empirical studies involving ground motion prediction. Such uncertainties are made up of (i) random (aleatory) uncertainties, and (ii) modelling (epistemic) uncertainties. Aleatory uncertainties are partly attributed to "intra-event" uncertainties (due to variations between sites of the same category and located at similar epicentral distances from the earthquake event) and partly also to "inter-event" variations (due to variations between the characteristics of earthquake ruptures for events of similar magnitude). It has been suggested [43] that the standard deviation of residuals in the natural logarithmic scale (ln σ) varies between 0.5-0.7 (implying that the mean plus one standard deviation for a given ground motion parameter is about 1.6 - 2 times the estimated mean), based on observations in WNA. Note that the actual degree of random uncertainties in other seismic regions can be significantly different to the above quoted range, for several reasons. First, intra-event uncertainties can be significantly affected by variations of the geology within the region. Second, the so-called "random" uncertainties can be reduced by the appropriate modelling of the wave modification characteristics of the individual site and path; the reduction depends on the degree of rigour adopted in the modelling. Third, inter-event uncertainties have been observed to decrease significantly with increasing earthquake magnitude, as reported by Somerville [4].

In regions of low to moderate seismicity, indigenous data are at best scarce and consequently it is difficult to obtain reliable estimates of the population averages, let alone quantifying the aleatory uncertainties. Epistemic uncertainties are as difficult to ascertain and to generalise, even in data abundant (high seismicity) regions. After all, the uncertainties in the ground motion prediction only consititute part of the overall uncertainties in the seismic performance evaluation of a structure. For example, there are significant uncertainties associated with the use of a linearised procedure in structural response analysis (such as the use of a structural response modification factor or equivalent viscous damping) to determine the performance of a structure experiencing significant inelastic behaviour. Last, but not least, the assumptions made regarding the MCE represent another major source of uncertainty that cannot be quantified rationally by numerical modelling.

It may therefore be concluded that the degree of rigour routinely employed in quantifying aleatory uncertainties in seismological studies has generally not been maintained in other parts of the overall seismic performance assessment procedure. In the opinion of the authors, it does not appear to be feasible, nor appropriate, to create uncertainty predictions for every step of the overall procedure since compounding multiple uncertainties can give misleading results. It is worthwhile to explore the viable alternative approach of introducing margins of uncertainty in the MCE magnitude prediction. This appears to be much simpler to interpret and at the same time is as effective in providing conservative ground motion estimates accounting for the complicated series of uncertainties generated by the sequence of steps employed in the modelling process.

The widely-used phrase "Probabilistic Approach” has validity in dealing with uncertainties in earthquake engineering. But it shouldn't be taken for granted that the Probabilistic Approach would always be satisfactory if the uncertainties become so large that they may not be quantifiable in a meaningful sense (for example, the MCE in low seismicity regions). The authors’ preferred approach of working with a specific set of pseudo-deterministic earthquake M-R combinations in seismic assessment using PBSE, is sometimes criticised as being a retrograde step, in comparison with the fully Probabilistic Approach. It is our opinion that it should not be judged this way, since in reality the design earthquake scenarios (M-R combinations) approach has a number of key conceptual and computational advantages as well as being more clear-cut and transparent.

7. Conclusions

The evolution from the deterministic to the probabilistic seismic hazard and response spectrum modelling approaches has been described. Significantly, there are fundamental limitations associated with both approaches. The developing concept of the Characteristic Response Spectrum (based on the Component Attenuation Model) for applications in low to moderate seismicity regions has been introduced. Thus, an initial probabilistic seismic hazard analysis (based on the various magnitude recurrence models) has been reduced to a psuedo-deterministic analysis based on the Maximum Considered Earthquake (MCE) and the regional crustal properties that affect seismic wave transmissions. The authors' preferred approach of working with design earthquake scenarios and the associated "deterministic" response spectra has a number of key conceptual and computational advantages as well as being more clear-cut and transparent.

Acknowledgements

The methodologies and procedures described in the paper have been developed as a result of a project funded by the Australian Research Council (large grant), entitled: "Earthquake Induced Displacements for Building Structures in Australia" (A10080206). This support is gratefully acknowledged. The work described in this paper has also been funded by the Research Grants Council of Hong Kong, China (Project No.'s HKU 7023/99E and HKU 7002/00E), whose support is gratefully acknowledged.

REFERENCES

1. A.M. Chandler, N.T.K. Lam, J.L. Wilson, and G.L. Hutchinson, "Review of Modern Concepts in the Engineering Interpretation of Earthquake Response Spectra", *Proceedings of the Institution of Civil Engineers, Journal of Structures & Buildings*, Vol.146, Issue 1, 2001, pp.75-84.
2. Structural Engineers' Association of California (SEAOC): Vision 2000 Committee, "Performance Based Seismic Engineering of Buildings", J. Soulages, ed. 2 Volumes. *SEAOC*, Sacramento, CA, 1995.
3. R.S. Yeats, K. Sieh, and R.A. Clarence, "The Geology of Earthquakes", *Oxford University Press*, New York and Oxford, 1997.
4. P. Somerville, "Seismic Hazard Evaluation", *12th World Conference on Earthquake Engineering*, Auckland, N.Z., 2000, Paper.2822, State-of-the-Art Report, 16pp.
5. N.T.K. Lam, A.M. Chandler, J.L. Wilson, and G.L. Hutchinson, "Seismic Hazard Determination for the Coastal Region of South China I: Generic Crustal Modelling", *Journal of Seismology and Earthquake Engineering*, Vol.2, No.1, 1999, pp.1-16.
6. N.T.K. Lam, A.M. Chandler, J.L. Wilson, and G.L. Hutchinson, "Seismic Hazard Determination for the Coastal Region of South China II: Regional Crustal Modelling", *Journal of Seismology and Earthquake Engineering*, Vol.2, No.2, 2000, pp.1-15.
7. N.T.K. Lam, J.L. Wilson, and G.L. Hutchinson, "Generation of Synthetic Earthquake Accelerograms Based on the Seismological Model: A Review", *Journal of Earthquake Engineering*, Vol.4, No.3, 2000, pp.321-354.
8. C.A. Cornell, "Engineering Seismic Risk Analysis", *Bulletin of the Seismological Society of America*, Vol.58, 1968, pp.1583-1606.
9. T. Reiter, "Earthquake Hazard Analysis", *Columbia University Press*, New York, 1990.
10. N.M. Newmark, and W.J. Hall, "Earthquake Spectra and Design", Earthquake Engineering Research Institute Monograph Series, *EERI Monograph No.3,* Berkeley, California, 1982.

11. Applied Technology Council, "Tentative Provisions for the Development of Seismic Regulations for Buildings", *Report ATC 3-06*, California, 1978.
12. Standards Association of Australia, "Minimum Design Loads on Structures, Part 4: Earthquake Loads", *AS1170.4*, 1993.
13. Associate Committee on the National Building Code, "National Building Code of Canada 1995", *National Research Council of Canada*, Ottawa, Canada, 1995.
14. N.T.K. Lam, J.L. Wilson, A.M. Chandler, and G.L. Hutchinson, "Response Spectral Relationships for Rock Sites Derived from the Component Attenuation Model", *Journal of Earthquake Engineering and Structural Dynamics*, Vol.29, 2000, pp.1457-1489.
15. D.M. Scott, J.W. Pappin, and M.K.Y. Kwok, "Seismic Design of Buildings in Hong Kong", *Transactions of the Hong Kong Institution of Engineers*, Vol.1, No.2, 1994, pp.37-50.
16. IBC (2000), "International Building Code, 2000", *International Code Council*, U.S.A, 2000.
17. G.M. Atkinson, "Use of the Uniform Hazard Spectrum in Characterising Expected Levels of Seismic Ground Shaking", *Proceedings of the 6th Canadian Conference in Earthquake Engineering*, Toronto, 1991, pp.469-476.
18. Federal Emergency Management Agency, "FEMA-273: NEHRP Provisions for the Seismic Rehabilitation of Buildings – Guidelines", *FEMA*, Washington D.C., U.S.A., 1998.
19. N.T.K. Lam, J.L. Wilson, A.M. Chandler, and G.L. Hutchinson, "Response Spectrum Modelling for Rock Sites in Low and Moderate Seismicity Regions Combining Velocity, Displacement and Acceleration Predictions", *Journal of Earthquake Engineering and Structural Dynamics*, Vol.29, 2000, pp.1491-1525.
20. F. Naeim, and M. Lew, "Deficiencies of Design-Spectrum Compatible Accelerograms", *The Structural Design of Tall Buildings*, Vol.3, 1994, pp.275-283.
21. D.M. Boore, W.B. Joyner, and T.E. Fumal, "Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work", *Seismological Research Letters*, Vol.68, No.1, 1997, pp.128-153.
22. D.M. Boore, and G. Atkinson, "Stochastic Prediction of Ground Motion and Spectral Response Parameters at Hard-Rock Sites in Eastern North America", *Bulletin of the Seismological Society of America*, Vol.73, 1987, pp.1865-1894.
23. S.G. Scott, J.J. Bommer, and S.K. Sarma, "Definition of Hazard-Consistent Ground Motions through Multi-Parameter Seismic Hazard Assessment", *Proceedings of the 6th SECED Conference : Seismic Design Practice into the Next Century*, Oxford, U.K., 1998, pp.229-236.
24. M. Edwards, N.T.K. Lam, J.L. Wilson, and G.L. Hutchinson, "The Prediction of Earthquake-Induced Displacement Demand of Buildings in Australia: An Integrated Approach", *Proceedings of the New Zealand National Society of Earthquake Engineering (NZSEE) Conference*, Rotorua, 1999, pp.43-50.
25. PEER Center News, "Advancing Performance-Based Earthquake Engineering", *Pacific Earthquake Engineering Research Center Newsletter*, Vol.2, No.1, 1999, pp.1-6.
26. G. Atkinson, and D.M. Boore, "Ground-motion Relations for Eastern North America", *Bulletin of the Seismological Society of America*, Vol.85, No.1, 1995, pp.17-30.
27. N.T.K. Lam, J.L. Wilson, and G.L. Hutchinson, "Development of Intraplate Response Spectra for Bedrock in Australia", *Proceedings of the 1998 Technical Conference of the New Zealand National Society for Earthquake Engineering*, Wairakei, New Zealand, 1998, pp.137-144.
28. N.N. Ambraseys, K.A. Simpson and J.J. Bommer, "Prediction of Horizontal Response Spectra in Europe", *Journal of Earthquake Engineering and Structural Dynamics*, Vol.25, pp.371-400.

29. G. Atkinson, "Earthquake Source Spectra in Eastern North America", *Bulletin of the Seismological Society of America*, Vol.83, 1993, pp.1778-1798.
30. G. Atkinson and D.M. Boore, "Evaluation of Models for Earthquake Source Spectra in Eastern North America", *Bulletin of the Seismological Society of America*, Vol.88, No.4, 1998, pp.917-934.
31. G. Atkinson, and W. Silva, "An Empirical Study of Earthquake Source Spectra for Californian Earthquakes", *Bulletin of the Seismological Society of America*, Vol.87, 1997, pp.97-113.
32. N.T.K. Lam, J.L. Wilson, A.M. Chandler, and G.L. Hutchinson, "A Generic Displacement Spectrum Model for the Seismic Assessment of Structures", *Journal of Earthquake Engineering and Structural Dynamics* (Paper submitted in January 2001)
33. N.T.K. Lam, A.M. Chandler, L.S. Chan, J.L. Wilson, and G.L. Hutchinson, "Motion Induced by Distant Earthquakes: Estimated Ground Shaking in Hong Kong", *International Conference on Advances in Structural Dynamics, ASD 2000*, Hong Kong, December 2000, Vol.1, pp.209-216.
34. N.T.K. Lam, A.M. Chandler, and J.L. Wilson, "The Component Attenuation Model for Predicting Earthquake Ground Motions Affecting Hong Kong from the Far-Field", *Proceedings of the Mini-Workshop on Design Ground Motion for East-Asia Region*, The University of Tokyo, 4th March, 2000, pp.74-88.
35. N.T.K. Lam, J.L. Wilson, A.M. Chandler, and G.L. Hutchinson, "Response Spectrum Predictions for Potential Near-Field and Far-Field Earthquakes Affecting Hong Kong: Rock Sites", *Journal of Soil Dynamics and Earthquake Engineering*, 2001 (Paper submitted in December,2000)
36. R. Koo, A. Brown, N.T.K. Lam, J.L. Wilson, and G. Gibson, "A Full Range Response Spectrum Model for Rock Sites in the Melbourne Metropolitan Area", *Proceedings of the Australian Earthquake Engineering Society Seminar*, Tasmania, 2000, Paper no.16.
37. T. Balendra, N.T.K. Lam, J.L. Wilson, and K.H. Kong, "Analysis of Long-Distance Earthquake Tremors and Base Shear Demand for Buildings in Singapore", *Journal of Engineering Structures,* 2001, (Paper accepted)
38. T. Ngo, R. Koo, N.T.K. Lam, and J.L. Wilson, "Estimates of Seismic Loading for Concrete Structures in Hanoi, Vietnam", *Proceedings of the International Conference on Advanced Technologies in Design, Construction and Maintenance of Concrete Structures*, March 2001, Hanoi, Vietnam.
39. Q.F. Luo, "Estimation of Ground Motions Affecting Shanghai by Long Distance Earthquakes", *International Conference on Advances in Structural Dynamics (ASD2000),* The Hong Kong Polytechnic University, December 2000, Vol.1, pp.225-232.
40. K.H. Jacob, "Scenario Earthquakes for Urban Areas Along the Atlantic Seaboard of the United States", *National Center for Earthquake Engineering Research*, NCEER-SP-0001, Buffalo, New York, 1997.
41. C.A. Kircher, "United States Building Code Approach to Variations in Regional Seismicity", *Proceedings of the New Zealand National Society of Earthquake Engineering (NZSEE) Conference*, Rotorua, 1999, pp.19-26.
42. P. Somerville, "Recent Advances in Strong Ground Motion Prediction", *8th Canadian Conference on Earthquake Engineering,* Vancouver, Canada, 1999, pp.7-28.
43. G. Atkinson, and D.M. Boore, "Some Comparisons Between Ground Motion Relations", *Seismological Research Letters,* Vol.68, No.1, 1997, pp.24-40.