Seismic Hazard Determination for the Coastal Region of South China II: Regional Crustal Modelling

Nelson Lam[1], Adrian Chandler[2], John Wilson[3], and Graham Hutchinson[4]

1. Senior Research Fellow and Senior Lecturer, Department of Civil and Environmental Engineering, The University of Melbourne, Parkville, Victoria, 3052, Australia
2. Professor, Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, Special Administrative Region, China
3. Senior Lecturer, Department of Civil and Environmental Engineering, The University of Melbourne, Parkville, Victoria, 3052, Australia
4. Professor of Civil Engineering and Head of Civil and Environmental Engineering Dept., The University of Melbourne, Parkville, Victoria, 3052, Australia

ABSTRACT: *This paper extends a rational seismological modelling approach for earthquake response spectra in a moderate seismicity region, using the Coastal Region of South China as the example, by incorporating into the model the regional crustal effects on bedrock earthquake ground motions. Such crustal effects cause significant modifications to peak ground motion predictions and hence have an important influence on the amplitudes of spectral responses (accelerations, velocities and displacements) developed in the form of design response spectra associated with a range of return periods from 500 to 2,500 years. The concept of the Characteristic Response Spectrum (CRS) is introduced. The CRS, which is solely a function of the crustal properties and the assumed Maximum Credible Earthquake (MCE) magnitude, has been found to dictate the seismic hazard of the subject region. The adopted approach emphasizes the importance of studying the composition and the structure of the earth's crust in modelling the seismic hazard in regions of moderate seismicity. It is found that the predictions made by the seismological model based on characteristic Magnitude-Distance (M-R) combinations are very consistent with current code provisions in the velocity-controlled period range. However, significant discrepancies have been identified in other period ranges. In addition, the empirical modelling methodology based on adapting the properties of western United States (primarily Californian) seismic data, as used by some previous researchers to predict peak ground motions (for engineering purposes) for the South China region, appears to give overly conservative results when extrapolated to large magnitude characteristic events.*

Keywords: Seismic hazard; Earthquake ground motion; Response spectrum; Seismological model; Acceleration; Velocity; Displacement; South China; Hong Kong

1. INTRODUCTION AND SOURCE MODELLING (STAGE ONE)

In the first part of this paper [1], design response spectra have been developed for the Coastal Region of South China (CRSC) for Return Periods ranging between 500 years to 2500 years using a rational procedure developed by the authors based on the seismological model. The procedure assumed that the crustal condition of CRSC was identical to that of the generic "Hard Rock" conditions in Eastern North America (ENA). Consequently, the acceleration (short period) components of the seismic shear waves have been modified in accordance with the distance dependent attenuation properties of the earth's crust in ENA, whilst the velocity and displacement (medium and long period) components have only been modified in accordance with spherical attenuation and surface amplification. Thus, the only regional information from CRSC itself which has been input to the procedure was the magnitude-recurrence relationships of the various source models which define the seismicity of the region. However, the typically infrequent and seemingly random occurrences of intraplate earthquakes for such regions have resulted in insufficient data to clearly identify the spatial and temporal trends in the earthquake occurrences. Such modelling uncertainties were manifested in the high variability between the individual source models. It was therefore prudent to adopt the conservative approach of selecting the most onerous magnitude-distance (M-R) combinations from amongst the considered source models.

In the revised procedure described in this paper, the regional shear wave velocity profiles and the depth of the earth's crust (defined as the depth to the Moho discontinuity) have been derived from published regional surface wave dispersion analyses. Such seismological information has been considered alongside qualitative geological information of the region to determine the path modification effects of the seismic shear waves, using the generic crustal models [1] as reference. Meanwhile, the same source models as described in the first part of the paper have been used here to define the M-R combinations. The manner in which the design response spectra are derived from the respective peak ground motion parameters is again very similar to the procedure described in the first part of the paper. Importantly, mid-crust amplifications and tri-linear attenuation associated with the regional crustal model have resulted in a significant increase in the amplitude of the predicted earthquake ground motion over the entire period range of interest. The influence of the tri-linear attenuation mechanism (which is crustal-depth dependent) is particularly significant in CRSC. The ground motions arising from earthquakes generated from a source located beyond a certain distance range have been found to be relatively insensitive to distance as a result of such mechanisms. This has led to the very interesting observation that thc critical seismic hazard is well represented by what is here termed the "Characteristic Response Spectrum" (CRS). The CRS, as discussed below, represents the response spectrum applicable to characteristic M-R combinations derived for a range of return periods, and has been found to be dominated by maximum credible (large magnitude) earthquake events at distances from the source equal to 1.5D, where D is the earth's crustal depth.

This paper has been structured similarly to the first part of the paper in that the modeling procedure comprises the following stages: (I) Source Modelling (Stage One) [description of this has been omitted since it has been covered in the first part of the paper] (II) Regional crustal modelling (Stage Two) [Section 2], (III) Ground motion parameter predictions (Stage Three) [Section 3] and (IV) Response spectrum modelling (Stage Four) [Section 4]. The predicted ground motion parameters and response spectra have been compared with the design response spectra recommended in the research literature and by the current Chinese earthquake building code [Section 5]. Finally, the empirical modelling approach for earthquake ground motions currently adopted in China and the critical determination of the Maximum Credible Earthquake (MCE) have been discussed [Section 6].

2. REGIONAL CRUSTAL MODELLING (STAGE TWO)

Having established [1] two distinct generic crustal models, associated with the developed "Hard Rock" and "Rock" models, it is necessary to identify the study region (CRSC) with the appropriate model, by adopting one of the following recommended approaches:

(i) *First Approach*: Determine all path parameters listed in Table 4 of Reference [1] and compare with the "benchmark" values associated with the generic crustal models. This is not always feasible since some of the path parameters can be difficult to obtain.

(ii) *Second Approach:* Compare the regional geological structure and the measured shear wave velocity profile of the subject region with those of the generic models. Initially, the average shear wave velocity measured at a reference depth of, say, 100m (β_{100}) can be compared with the corresponding benchmark values of the generic models to determine the crustal classification of the region. Implicit in this approach is the assumption that the various parameters affecting path modifications are inter-linked. That is to say, the relatively high anelastic attenuation, steep shear wave velocity gradient and low average crustal density are assumed to co-exist with a low reference shear wave velocity. Qualitative description of the regional geology related to the age of the rock formation can be used as additional information to assist with the classification.

(iii) *Third Approach:* Compare ground motion parameters predicted from existing empirical local attenuation relationships with the corresponding parameters predicted from simulations based on one of the generic models. It is important to ensure that the empirical models have been derived from authentic indigenous data.

The second approach has been attempted in the following, to determine a preliminary crustal classification of the Coastal Region of South China based on the limited information (to the authors's knowledge) currently available. The dispersion characteristics [2] of surface waves recorded in the region are first considered. The velocity of surface waves is a function of the average shear wave velocity within an upper portion of the earth's crust. The period of an individual wave component dictates the depth of that upper portion. In a uniform half space, all wave components travel with the same velocity and there is no dispersion. If there is a discontinuity separating two crustal layers with significantly different average shear wave velocities, the surface waves will disperse at a period corresponding to the depth of the discontinuity.

The regional structural geology of China as a whole has been studied by analysing such dispersion characteristics [3]. The study concluded that the crustal structure of China generally consists of an upper sedimentary rock layer which is underlain by crystalline rocks such as gneiss and granite. The total crustal thickness (D) varies across China between 30-70km, depending on the region. Along the Coastal Region of South China (CRSC), the crustal thickness is only about 28-30km. Similarly, the top sedimentary rock layer in the CRSC may also be relatively shallow (perhaps just a few km), although data on this is scarce.

The shear wave velocity of the underlying crystalline rock layer was determined [3] to be about 3500m/sec at a depth of 10km, whereas the shear wave velocity of the sedimentary rock layer, which contributes most to crustal modifications, was found to be in the order of 2600m/sec-2800m/sec (see Figure 1). If this sedimentary rock layer is

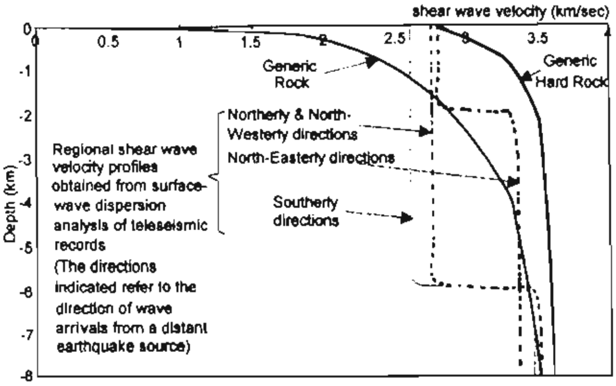

Figure 1. Regional shear wave velocity profiles of the CRSC.

assumed to possess uniform properties, the reference shear wave velocity (taken at a depth of 100m) would be comparable to that of the generic "Hard Rock" model defined in Table 4 of Reference [1]. However, it is important to note that such regional shear wave velocity information [3] has been derived from tele-seismic measurements which at best only provide "broad-brush" indications of the major building blocks constituting the geological structure of the region. Further, the shear wave velocity so obtained represents only the average over the entire block of sedimentary rock and does not provide information concerning possible variations within the block. Consequently, shear wave velocities within the depth range of engineering interest (the upper 500m or so) cannot reliably be ascertained from seismological information of this type alone.

Shear wave velocity can alternatively be obtained from refractive experiments carried out at the ground surface. The compressive body wave (P-wave) velocity is first derived from the measured wave travel time. The P-wave velocity profiles so obtained are then converted into the shear wave (S-wave) velocity profiles based on an assumed Poisson's ratio (typically taken as 0.25). Again, this method can only determine the average shear wave velocity within a layer bounded by noticeable discontinuities, and will not be able to detect gradual deterioration in the shear wave velocity close to the earth's surface. Moreover, the Poisson's ratio required for the P to S wave conversion can vary within the top 4km of the earth's surface due to the presence of rock cracks, and this creates further complications in making reliable predictions [4].

To counter the shortcomings of the surface monitoring methods, researchers have placed transducers in boreholes to measure directly the velocity of vertically propagating shear waves within the depth of the horehole. Such borehole data have been used to model the shear wave velocity distribution in the very shallow range of 30m in different parts of the United States [4]. Meanwhile, traditional surface monitoring provides shear wave velocity information at depths exceeding 4km. The two sets of information have been combined, through curve fitting, to predict the shear wave velocity profile at the intermediate depth range, within which the reference shear wave velocity is defined. The authors are unaware of any systematic study of a similar nature which has been carried out for the South China region. It is considered that some borehole measurements are essential to assist in determining a representative shear wave velocity at the reference depth of engineering interest.

In the interim, one must resort to considering qualitative information on the surface geology, based on regional observations of rock outcrops to support the assumption that the shear wave velocity within the upper part of the crust is in the order of 2800 m/sec, as measured from the wave dispersion study [3] described above. For example, the geological review of South China (Guangdong Province) published in Reference [5] shows that the subject region is largely covered by:

(i) An upper sequence of volcanic and sedimentary rocks intruded by granitic plutons of the Mesozoic era (in the order of 66 - 250 million years old). The volcanic rock is crystalline in nature and is therefore expected to possess good wave transmission properties. Further, the rocks of surrounding areas are expected to have been significantly hardened by metamorphism during the intrusive activities. This results in a relatively hard continental crustal which is consistent with the shear wave velocities described above. Also,

(ii) The area is extensively occupied by Late Precambrian-Early Paleozoic formations (more than 500 million years old), which generally again possess excellent wave transmission properties.

In summary, the available seismological and geological information presented above suggest that the appropriate crustal classification for the region should be allied closely to the "Hard Rock" model, whilst recognising that the subject region of CSRC has some features, notably the upper sedimentary rock layer and the relatively high recent (<500,000 years) levels of seismotectonic activity, which distinguish it from stable continental shield regions such as ENA, on which the "Hard Rock" crustal model is directly based. On the strict assumption of a "Hard Rock" generic crustal model, little or no upper crust amplification nor attenuation (as described in the first part of the paper, Reference [1]) is expected to occur. However, the measured shear wave velocity [3] of 3500m/sec in the depth range of 5-20km is generally comparable with the generic "Rock" model (see Figure 1). Fault rupturing in a crust possessing this type of shear wave velocity profile has been shown to result in mid-crust amplification factor of about 1.3 [6, 7]. However, a higher shear wave velocity of 3800m/sec, comparable to the generic "Hard Rock" model, has been measured [3] at depths exceeding 20-25km (below the Conrad discontinuity [5]). Thus, whether there is mid-crust amplification depends on the depth of the fault rupture in relation to the Conrad discontinuity. Such complications have not been taken into account in developing the generic crustal models [1].

3. GROUND MOTION PARAMETER PREDICTIONS (STAGE THREE)

3.1. Crustal Modifications to Displacement and Velocity Parameters

The generic "Hard Rock" crustal model has little effect on the medium and long period spectral properties of the ground motion, and hence the velocity and displacement predictions can be taken to be identical to those derived from the source model. However, the crustal conditions of South China are not wholly "Hard Rock" since it is apparent that mid-crust amplification can occur depending on the depth of the fault rupture, as described in Section 2 above. Mid-crust amplification is independent of frequency and hence the assumed effects in the CRSC can be allowed for reasonably conservatively by simply increasing the predicted effective peak ground displacement (EPGD) and effective peak ground velocity (EPGV) by an amplification factor of 1.3, as determined in Section 2 above. Further details may be found in References [6, 7]. The predicted EPGD and EPGV, without such an amplification, have been presented in Tables 5 and 6, respectively, of Reference [1].

Notwithstanding the crustal composition considerations, the geometrical attenuation relationship depends on the thickness of the earth's crust (taken as the depth measured from the surface of the earth to the surface of the Mantle, or the Moho discontinuity). A crustal thickness of D=30km for the CRSC (see Section 2) implies little or no attenuation of the ground motion intensity beyond a distance of 45km (1.5D) from the source, according to the tri-linear relationship defined by Eqs. (10a-10c) of Reference [1]. This tri-linear attenuation model was developed from seismological data recorded in ENA over a distance range from 10km to 1000km [7, 8]. Sucb attenuation characteristics bave not been identified previously in the empirical modelling of earthquake strong motion parameters in WNA, due to the traditional emphasis on strong motions associated with near field events.

The significance of the tri-linear relationship for medium to long distance events has been demonstrated in Table 1a by comparing the "predicted" attenuation (assuming tri-linear attenuation) with the "apparent" attenuation (assuming spherical attenuation). The two attenuation factors have also been compared diagrammatically in Figure 2a. The Effective Distance, R_{eff}, is defined as the distance from the same earthquake source which would have resulted in similar effects on the site had spherical attenuation been assumed. Thus, there is effectively no attenuation between 45km and around 90km from the source (see Column 3 of Table 1a) and this is in great contrast to the apparent attenuation shown in Column 4 of the table. Consequently, if the MCE is predicted to occur in the range 45km<R<90km based on probabilistic analysis employing the given seismicity parameters, the Effective Distance should be taken simply as 1.5D=45km.

The Actual Distances (R) calculated in accordance with Eq. (6) of Reference [1], based on MCE=7.0 and T_{RP}=500, 1000 and 2500 years, are shown along with the corresponding Effective Distances (R_{eff}) in Table 1b. Clearly, a uniform Effective Distance of 45km may be assumed regardless of the Return Period (except that a slightly shorter distance of 40km is more appropriate for the 2,500 years Return Period). The Actual and the Effective distances have been compared diagrammatically in Figure 2b across the entire period range of interest, for return periods of up to 2,500 years.

The largest M-R Combinations (shown in Table 3 of

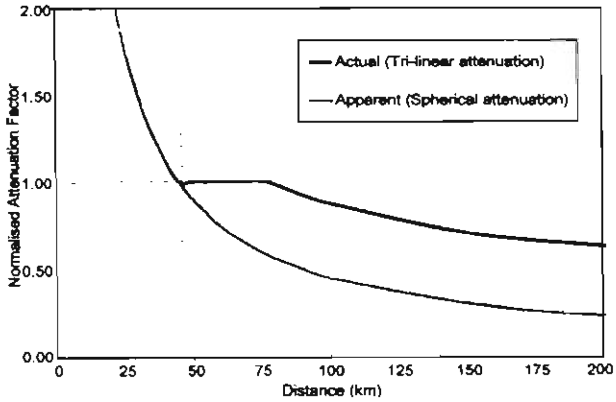

Figure 2a. Normalised attenuation factor assuming Spherical and Tri-linear attenuation.

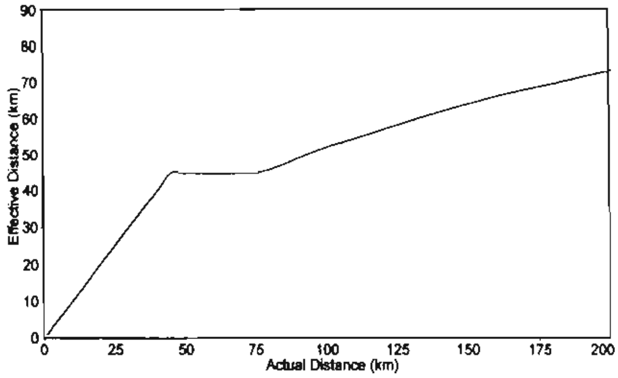

Figure 2b. Actual and effective distances associated with Tri-linear attenuation.

Table 1a. "Actual" versus "effective" distances and "predicted" versus "Apparent" attenuation based on a crustal thickness (D) of 30km.

Actual Distance (km) R	Effective Distance (km) R_{eff}	Predicted Normalised Attenuation Factor*	Apparent Normalised Attenuation Factor*
$R \leq 45$	$R_{eff}=R$	45/R	45/R
45	45	1	1
45-75	45	1	1-0.6
80	46	0.98	0.56
90	49	0.92	0.5
100	52	0.87	0.45
150	64	0.70	0.30
200	73	0.62	0.23
250	82	0.55	0.18
300	90	0.50	0.15

Note: *The attenuation factors have been normalised to unity at R=45km.

Table 1b. Effective & actual distances (km) for MCE=7.0.

	T_{RP}=500 years	T_{RP}=1000 years	T_{RP}=2500 years
Effective Distance (R_{eff})	45	45	40
Actual Distance (R)	85	60	40

Reference [1]) have therefore been revised in accordance with an assumed MCE of M=7.0 and an Effective Distance of 45km (see Table 2). Such an M-R Combination is defined here as the "Characteristic M-R Combination", which is independent of the usual seismicity parameters [1], defined as a (or a_s) and b, and is characteristic of the crustal structure of the region (for example, R_{eff}=1.5D).

The predicted Effective Peak Ground Displacement (EPGD) and Effective Peak Ground Velocity (EPGV) which take into account both the mid-crust amplification and the tri-linear attenuation effects have been listed in Tables 3a-3c and Tables 4a-4c, respectively. Note, the parameter values predicted for the characteristic M-R Combinations (shown in bold), tend to be critical regardless of the adopted Return Period.

Predictive models for PGD and PGV have been developed for different regions across China, including the subject region of CRSC, using the empirical procedure described in Reference [9]. The empirical PGD model may be described as follows:

$$log_{10} PGD\,(mm) = -2.2539 + 0.9801\,M - 1.9303\,log_{10} \left\{R + 0.3253\,e^{0.7055M}\right\} \quad (1)$$

Similarly, the two empirical PGV models, which have been developed from the same database but adopt slightly different forms, may be described as follows:

$$log_{10} PGV(cm/sec) = -1.7477 - 1.0503M - 2.1549 log_{10} \left\{R + 0.3314\,e^{0.7043M}\right\} \quad (2a)$$

$$log_{10} PGV\,(cm/sec) = -4.5949 + 2.0381\,M - 0.0868\,M^2 - 2.1207\,log_{10}\left\{R + 0.3253\,e^{0.7055M}\right\} \quad (2b)$$

Predictions of the EPGD and EPGV from seismological modelling (see Tables 3-4) and from the empirical procedure Eqs. (1, 2) have been compared in Table 5, for

Table 2. Revised critical M-R combinations.

		Moment Magnitude M		
R_{eff}	R	T_{RP}=500 years	T_{RP}=1000 years	T_{RP}=2500 years
10	10	4.6	5.0	5.4
20	20	5.3	5.6	6.1
30	30	5.7	6.1	6.7
40	40			7.0 (MCE)
45 (1.5D)	60		7.0 (MCE)	
45 (1.5D)	85	7.0 (MCE)		

Table 3a-3c. Modified effective peak ground displacement (EPGD) predictions.

(a) 500 years return period

R(km)	R_{eff}(km)	M	EPGD (mm)
10	10	4.6	negligible
20	20	5.3	7
30	30	5.7	10
50	45 (1.5D)	6.3	20
85	45 (1.5D)	7.0 (MCE)	50

(b) 1000 years return period

R(km)	R_{eff}(km)	M	EPGD (mm)
10	10	5.0	11
20	20	5.6	12
30	30	6.1	22
50	45 (1.5D)	6.8	40
60	45 (1.5D)	7.0 (MCE)	50

(c) 2500 years return period

R(km)	R_{eff}(km)	M	EPGD (mm)
10	10	5.4	16
20	20	6.1	33
30	30	6.7	53
40	40	7.0 (MCE)	56
45	*45 (1.5D)*	*7.0 (MCE)*	*50*

Note: M-R combinations in *italics* are clearly not critical and have only been shown for completeness.

Table 4a-4c. Modified effective peak ground velocity (EPGV) predictions

(a) 500 years return period

R(km)	R_{eff}(km)	M	EPGV(mm/sec)
10	10	4.6	negligible
20	20	5.3	42
30	30	5.7	45
50	*45 (1.5D)*	*6.3*	*60*
85	45 (1.5D)	7.0 (MCE)	113

(b) 1000 years return period

R(km)	R_{eff}(km)	M	EPGV(mm/sec)
10	10	5.0	68
20	20	5.6	59
30	30	6.1	73
50	*45 (1.5D)*	*6.8*	*96*
60	45 (1.5D)	7.0 (MCE)	113

(c) 2500 years return period

R(km)	R_{eff}(km)	M	EPGV(mm/sec)
10	10	5.4	92
20	20	6.1	109
30	30	6.7	132
40	40	7.0 (MCE)	127
45	*45 (1.5D)*	*7.0 (MCE)*	*113*

Note: M-R combinations in *italics* are clearly not critical and have only been shown for completeness.

Table 5. Comparison of EPGD & EPGV developed from seismological modelling with PGD & PGV developed from the empirical modelling (T_{RP}=1000 years).

M-R Combinations T_{RP}=1000 years (Table 2)		Displacement Predictions		Velocity Predictions		
M	R	EPGD Seismological Model [Table 3a]	PGD Empirical Model [Eq. (1)]	EPGV Seismological Model [Table 3b]	PGV Empirical Model (I) [Eq. (2a)]	PGV Empirical Model (II) [Eq. (2b)]
5	10	10	12	69	44	41
5.6	20	12	16#	60	56#	59#
6.1	30	22	24#	73	83#	85#
7.0	45	50	68	113	242	184
7.0	60	50*	50	113*	174	133

* The tri-linear attenuation relationship infers equal ground motion parameters at 45km and 60km distances.
\# The empirical model is most reliable in the magnitude range of M=5.5-6.5 which represents 80% of the earthquake events constituting the database [9].

M-R Combinations associated with a Return Period of 1000 years.

It is shown in Table 5 that both the displacement and velocity parameters predicted from the two different modelling approaches are in good agreement over the range where the empirical model is most reliable (see footnote to Table 5). However, the extrapolative predictions of the empirical model deviate significantly from those of the seismological model. Note, the two sets of empirical predictions of the PGV from the same database are highly model dependent at large magnitudes (compare Column 6 with Column 7 in Table 5).

3.2. Crustal Modifications to the Acceleration Parameter

The high frequency properties of the seismic shear waves are very sensitive to anelastic attenuation. In the generic "Hard Rock" crustal model, anelastic attenuation is moderate and is uniformly distributed along the wave travel path. For such crustal conditions, the derived A/V ratios from seismological simulations [10] have been evaluated in Reference [1], Eq. (13) and Table 8. It is noted that the ratio A/V is a function of the anelastic attenuation rather than the geometrical attenuation, and hence the ratio has been correlated [1] with R, as opposed to R_{eff}.

The derived A/V ratios defined in Reference [1] and listed in Table 8 of that paper, have been recombined herein with the EPGV listed in Tables 4a-4c to determine the EPGA in Tables 6a-6c, for earthquakes having different Return Periods (RP's). As previously observed [1], the critical EPGA results tend to be associated with small magnitude events in the near field, which is in contrast to the critical EPGD which is clearly associated with the MCE occurring in the far field.

Two empirical PGA models [9], which have been developed in parallel with Eqs. (1, 2), may be described as follows:

$$log_{10} PGA(cm/\sec^2) = 0.5750 + 0.8927 M - 2.2552 \, log_{10}\left\{R + 0.3618\, e^{0.6989M}\right\} \quad (3a)$$

$$log_{10} PGA(cm/\sec^2) = -1.2629 + 1.4956 M - 0.0513 M^2 - 2.2252\, log_{10}\left\{R + 0.3618\, e^{0.6989M}\right\} \quad (3b)$$

Clearly, there are large discrepancies in the predicted peak ground accelerations between the seismological model predictions (Tables 6a-6c) and the empirical model predictions (Table 7), and this is despite good agreement in the velocity predictions, as shown previously in Table 5. The A/V ratios implied by the empirical model are very low, which contradicts the assumed "Hard Rock" conditions identified with the subject area (see Section 2). Further, the insensitivity of the A/V ratio (in the empirical model) to the site-source distance contradicts results obtained from seismological model simulations [10] and is also contrary to intuitive expectations. The limitations of the described empirical modelling approach have been discussed below, in Section 6.1.

Table 6a-6c: Modified effective peak ground acceleration (EPGA) predictions using the seismological model.

(a) 500 years return period

R(km)	R_{eff}(km)	M	EPGA (g's)
10	10	4.6	--
20	20	5.3	0.30
30	30	5.7	0.29
50	45 (1.5D)	6.3	0.30
85	45 (1.5D)	7.0 (MCE)	0.31

(b) 1000 years return period

R(km)	R_{eff}(km)	M	EPGA (g's)
10	10	5.0	0.54
20	20	5.6	0.41
30	30	6.1	0.43
50	45 (1.5D)	6.8	0.40
60	45 (1.5D)	7.0 (MCE)	0.42

(c) 2500 years return period

R(km)	R_{eff}(km)	M	EPGA (g's)
10	10	5.4	0.69
20	20	6.1	0.68
30	30	6.7	0.68
40	40	7.0 (MCE)	0.56
45	45 (1.5D)	7.0 (MCE)	0.48

4. RESPONSE SPECTRUM MODELLING (STAGE FOUR)

Having evaluated the spectral parameters EPGD, EPGV and A/V in accordance with the specific seismicity and crustal conditions of the subject region (in Stages Two and Three, respectively), response spectra are next developed in Stage Four to define the seismic hazard for engineering applications. A simplified procedure for response spectrum modelling has been described and illustrated in the first part of the paper [1].

Based on the developed design response spectrum modelling procedure, full (revised) sets of values of EPGD, EPGV, T_2, A/V, T_1 and RSA_{peak} obtained for Return Periods (T_{RP}) of 500, 1000 and 2500 years has been given in Tables 8a-8c. The modifications resulting from the adoption of a regional, as opposed to generic crustal model for the CRSC, are apparent by comparing the results given in Tables 8a-8c with those presented in the first part of the paper [1], Tables 10a-10c.

The parameter values associated with the Charac-

Table 7. EPGA & A/V ratios derived from the empirical models for M-R combinations associated with T_{RP}=1000 years.

		Model I [9] (Eqs. 2a, 3a)			Model II [9] (Eqs. 2b, 3b)		
M	R	PGV (mm/sec)	PGA (g's)	A/V [g/(m/sec)]	PGV (mm/sec)	PGA (g's)	A/V [g/(m/sec)]
5	10	44	0.11	2.4	41	0.09	2.2
5.6	20	56	0.10	1.8	59	0.10	1.7
6.1	30	83	0.12	1.5	85	0.12	1.4
7.0	40	174	0.18	1.0	208	0.24	1.1
7.0	60	274	0.28	1.0	133	0.15	1.1
7.0	85	110	0.11	1.0	85	0.09	1.1

Table 8a. Response spectrum parameters for 500 years return period.

M	R_{eff} (R) km	EPGD mm	EPGV mm/sec	T_2 secs	A/V g/(m/sec)	T_1 secs	RSA_{peak} g's
4.6	10(10)						
5.3	20(20)	7	42	0.52	7.2	0.10(.06)	0.53
5.7	30(30)	10	45	0.70	6.4	0.10(.07)	0.58
7.0*	**45*(85)**	**50**	**113**	**1.39**	**2.8**	**0.15**	**0.97**

Table 8b. Response spectrum parameters for 1000 years return period.

M	R_{eff} (R) km	EPGD mm	EPGV mm/sec	T_2 secs	A/V g/(m/sec)	T_1 secs	RSA_{peak} g's
5.0	10(10)	11	68	0.50	7.9	0.10(.05)	0.87
5.6	20(20)	12	59	0.65	6.8	0.10(.06)	0.76
6.1	30(30)	22	73	0.94	5.9	0.10(.07)	0.93
7.0*	**45*(60)**	**50**	**113**	**1.39**	**3.7**	**0.12**	**1.21**

Table 8c. Response spectrum parameters for 2500 years return period.

M	R_{eff} (R) km	EPGD mm	EPGV mm/sec	T_2 secs	A/V g/(m/sec)	T_1 secs	RSA_{peak} g's
5.4	10(10)	16	92	0.55	7.4	0.10(.06)	1.19
6.1	20(20)	33	109	0.94	6.2	0.10(.07)	1.40
6.7	**30(30)**	53	**132**	**1.25**	**5.2**	**0.10(.08)**	**1.69**
7.0	**40(40)**	**56**	127	1.39	4.4	0.10	1.63
7.0*	45*(45)	50	113	1.39	4.3	0.10	1.45

Notes:
(i) * Characteristic M-R combination: M=MCE and R_{eff}=1.5D
(ii) Certain M-R combinations enlisted in Tables 3, 4, and 6 which are clearly non-critical have not been shown.
(iii) M-R combinations critical for design have been shown in bold.

teristic M-R Combination tend to be critical for design return periods of 500 and 1000 years. This is clearly reflected in the "Characteristic" Displacement and Acceleration Response Spectra Shown in Figures 3a and 3b, along with Figures 4a and 4b, respectively. For a design return period of 2500 years (Figures 3c and 4c), the Characteristic Displacement and Acceleration response spectra are only marginally exceeded. The characteristic displacement response spectrum (dark solid curve in Figures 3a-3c) has a maximum EPGD of 50mm, a maximum EPGV of about 110mm/sec and a corner period, T_2, of approximately 1.4 seconds. This response spectrum provides by far the governing criteria amongst the M-R combinations derived for the 500 and 1000 year return periods (Tables 8a and 8b). However, other M-R combinations give comparable demands for Return Periods approaching 2500 years.

In theory, small magnitude events give very high RSA_{peak} values. However, the arbitrarily defined minimum corner period (T_1) of 0.1 seconds has significantly capped its value for those M-R combinations associated with small magnitude events. Consequently, the RSA_{peak} values of the characteristic spectra also tend to be critical.

Interestingly, the above results contradict the intuitive expectations that high frequency responses are always dominated by small magnitude "bull-eye" events occurring very close to the site. The results imply that,

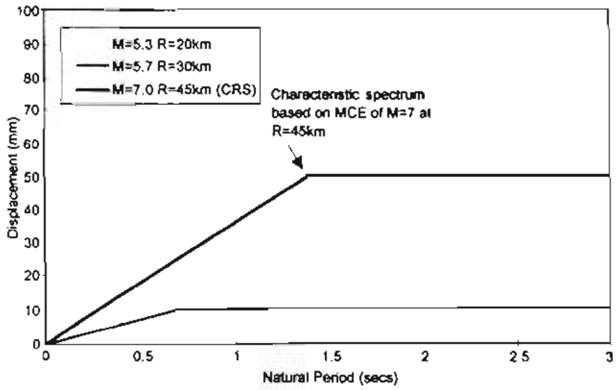

Figure 3a. Displacement response spectra for 500 years return period.

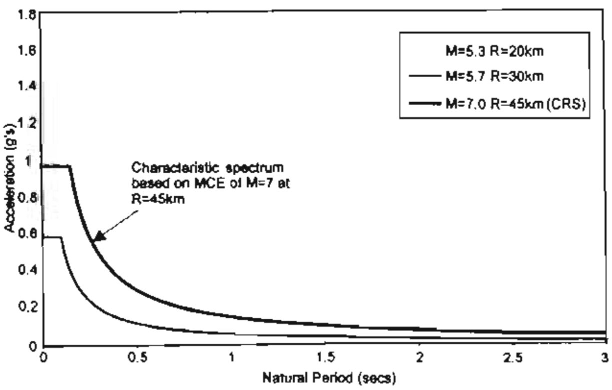

Figure 4a. Acceleration response spectra for 500 years return period.

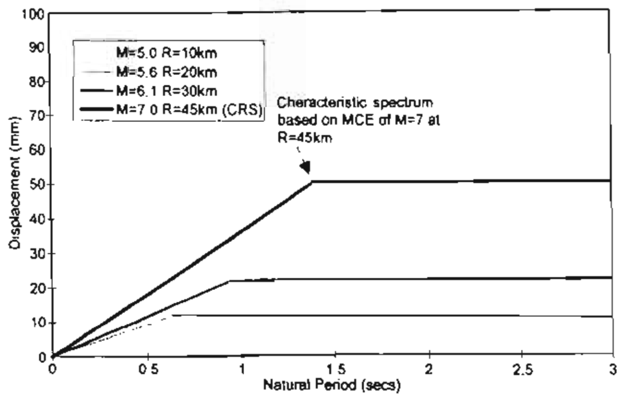

Figure 3b. Displacement response spectra for 1000 years return period.

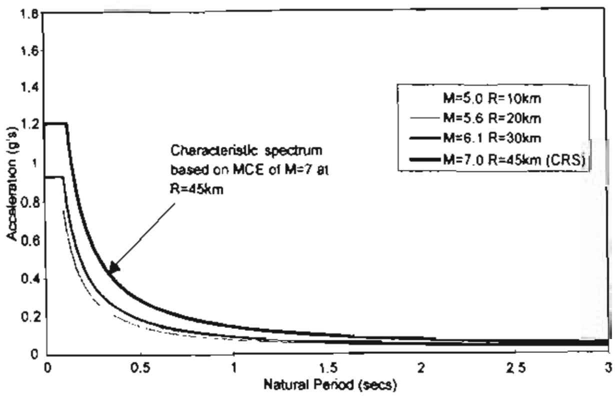

Figure 4b. Acceleration response spectra for 1000 years return period.

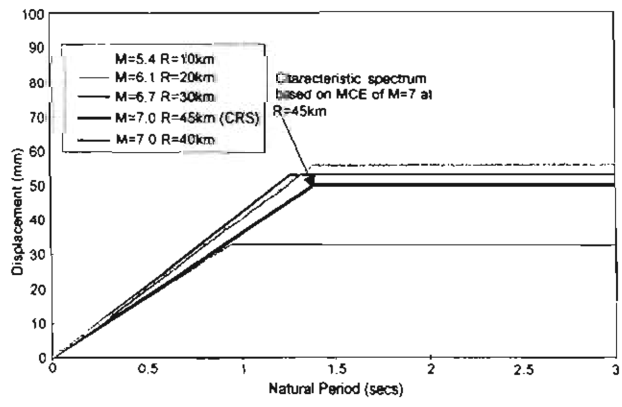

Figure 3c. Displacement response spectra for 2500 year return.

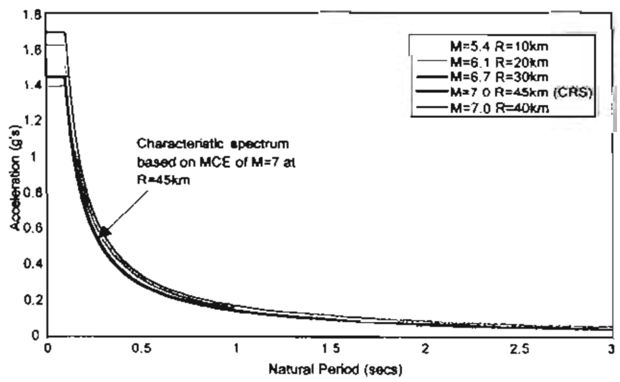

Figure 4c. Acceleration response spectra for 2500 years return period.

with regard to predicting the highest intensity ground shaking such as peak acceleration, there is by far a higher probability of this arising due to a Magnitude 7.0 (=MCE) earthquake event occurring within 90km from the site (within the zero attenuation zone as shown in Table 1a) than from an event of magnitude 5.4 occurring within 10km distance from the site. Moreover, the displacement demand of the Magnitude 5.4 event is considerably smaller than that produced by the Magnitude 7.0 event.

5. COMPARISONS WITH SCOTT RECOMMENDATIONS AND CHINESE EARTHQUAKE DESIGN CODE

The Scott et al design response spectrum model for the Hong Kong region [11], which has been compared initially with the response spectrum predictions based on the Generic Crustal Model in the first part of the paper [1], has further been compared in Figures 5a and 5b of this paper with the revised predictions of the response spectrum based on the regional crustal model. Clearly, the Scott's response spectrum model is generally unconservative as it has not taken into account the mid-crust amplification and tri-linear attenuation, both of which have been identified for the CRSC (see Section 2).

The Chinese Code provisions for the CRSC [12], which have also been reviewed in the first part of the paper [1], have been compared in Figures 6a and 6b with the Characteristic Response Spectra (CRS) associated with a MCE of Magnitude 7.0, as derived from this study. Such CRS have been found to be generally representative of the critical conditions for Return Periods ranging between 500 years and 2500 years (Figures 3a-3c and 4a-4c). It is noted in the first part of the that the CRS are very consistent with the current code provisions for the South China region in the velocity-controlled period range (0.3 - 1.5 seconds).

In contrast, the code provisions are clearly unconservative in the short period range, as evidenced by the acceleration response spectra (Figure 6b). However, high peak response spectral accelerations in the very short period range do not normally result in significant damages to normal structures since the associated displacements (hence deformation) are generally very small. Note that the dashed line in Figure 6b, for the long period range, corresponds to the tri-linear compatible velocity spectrum as shown in Figure 5b in Reference [1]; the solid graph corresponds to the hyperbolic acceleration spectrum extrapolated into the long period range ($T > T_2$), as in Figure 5c of Reference [1]. It is also noticeable that the Chinese code spectra are overly conservative in the long period range (Figure 6a), especially due to the minimum level of design spectral acceleration of 0.1g (20% of the peak spectral acceleration) imposed in the long period

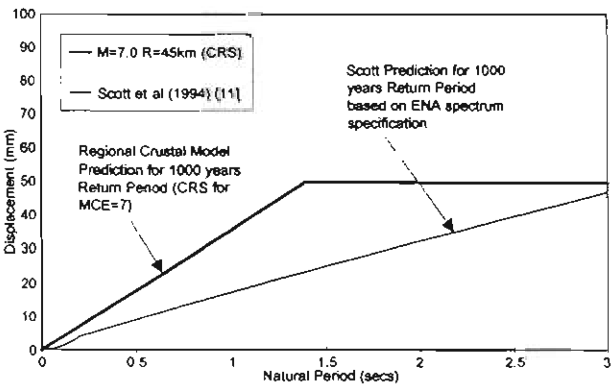

Figure 5a. Comparison of displacement response spectra for 1000 years return period.

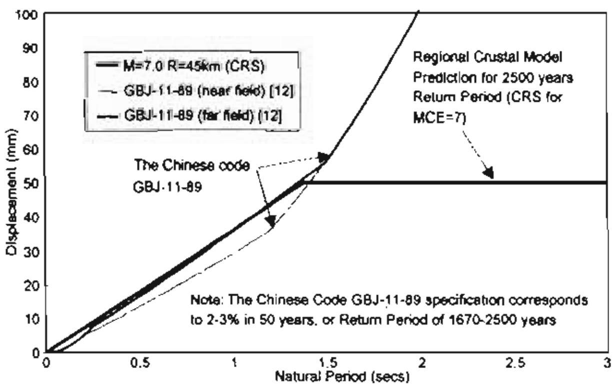

Figure 6a. Comparison of the displacement response spectra for 2500 years return period.

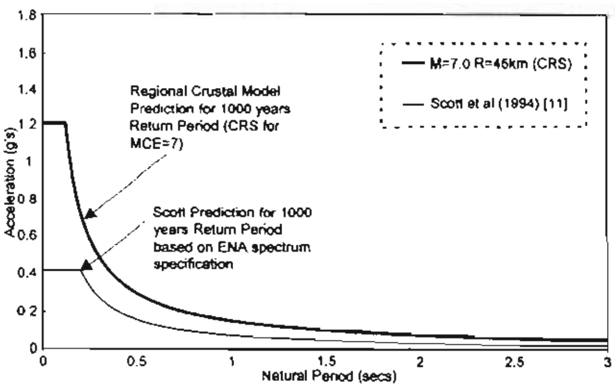

Figure 5b. Comparison of acceleration response spectra for 1000 years return period.

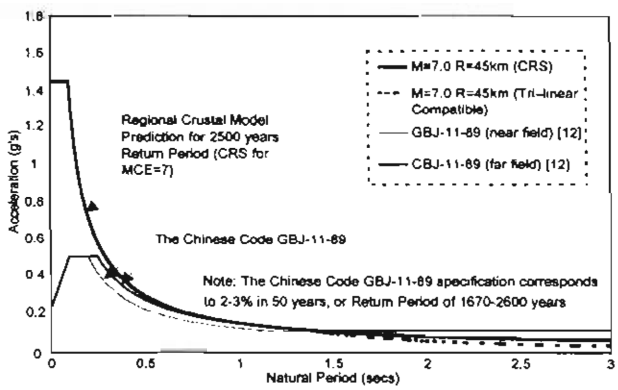

Figure 6b. Comparison of the acceleration response spectra for 2500 years return period.

range (approximately for $T > 1.5$ seconds), as shown in Figure 6b.

6. DISCUSSION

The seismological modelling and the comparative analyses described in this and the first part of the paper [1] have identified the following issues which require further discussion:

(i) The Empirical Modelling Approach adopted in China
(ii) Determination of the MCE Magnitude.

6.1. The Empirical Modelling Approach Adopted in China

The earthquake affected area of China is wide and diffused. Predicting the locations of future earthquakes in the low to moderate seismicity regions of South China are particularly difficult as earthquakes occur infrequently and apparently randomly. Consequently, it has not been viable to deploy instrumentation which is capable of collecting sufficient strong motion data for a direct study of the attenuation of the key ground motion parameters: PGA, PGV and PGD along with response spectral accelerations. However, China possesses substantial valuable seismic Intensity information which has been obtained in accordance with broad-based observations and reconnaissance of damage following many of the major historical earthquake events which have occurred during its very long recorded history.

It is strictly speaking not feasible to incorporate Intensity information into ground motion modelling, since Intensity is not directly derived from ground motion measurements. However, Intensity records have been the only major source of information in China (and especially South China) concerned with the study of seismicity. In view of the urgent need in China to predict seismic hazard for engineering applications, ground motion attenuation relationships have been developed from Intensity attenuation relationships using various techniques [9, 13]. One recently proposed technique [9] may be summarised by the following sequence of steps:

1. Consider a reference region such as California, where there are sufficient strong motion data from which to develop reliable ground motion attenuation relationships.
2. These ground motion attenuation relationships may typically be expressed in the following form:

$$log\ Y_R = b_1 + b_2 M + b_3 M^2 + b_4 log\left\{R + R_{oy}(M)\right\} + \varepsilon_{yR} \quad (4)$$

where
Y_R is the ground motion parameter being modelled in the reference region,
M is the earthquake magnitude,
R is the site-source distance,
$R_{oy}(M)$ is the magnitude dependent additional distance to account for the effect of saturation in near field large magnitude events, and
ε_{yR} is the term to account for the deviation from the averages.

3. The Intensity attenuation relationships in the same reference region may similarly be expressed in the form

$$I_R = c_1 + c_2 M + c_4 log\left\{R + R_{oI}(M)\right\} + \varepsilon_{IR} \quad (5)$$

4. Combining Eq. (4) with Eq. (5) produces a ground motion attenuation function (fn_R) which is expressed in terms of the Intensity (I_R) and the site-source distance (R)

$$Y_R = fn_R(I_R, R) + \varepsilon_{yR} \quad (6)$$

It is assumed in Eq. (6) that the magnitude (M) necessary to determine Y_R is implied by a given Intensity (I_R) and site-source distance (R).

5. Consider the subject region and identify the Intensity attenuation relationship from the historical record, which may be expressed in the form

$$I_s = d_1 + d_2 M + d_4 log\left\{R + R_{oy}(M)\right\} + \varepsilon_{IS} \quad (7)$$

6. Substituting the right-hand side of Eq. (7) into the variable, I_R, in Eq. (6) produces the ground motion attenuation function (fn_s) for the subject region

$$Y_s = fn_s(M, R) + \varepsilon_{ys} \quad (8)$$

The major assumption made in the above method is that the relationship between the ground motion parameter (Y_R), the Intensity (I_R) and the distance (R) as defined by Eq. (6) in step 4 is applicable to both the subject region and the reference region. This assumption is critically reviewed in the following, with reference to existing knowledge on Intensity and the seismological model.

The determination of Intensity is typically based upon the following criteria:

(i) Extent of human awareness of the earthquake which is linked with the acceleration (at low intensity),
(ii) Damage to building components and contents, which are linked to the developed maximum kinetic energy and the peak ground velocity (at medium intensity),
(iii) Incidences of severe damage and collapse of buildings and infrastructure, which are linked with stability and hence peak ground displacement (at high intensity).

Thus, the correlation of Intensity with ground motion parameters varies with the intensity level. At the intensity level of engineering interest, velocity and displacement parameters appear to be more important than acceleration parameters.

The peak ground velocity (PGV), in particular, has been traditionally correlated with Intensity. For example, based on California data, the Modified Mercalli Intensity (MMI) has been correlated with PGV (in mm/sec) using the following expression [14]:

$$2^{MMI} = 7PGV / 5 \quad (9a)$$

For China, the seismic intensity scale [15] also indicates a logarithmic relationship between intensity and PGV. The equation defining the Chinese intensity scale may correspondingly be written

$$2^{MMI} = 19PGV/20 \tag{9b}$$

For the subject region of CRSC, the Chinese earthquake code [12] has assigned an intensity level of VII (seven). Hence, based on Eq. (9b), this indicates a PGV in the order of 134mm/sec. It is noted that no account is taken in the above equations of site soil conditions, although stiff soil or bedrock may generally be assumed. The codified PGV of 134mm/sec agrees closely with the predictions of the seismological model (see Table 4c), for very long return periods (T_{RP}=2500 years). Alternatively it may be related to the 1000 year event, with predicted PGV=113 mm/sec (see Table 4b), allowing for a site factor of about 1.2.

Further, PGV has been shown to dictate the spectral response levels (in terms of acceleration, velocity and displacement) over the period range of general engineering interest excluding long-period structures (around 0.2 - 2 seconds). Thus, the close association between the Intensity and the PGV is well established.

In contrast, the apparent correlation of PGA with the Intensity is indirect and is mainly a manifestation of the correlation between the PGA and the PGV. The (PGA/PGV) or A/V ratio is dependent on distance since the acceleration-associated (high frequency) components of the ground motions are attenuated more rapidly than the velocity associated components. Thus, the Intensity alone cannot define the PGA without specifying the distance (R) at the same time (see Eq. (6)).

Significantly, this A/V ratio is dependent not only on distance and moment magnitude M (see Reference [1]) but also, importantly, on the regional crustal properties as evaluated in this paper for the CRSC study region. For example, as discussed earlier, the generally younger and softer earth crusts in California result in a much higher anelastic attenuation rate than the much harder shield regions of Eastern North America (ENA). Consequently, A/V rations derived from accelerograms recorded in California would not be representative of the conditions in ENA and in regions covered by relatively hard crystalline metamorphic or volcanic rock such as the Coastal Region of South China.

The apparent correlation between the Intensity and the Peak Ground Displacement (PGD), which is associated with the very long period components of the ground motion is also indirect. It has been shown by the seismological model simulations that the V/D (PGV/PGD) ratio is highly dependent on the Moment Magnitude. For example, a near field small magnitude earthquake (M=5, R=10km say) and a far field large magnitude earthquake (M=7, R=70km say) can result in similar PGVs and yet the far field combination generates a much larger PGD. Thus, the Intensity alone cannot define the PGD without specifying the moment magnitude (M) at the same time. However, M is implied by R combined with the Intensity. Thus, the PGD can indeed be predicted by relationships of the form defined by Eq. (6). Interestingly, the V/D ratio (see Table 7 of Reference [1]) is very much less dependent on the regional crustal properties than the A/V ratio.

In conclusion, the methodology used to transform Intensity relationships to ground motion attenuation relationships as described above will generally give reliable predictions of the PGV and PGD. However, the accuracy of the PGA predictions depend on the accurate modelling of the crustal conditions of the subject region. Such high frequency parameters can only be reliably predicted by

(i) Empirical analyses of locally recorded strong motion accelerograms or
(ii) Seismological model simulations based on representative anelastic attenuation parameters [1].

The latter are normally predicted by seismological monitoring of microtremors or aftershocks, on ground surface or in boreholes, in regions of low to moderate seismicity.

In the absence of the above information, one must resort to using the generic "Hard Rock" crustal model [1], with peak ground motions modified appropriately to account for regional crustal amplification effects as herein, to obtain a conservative (upper bound) prediction of the EPGA, and RSA_{peak}. The very high spectral accelerations predicted by the generic "Hard Rock" model are associated with the excellent wave transmission quality of the earth's crust which characteristics the shield regions of ENA. Although such excellent rock quality has not been confirmed in this study in relation to the CRSC, it is prudent to assume it is so in view of the lack of evidence to suggest otherwise.

6.2. Determination of the MCE Magnitude

The dominance of the Characteristic M-R Combination and the associated response spectra is a significant finding of this study. Thus, an initial probabilistic seismic hazard analysis (based on the various magnitude recurrence models described in Section 2 of the first part of the paper [1]) has been reduced to a deterministic analysis based on the MCE, the regional thickness of the earth's crust and the regional crustal properties. This has very interesting implications for the future development of seismic hazard evaluation in low and moderate seismicity regions.

In fact, the conventional probabilistic procedure for calculating the recurrence intervals for earthquakes of a given magnitude may not be totally appropriate in moderate or low seismicity regions, due to the highly extrapolative nature of the process for design-level events with long return periods. Reference [1] indicates that some significant differences exist between the various magnitude recurrence models referred to above, when their results are extrapolated to events with magnitudes above M6.0, which are relatively rate in the subject region of CRSC. Ultimately, the source models employed in this study require the use of an MCE constraint, taken above to be a Magnitude 7.0 earthquake for the CRSC. The combined uncertainties in the extrapolation of magnitude-recurrence models and the designation of the MCE magnitude present considerable challenges for moderate seismicity regions.

The regional crustal structure can 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. It has so far been assumed in the analyses presented in this paper that the MCE corresponds to a Magnitude 7.0 earthquake. If the assumed MCE level were to be increased to Magnitude 7.5, the corresponding response spectra would assume significantly higher levels, as shown in Figures 7a and 7b.

Methodologies currently adopted in the determination of the MCE may be summarised as follows [16]:

(i) Geological and Paleoseismic evidence based on measurements of fault lengths and pre-historical fault slip (using carbon-dating techniques or geomorphology).
(ii) Review of historical and pre-historical records in the region.
(iii) Studying the seismogenic properties of the earth's crust.

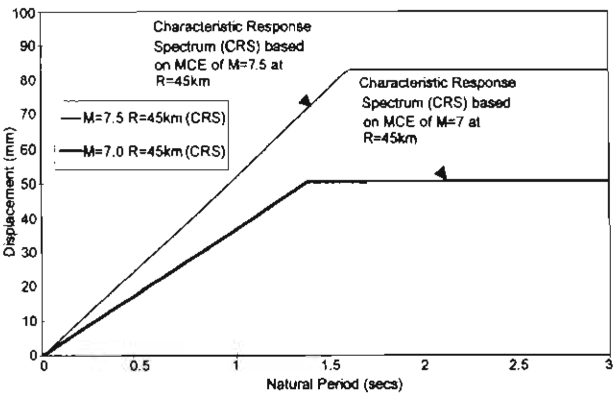

Figure 7a. Characteristic displacement response spectra.

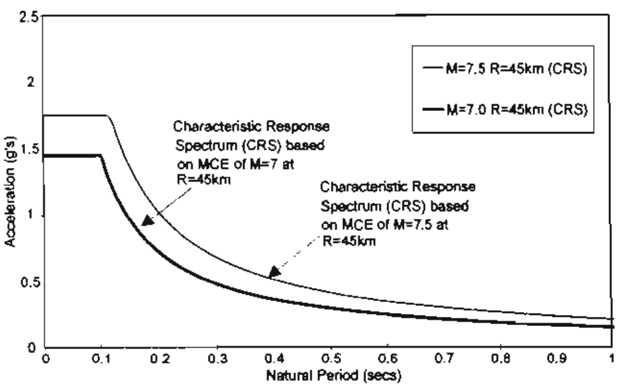

Figure 7b. Characteristic acceleration response spectra.

Method (i) is usually problematic when applying to broad geographical regions with diffuse seismicity such as South China and Australia, since many potential causative faults are still unknown. Moreover, many intraplate earthquakes occur on blind thrust faults with no surface ruptures. Further, pre-historical surface ruptures are often buried by sedimentation during the long intervals between consecutive ruptures on the same fault.

On the other hand, regions such as South China which cover a very large surface area and with a long recorded history can possess large volumes of historical and pre-historical data, and this at least partially compensates for some of the difficulties associated with the infrequent and seemingly random earthquake occurrences in a moderate seismicity region. A traditional rule-of-thumb to determine the MCE is to add one-half unit to the recorded maximum magnitude. However, this additive method can result in a unconservative estimate or an overly conservative estimate, depending on the size of the database and whether the distribution of seismicity within the region is truly "uniform" as assumed. For example, it is questionable whether the size of a major recorded event which occurred at some 300-400km away from the coastline in the South China sea should be taken as indicative of the MCE of the coastal cities. Thus, there is always a significant element of doubt in determining the MCE, which indicates that the most promising approach may be to explore further the third method, namely studying the seismogenic properties of the earth's crust. The latter method, which is still under investigation, involves identifying the subject region with other analogous regions having similar crustal structures, in order to predict the MCE magnitude in more reliable fashion.

It may also be commented that, in the derivation of design response spectra for the CRSC, a notable feature has been the dominance of the CRS for predicting the peak ground motions at all return periods. The insensitivity of the design response spectrum to the selected return period is an unusual result, given that this is usually matter of some debate amongst designers and code-drafting authorities. This peculiarity has arisen for the CRSC due to the interaction between seismicity parameters (which display rather low b-values for earthquake source areas containing the larger magnitude events [1]), the tri-linear attenuation relationships and the crustal thickness property, whereby the *effective* M-R parameters of the CRS become almost identical over the range of return periods of interest (500-2,500 years).

6.3. General

In view of the findings from this study and the first part of the paper [1], together with the above discussions, it may be stated that increased research effort is required in:

(i) Studying the crustal properties of the considered region (CRSC), in particular with regard to upper crust wave modification mechanisms which dictate the short period response spectral properties, and

(ii) Studying the regional seismogenic properties of the earth's crust, which dictate the MCE magnitude and consequently affect significantly the crucial medium and long period response spectra properties.

Interestingly, the above recommended targeted information are associated with "static' properties (which are feasible to obtain without necessarily having to capture information from a major local earthquake event) rather than on "dynamic" properties which are associated with fault movements and earthquake ruptures.

7. CONCLUSION

- ❖ A procedure to determine the seismic hazard of the Coastal Region of South China, based on the assumption of uniform seismicity, has been introduced within the framework of a seismological model. The procedure has been developed from that described in the first part of the paper [1], in four major stages.
- ❖ The source models to be developed in Stage One were already available, and hence no additional analyses was involved.
- ❖ In Stage Two, the regional crustal structure was identified to be generally consistent with the generic "Hard Rock" model, based on matching the shear wave velocity profiles. Results from surface wave dispersion analyses and geological description of the region have been used to assist in the crustal classification. The significance of the mid-crust amplification and the tri-linear geometrical attenuation have also been addressed.
- ❖ In Stage Three, spectral parameters such as EPGD, EPGV, A/V and EPGA have been predicted for return periods ranging between 500 years to 2500 years, taking into account all the enlisted effects. Comparison of these predictions with existing empirical relationships showed reasonable agreement within a particular magnitude range corresponding to the majority of the available data.
- ❖ In Stage Four, the displacement, velocity and acceleration response spectra were derived in accordance with the predicted ground motion parameters and allowing for regional mid-crust amplification effects. Response spectra associated with the characteristic M-R Combinations (based on the assumed MCE Magnitude of 7.0 and a distance of 1.5 times the crustal thickness) have been found to be critical, particularly when considering a return period of 500 - 1000 years. Thus, the significance of the assumed MCE magnitude has been highlighted.
- ❖ Predictions by the seismological model based on the characteristic M-R combination show unconservatism of the Scott response spectrum model, but were very consistent with current Chinese code provisions in the velocity controlled period range. However, significant discrepancies have been identified in other period ranges.
- ❖ An existing empirical modelling methodology for China has been critically reviewed and the limitations discussed. Meanwhile, it is recommended to target future research efforts at:

(i) Studying the crustal properties of the region in particular regard to mid- and upper crust wave modification mechanisms, and

(ii) Studying the regional seismogenic properties of the earth's crust, which determine the MCE magnitude.

ACKNOWLEDGMENTS

The procedure described in this paper has been developed as part of a project funded by the Australian Research Council (large grant), entitled: "Earthquake Design Parameters and Design Methods for Australian Conditions" (AB89701689). This support is gratefully acknowledged. The provision of valuable seismological and geological information by Professor C.F. Lee and Dr. L.S. Chan of The University of Hong Kong is also gratefully acknowledged.

REFERENCES

1. Lam N.T.K., Chandler, A.M., Wilson J.L., and Hutchinson, G.L. (1999). "Seismic Hazard Determination for the Coastal Region of South China I: Generic Crustal Modelling", *International Journal of Seismology and Earthquake Engineering*, **2**(1), 1-17.

2. Doyle, H. (1995). "Seismology", J. Wiley and Sons Ltd., Chichester, U.K.

3. Feng, R., Zhu, J., Ding, Y., Chen, G., He, Z., Yang, S., Zhou, H., and Sun, K. (1981). "Crustal Structure in China from Surface Waves", *ACTA Seismological Society*, **3**(4), 336-350.

4. Boore, D.M. and Joyner, W.B. (1997). "Site Amplifications for Generic Rock Sites", *Bulletin of the Semiological Society of America*, **87**(2), 327-341.

5. Bureau of Geology and Mineral Resources of Guangdong Province (1982). "Regional Geology of Guangdong Province", Geological Publishing House, Beijing, Series 1, No. 9.

6. Lam, N.T.K., Wilson, J.L., and Hutchinson, G.L. (2000). "Generation of Synthetic Earthquake Accelerograms Based on the Seismological Model : A Review", *Journal of Earthquake Engineering (paper accepted)*.

7. Atkinson, G.M. and Boore, D.M. (1998). "Evaluation Models for Earthquake Source Spectra in Eastern North America", *Bulletin of the Seismological Society of America*, **88**(4), 917-934.

8. Atkinson, G.M. and Boore, D.M. (1995). "Ground-Motion Relations for Eastern North America", *Bulletin of the Seismological Society of America*, **85**(1), 17-30.

9. Huo, J., Hu, Y., and Feng, Q. (1992). "Study on Estimation of Ground Motion from Seismic Intensity", *Earthquake Engineering and Engineering Vibration*, **12**(3), 1-15.

10. Lam, N.T.K., Wilson, J.L., Chandler, A.M., and Hutchinson, G.L. (1999). "Response Spectrum Modelling in Low and Moderate Seismicity Regions Combining Velocity, Displacement and Acceleration Predictions", *Earthquake Engineering and Structural Dynamics (under review)*.

11. Scott, D.M., Pappin, J.W, and Kwok, M.K.Y. (1994). "Seismic Design of Buildings in Hong Kong", *Transactions of the Hong Kong Institution of Engineers*, **1**(2), 37-50.

12. Ministry of Construction of the People's Republic of China (1994). "Code for Seismic Design of Buildings", National Standard of the People's Republic of China GBJ 11-89.

13. Tian, Q., Liao, Z., and Sun, P. (1986). "Estimation of Ground Motion Attenuation in China Based on Intensity Data", *Earthquake Engineering and Engineering Vibration*, **6**(1), 21-36.

14. Newmark, N.M. and Rosenbluenth, E. (1971). "*Fundamentals of Earthquake Engineering*", Prentice Hall Inc., New Jersey, U.S.A.

15. Liu, H.X. (1980). "On the Chinese Seismic Intensity Scale", *Proceedings of the 7th World Conference on Earthquake Engineering*, **2**.

16. Yeats, R.S., Sieh, K., and Clarence, R.A. (1997). *"The Geology of Earthquakes"*, Oxford University Press, New York and Oxford.