Seismic Hazard Assessment and Site Response Evaluation in Hong Kong

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Abstract

This paper presents the results of a study to assess the seismic hazard and evaluate site response in Hong Kong. The hazard has been determined in terms of uniform hazard response spectra for probabilities of being exceeded of 50%, 10% and 2% in 50 years. The ground conditions in Hong Kong have been categorised using the IBC2006 site classification system. One-dimensional site response analyses have been used to determine how the various types of ground profiles are likely to amplify the expected levels of earthquake ground motion. The results are presented in terms of spectral ratios and uniform hazard response spectra for the different site classes and are compared with the IBC2006 and the China code of practice for buildings.

1 INTRODUCTION

Hong Kong is located in an area of low to moderate seismicity. The current codes of practice for building design in Hong Kong do not require any seismic considerations. However, the Chinese Code of Practice for seismic design of buildings, GB 50011 (2001), categorises Hong Kong as being in Zone VII+ with a 10% in 50 year peak ground acceleration of 15%g. The application of an international seismic code for the design of buildings in Hong Kong is a possibility but may not be directly applicable due to the difference in seismicity and geological conditions.

This paper presents a study to evaluate seismic hazards and site response for the geological conditions of Hong Kong and the results are compared with the IBC2006 and the China code of practice.

2 REGIONAL TECTONICS AND GEOLOGY OF HONG KONG

As shown in Fig. 1 Hong Kong is situated in southeast China near the south-eastern margin of the Eurasian Continental Plate in a stable continental intraplate region about 700 km from the nearest plate boundary, which underlies Taiwan and trends south to the Philippines.

The geology of Hong Kong is described in detail by Sewell et al. (2000) and Fyfe et al. (2000). More than three-quarters of the land area of Hong Kong is underlain by igneous rocks predominantly volcanic tuffs and granites of Late Jurassic to Early Cretaceous age (140 to 120Ma). Superficial deposits comprising Quaternary (less than 2Ma) alluvium and other unconsolidated deposits are also present throughout the territory. Large areas of reclamation have been formed around some of the coastal areas in the territory.

Fig. 1 Tectonic setting of Hong Kong

3 SEISMIC HAZARD ASSESSMENT

3.1 *Seismic Hazard Assessment Methodology*

The probabilistic seismic hazard assessment (PSHA) methodology, e.g. Cornell (1968), McGuire (1993), has been applied using Oasys SISMIC, the in-house PSHA program of Arup. The PSHA methodology used the following steps:

i. Potential seismic sources were defined on the basis of regional geology and seismicity.
ii. Seismicity parameters defining the rate of earthquake activity were derived for each of the potential seismic sources.
iii. Ground motion attenuation relationships, considered to be appropriate for the region, have been defined.
iv. The annual frequencies of various levels of specified ground motion levels being

exceeded have been derived by first determining the likelihood that each ground motion will be exceeded if an earthquake of a certain magnitude at a certain distance occurs. By multiplying this likelihood with the annual frequency of such an event occurring in any of the source zones, the annual frequency of the ground motion occurring is derived. By summing the results from all relevant earthquake distances and magnitudes the overall annual frequency is established.

3.2 *Seismic Source Zones and Parameters*

Hong Kong is located within a stable continental intraplate region and the association of earthquakes with defined faults is not clear and, as a result, the identification of seismic sources was based upon the spatial pattern of seismicity and the understanding of the regional geology. The derived source zone model is shown in Fig. 2. In order to determine the activity rates it is necessary to define the magnitude and time ranges over which the earthquake catalogue is complete. For the onshore and near-shore seismic source zones three completeness ranges have been defined (since 1500 for M≥7.0, since 1870 for M≥5.0 and since 1971 for M≥2.5). For the offshore seismic sources (Zones 5, 6 and 7) two completeness ranges have been defined (since 1920 for M≥5.5 and since 1971 for M≥4.5). The model extends out to a distance of 500km from Hong Kong. A more distant seismic source zone was also included for the highly seismic region of Taiwan.

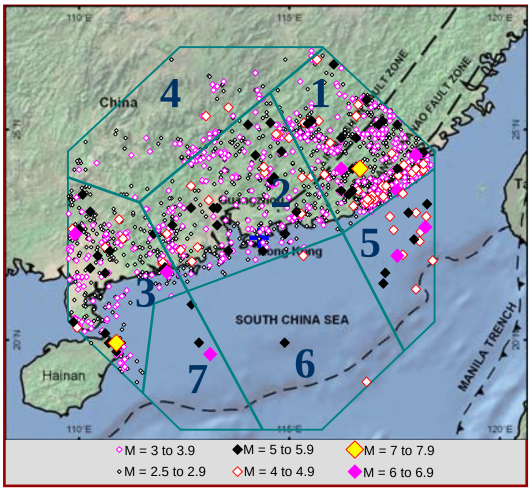

Fig. 2 Complete earthquake catalogue and Source zone model adopted for Hong Kong

The seismic activity rate in the Hong Kong region can be directly compared with that observed in other parts of the world and the results are shown in Fig. 3. It is seen that the seismic activity is similar to that observed in the Eastern North America and about 50 times less than that in highly seismic areas such as Japan, Taiwan or the Philippines.

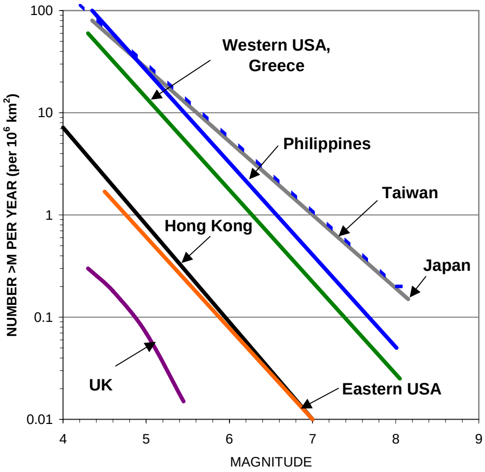

Fig. 3 Comparison of seismicity of the Hong Kong region with other regions (The Dept. of the Environment, UK, 1993)

Statistical analyses show that the return period for a large magnitude, M = 7 or greater event, within 100km of Hong Kong, is greater than 3,500 years. For a moderate size event, with magnitude M = 6 or greater, within 100km of Hong Kong, the return period reduces to between 400 to 800 years. For a smaller size event, with a magnitude M = 5 or greater, within 100km of Hong Kong, the return period is approximately 40 to 60 years. For a very small magnitude event, with M = 4 or greater, within 100km of Hong Kong, the return period is between 4.5 to 7 years.

3.3 *Attenuation Relationships*

Very few strong motion records have been recorded in the Southeast China region and consequently it is not possible to derive empirical attenuation equations for the region. Attenuation relationships for Southeast China for peak ground acceleration and response spectral values have been derived for this study based on stochastic simulations of a model developed by Lam et al. (2000a) and Lam et al. (2000b). The model is based upon the stochastic model of Boore (1983) and Atkinson and Boore (1995) and further details are given in Free et al. (2004).

3.4 *Seismic Hazard Assessment Results*

The calculated hazard levels, in terms of horizontal response spectral acceleration (for 5% damping) on rock, at three probabilities of being exceeded, are shown in Fig. 4.

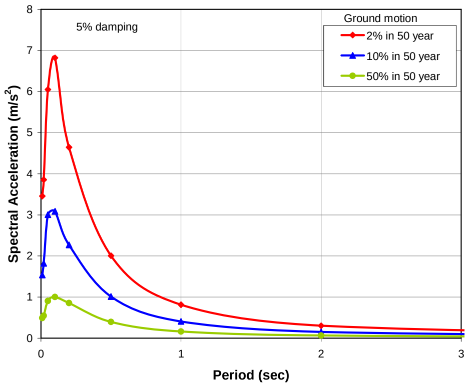

Fig. 4 Uniform Hazard Response Spectra for bedrock horizontal motion

Fig. 5 shows a comparison of the 2% in 50-years ground motion acceleration response spectra with the 0.2 and 1.0 second spectral values defined in IBC 2006 (ICC, 2006) for New York City and the acceleration response spectral values determined for New York by Weidlinger Associates (2000). It can be seen that the 2% in 50-year hazard level for New York is very similar to the hazard level calculated for Hong Kong.

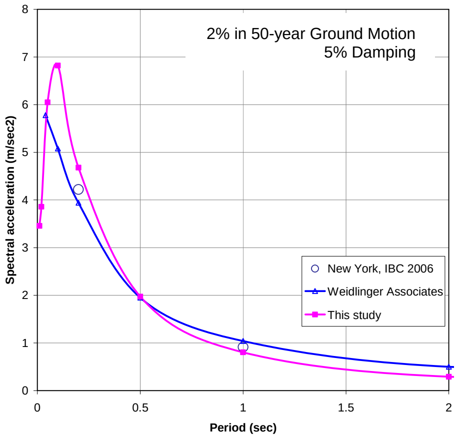

Fig. 5 Comparison of bedrock 2% in 50-year UHRS with spectra for New York (ICC, 2006 and Weidlinger Associates, 2000)

3.5 *De-aggregation*

The hazard results have been de-aggregated, in terms of magnitude and distance, to investigate earthquake occurrences that contribute most to the resulting ground-motion hazard. The de-aggregation was undertaken in accordance with the procedure recommended by McGuire (1995). The results are shown in Fig. 6 for the 0.2 second and 2 second period response spectral accelerations for a 2% probability of being exceeded in 50 years. It is seen that the short period 0.2 second motion is dominated by magnitude 6 events within about 30km from Hong Kong whereas the longer period motion is dominated by magnitude 7 to 7.5 events over 200km distant.

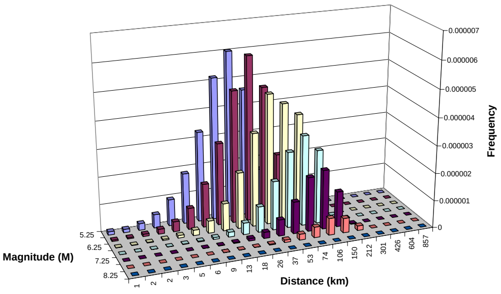

Fig. 6a De-aggregation of hazard levels for the 0.2 seconds acceleration response spectral values (2% in 50-year ground motion)

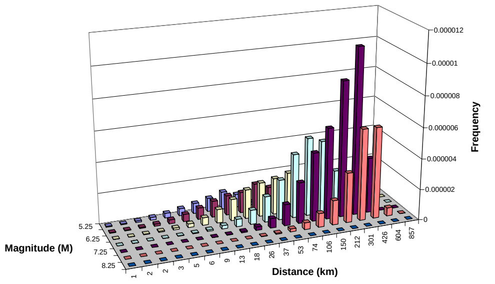

Fig. 6b De-aggregation of hazard levels for the 2.0 second acceleration response spectral values (2% in 50-year ground motion)

4 SITE RESPONSE ANALYSIS

4.1 *Ground Investigation Data*

Ground investigation information for Hong Kong has been compiled from three main sources:

- Geotechnical Information Unit at the Geotechnical Engineering Office (GEO);
- Arup in-house databases; and
- Ground investigation contractors databases.

4.2 *Ground Investigation Boreholes*

Over 1,200 borehole logs have been compiled into a GIS and analysed for the purposes of ground conditions categorisation. As would be expected the available ground investigation information coincides closely with the built up regions of Hong Kong. The borehole logs include, as a minimum, detailed soil profile descriptions and standard penetration test (SPT) results.

4.3 *Shear-Wave Velocity Data*

Shear-wave velocity testing is not commonly carried out in Hong Kong for general ground investigation purposes and therefore the number of shear-wave velocity profiles is limited. A database of published and unpublished shear-wave velocity test results has been compiled for this study (Wong et al. ,1998, Kwong, 1998, Lee et al., 1998, Chan & Bell, 2000, Tam, 2002 and Arup, 2002). Shear-wave velocity measurements have been determined using a range of techniques including crosshole, downhole (both within boreholes and by seismic cone), suspension PS Logging, refraction, Spectral Analysis of Surface Waves and continuous surface waves. The different techniques give similar but slightly different results. At some typical reclamation locations the shear-wave velocity profiles passed through 50m of soil and extended into bedrock (see Fig. 7).

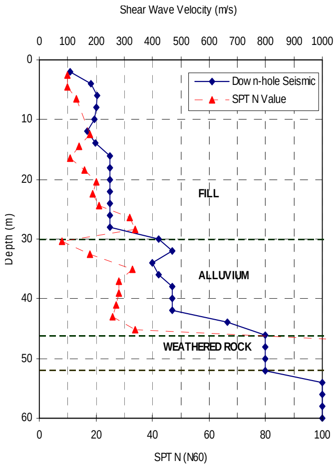

Fig. 7 Example shear wave velocity profiles

4.4 *Correlation of SPT and Shear-Wave Velocity Test Results*

The database of SPT and shear-wave velocity test results was used to generate a suite of correlation relationships between SPT N value and shear-wave velocity. These correlation relationships were then used to estimate the mean value of shear-wave velocities for materials when only SPT data is available. The correlation relationships generally have a large scatter. The scatter can be attributed to both the inherent variability of the materials and the variation in results from different shear wave velocity and SPT testing techniques. Correlation relationships were developed for fill, marine deposits (silt/clay), alluvium deposits (silt/clay), alluvium deposits (sand) and completely decomposed granite. An example of the correlation relationship for decomposed granite is shown in Fig. 8.

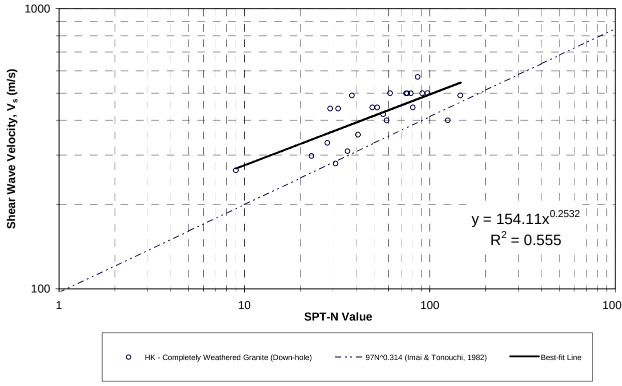

Fig. 8 Correlation between shear wave velocity and SPT-N value for weathered granite residual soil

4.5 *Classification According to the IBC2006 Site Classification System*

The IBC2006 (ICC, 2006) Site Class has been derived for 1,217 boreholes using SPT N data, shear wave velocities and/or undrained strength measurements. Fig. 9 shows some of the locations of the ground investigation boreholes where the site classes were evaluated. These resulting classifications from Site Class B (weak rock) to Site Class E (soft soil) were then combined with the geological map to develop a site classification map (see Figure 9). The site class boundaries were found to broadly coincide with geological boundaries across the territory. In particular, the boundary between Quaternary and pre-Quaternary age materials tends to coincide with the boundary between Site Class C and Class D. The boundary between Site Class C and Class B is associated with the presence or not of a relatively thin layer of saprolite over bedrock, which was found to generally coincide with slope gradient. Site class E is typically determined in areas where there is a considerable thickness of reclamation material and/or reclamation material overlying a considerable thickness of soils such as marine or alluvial deposits.

4.6 *One-Dimensional Site Response Analysis Methodology*

In order to investigate the seismic site response characteristics of the Hong Kong ground conditions, a series of one-dimensional site response analyses were undertaken for a wide range of soil profiles and input parameters. The site response effects were analysed using the following steps:

- i. 41 representative soil profiles were compiled to represent the range of ground conditions encountered in Hong Kong (6 Site Class B, 7 Site Class C, 15 Site Class D and 13 Site Class E). Each profile is defined in terms of the soil and rock material types encountered and the variation in small strain shear modulus (G_0) versus depth. In each case the profile extends into bedrock.
- ii. A shear modulus degradation curve, representing the non-linear behaviour of the soil was defined as a function of shear strain amplitude for each soil and rock material type, as was the soil density. The main soil types encountered were reclamation fill sand, marine silt/clay, colluvium sand and gravel deposits, alluvium sand and silt/clay deposits and in situ weathered rock or saprolite.
- iii. Bedrock response spectra determined from the seismic hazard analysis, (see Fig. 4) were used to define appropriate earthquake strong-motion records for input as reference bedrock ground motions.
- iv. One-dimensional site response analyses were carried out using Arup in-house program Oasys SIREN, Henderson et al. (1990).
- v. Spectral amplification ratios were determined for each soil profile.
- vi. Design surface response spectra were obtained by multiplying the bedrock design response spectra by amplitude dependent spectral ratios for a range of structural periods.

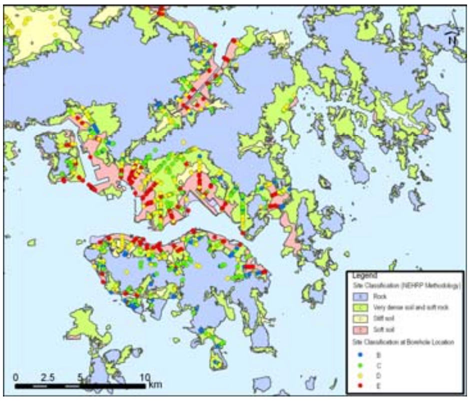

Fig. 9 Extract of site classification map for Hong Kong

4.7 *Input Ground Motions*

In the absence of appropriate measured strong-motion records in the South China region, time histories from stable continental regions and elsewhere have been modified by adjusting them to a target spectrum in the frequency domain. The target design spectra were represented by the scenarios for earthquake motion level with 50%, 10% and 2% probability of being exceeded in 50 years as described in Pappin et al. (2004).

4.8 *Site Amplification Factors*

The adjusted time histories were used to determine ground-motion amplitude and period dependent factors for each of the site classes. The factors specific to Hong Kong in terms of the local soil conditions and the amplitude of the reference input motion.

4.9 *Results of Site Response Analysis*

For each input time history and each soil class, the mean spectral ratio was assessed at structural periods of 0.01, 0.1, 0.2, 0.5, 1.0. 2.0 and 5.0 seconds by calculating a running average spectral ratio. Figure 10 shows the calculated spectral ratios for Site Class D sites when subjected to the short period 2% in 50 year ground motion for example. Also shown on the figure is the inferred variability of the spectral ratios in terms of standard deviation (sigma) assuming a log-normal distribution.

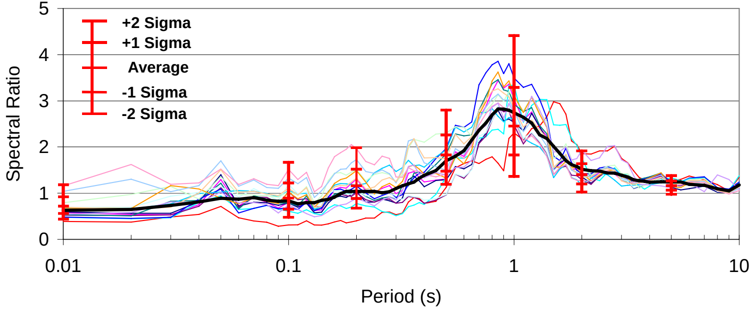

Fig. 10 Spectral ratios for Site Class D sites (2% in 50 year ground motion)

Figs. 11a and 11b show the amplification functions against input earthquake ground motion for periods of 0.2 seconds and 1 second respectively. For the short period 0.2 second ground motion, the predicted amplifications are up to 3 times, with greater amplifications for Site Class C than for Site Classes D and E. The long period 1 second motion is not significantly amplified for Site Classes B and C, irrespective of the amplitude of the input motion. For Site Classes D and E amplifications of 2 to 3 times are found.

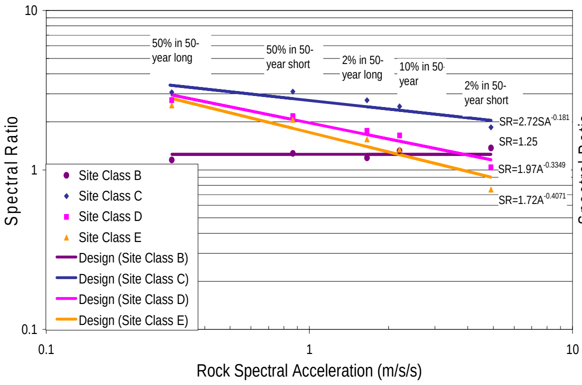

Fig. 11a Spectral Ratio Values at Period 0.2 second for Site Classes B to E

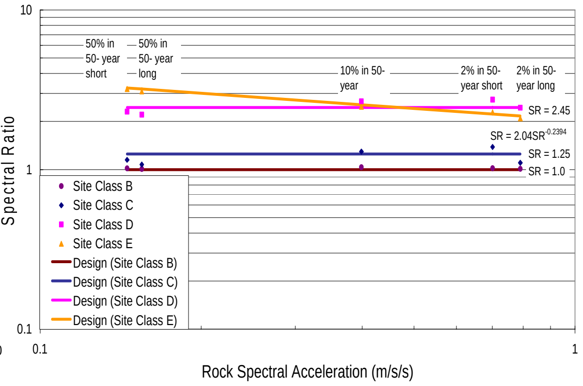

Fig. 11b Spectral Ratio Values at Period 1.0 second for Site Classes B to E

5 COMPARISON WITH INTERNATIONAL STANDARDS

5.1 *Comparison with IBC2006*

The acceleration response spectra are compared in Fig. 12 with the spectra determined using the IBC2006 site amplification coefficients applied to the 0.2 and 1 second bedrock spectral acceleration values derived in this study. The comparison shows that the spectra for Site Class B and C spectra exceed those of the IBC2006 spectra at short periods of less than about 0.5 seconds. It can also be seen that while the spectrum for Site Class D is similar to IBC for 0.5 to 1 seconds the spectrum for Site Class E is significantly lower than IBC. The spectra fall below the IBC2006 values at periods greater than 0.5seconds. It should be noted that the spectra determined using IBC2006 coefficients are for design purposes and represent upper bound values while the spectra shown here are mean values that were used for risk estimation purposes.

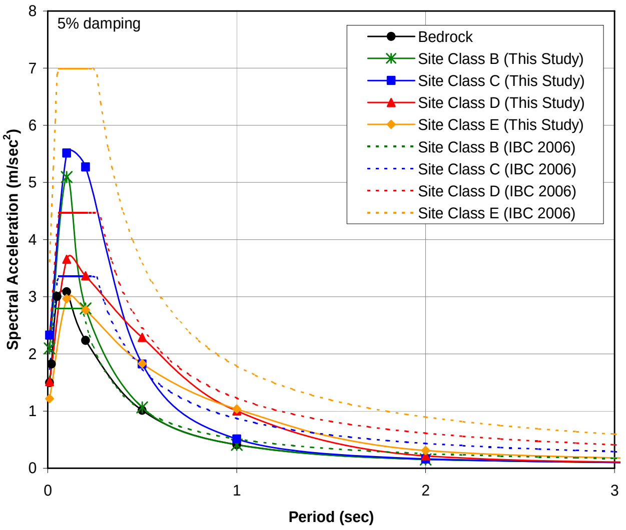

Fig. 12 Comparison of Acceleration Response Spectra – 10% in 50-year Ground Motion with IBC2006

5.2 *Comparison with Chinese Seismic Code for Buildings*

The acceleration and velocity response spectra are compared with the spectra determined using the Chinese Seismic Code for Buildings GB 50011-2001(GB 50011, 2001) in Figure 13. The Chinese Code values have been derived using the coefficients listed in the code for Hong Kong. The Chinese Code spectra are greater except for the very low period response particularly for Site Classes B and C. Again it should be noted that the spectra using Chinese Seismic Code for Buildings coefficients are for design purposes and represent upper bound values and intrinsically include other design factors while the spectra determined in this paper are mean values for risk estimation purposes. However, it is quite apparent that the Chinese Seismic Code for Buildings design spectra is very conservative at longer periods.

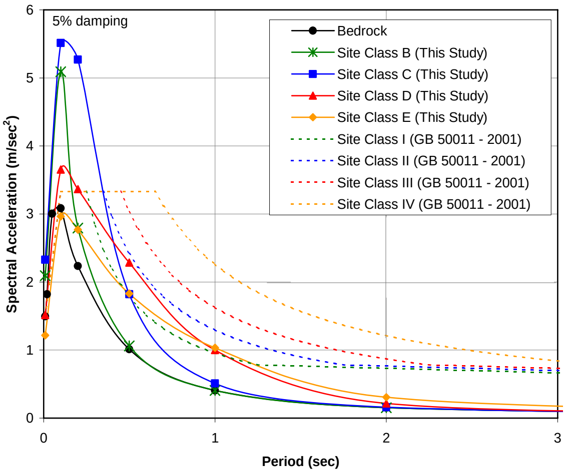

Fig. 13 Comparison of Acceleration Response Spectra – 10% in 50 year Ground Motion with Chinese Code GB 50011 – 2001

6 CONCLUSIONS

A probabilistic seismic hazard assessment has been carried out for the Hong Kong region. The results of the seismic hazard assessment are presented in terms of horizontal peak ground acceleration and uniform hazard response spectra for structural periods up to 5 seconds for bedrock ground conditions. The results are presented for ground motions with 50%, 10 % and 2% probability of being exceeded in 50 years. The response spectral values in the medium to long structural period range are similar to those published for New York City.

Site classification, using the system defined in the IBC2006, has been undertaken for the subsoil conditions in Hong Kong. A site classification map has been produced, which shows the distribution of the different site classes across Hong Kong.

Spectral ratios have been presented for the different site classes with respect to the level of the input bedrock motion such that site response effects can be determined for a range of scenario input ground motion levels within appropriate limits. The site response effects are found to be dependent on both structural period and input amplitude with maximum mean spectral ratios up to about 3. Significant variability is also found for the spectral amplification ratios.

The response spectra are compared with those determined using the IBC2006 coefficients and the spectra determined using the Chinese Seismic Code for Buildings. The comparison shows that the spectra generally exceed those of the IBC2006 spectra and the Chinese Seismic Code at short periods of less than about 0.5 seconds and are lower at longer periods greater than 0.5 seconds. It should be noted however that the code spectral ratios are for design purposes and contain some conservatism whereas the spectra shown here are for mean amplification and would need to be increased somewhat to be suitable for use in design.

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