Seismic Microzonation Assessment in Hong Kong

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SUMMARY:
This paper describes a comprehensive investigation on the potential seismic site response effects for the ground conditions in Hong Kong. The ground conditions in the North-west New Territories region of Hong Kong have been selected for this investigation and the results are formulated into seismic microzonation maps. Published geological maps and detailed ground investigation information from over 3000 boreholes have been used for the microzonation assessment. The site classification for microzonation is based on the site classification system developed in the United States and China, with modifications to suit Hong Kong's ground conditions.

One-dimensional site response analyses have been carried out to establish how various types of site profiles, representative of Hong Kong subsoil conditions in the study area, will potentially respond to earthquake ground motion. The soil properties are determined based on field and laboratory dynamic tests. The response of a suite of soil profiles was investigated using three input earthquake ground-motion levels corresponding to rock motion having a 63%, a 10% and a 2% chance of being exceeded in the next 50 years. The results are presented in terms of defining site classes and deriving surface response spectra for each of these site classes.

Keywords: Microzonation, Site response, Dynamic soil properties, Hong Kong, Microtremor tests

1. INTRODUCTION

Hong Kong is situated in a region of low to moderate seismicity and is one of the most densely populated areas in the world. Seismic hazard assessments are currently not required for general buildings and civil engineering structures in Hong Kong. Nevertheless, such assessments have been conducted for some major civil engineering projects. Seismic microzonation offers an effective tool for evaluating the seismic hazards by dividing a given domain into small units of similar geology, topography and likely ground response to an earthquake. Seismic microzonation has been carried out for some adjacent cities, such as Macau, Shenzhen and Dongguan. A pilot seismic microzonation study in the North-West New Territories of Hong Kong has been completed recently by Arup, supported by the Guangdong Engineer Earthquake Resistance Research Institute (GEERRI), for the Geotechnical Engineering Office (GEO) of the Hong Kong Government. The scope of work of the pilot seismic microzonation study included:

- (i) reviewing historical seismic data of the region;
- (ii) compiling the available geological and geotechnical data for ground characterisation;
- (iii) carrying out ground investigation and field tests, including in-situ shear wave velocity measurements and laboratory cyclic testing; and
- (iv) evaluating the ground motion parameters to study topographic and site response amplification effects to develop seismic microzonation maps.

2. NORTH NEW TERRITORIES PILOT STUDY AREA - GROUND CONDITIONS

2.1. Topography and Geological Setting

Published geological maps and detailed ground investigation information from over 3000 boreholes have been used for the microzonation assessment. Figure 1 shows a topographic image of the study area, overlain with the 1:100,000 Hong Kong geological map.

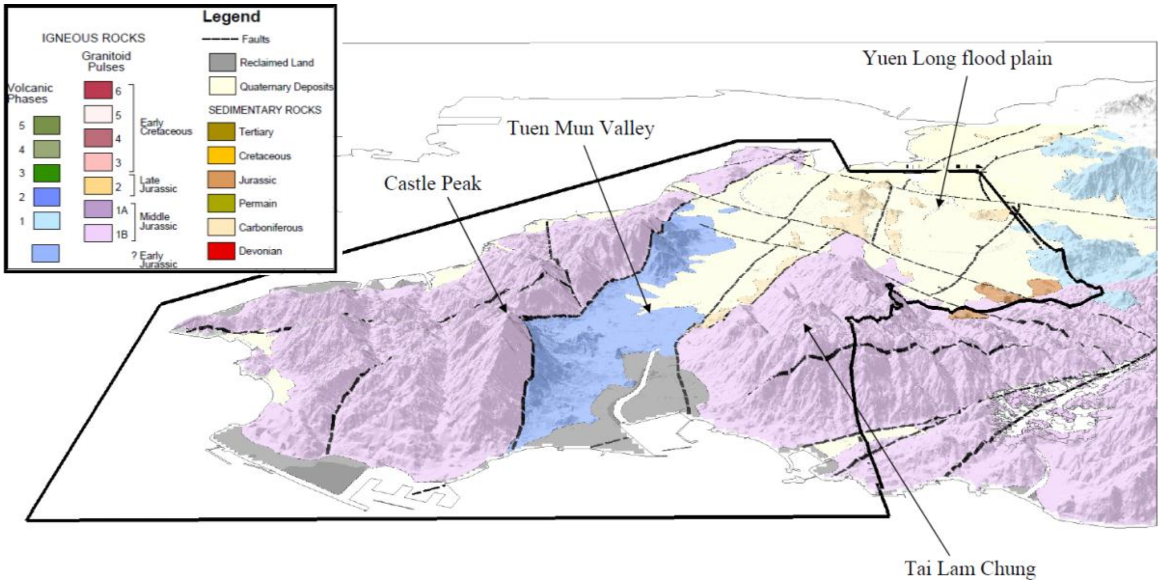


Figure 1. Topography of the study area overlain with the geological map

2.2. Ground Characterisation

Figure 2 shows the locations of 27 boreholes investigated in the study area, and the type of geophysical tests carried out at the different locations. Standard penetration tests (SPT) were carried out at all drillholes. The depth to the SPT N value of 100 is considered to depict the depth to very stiff soil.

2.2.1. In situ shear wave velocity tests

One of the purposes of the study is to compare the results of shear-wave velocity V_S by different measurement methods, such as PS logging, downhole and crosshole seismic and multi-analysis of surface wave (MASW) tests. Summaries of the range of soil layer thickness, SPT N values and measured shear wave velocities for each soil type encountered in all drillhole locations are listed in Table 1.

a. PS logging vs. downhole seismic

PS logging and downhole seismic measurements were ranked according to their quality, from Q1 (best) to Q4 (worst). Only Q1 and Q2 data were considered for the determination of the shear wave velocity design profiles used in the site response analyses. Downhole seismic provides Q1 and Q2 measurements down to 30 m, against 51 m for PS logging. The comparison of data quality between Downhole and PS Logging Seismic tests is shown in Figure 3 which clearly shows that PS logging gives better quality data than the downhole seismic testing method. However, it should be noted that PS logging and downhole seismic tests have not been carried out on the same boreholes, or down to the same depth and that downhole seismic tests were carried out on shallower boreholes. Also, PS logging can be representative of local features and effects, and can sometimes diverge quite significantly from the overall V_S trend along the whole profile.

In general, the quality assessment is found to be adequate to suggest the PS logging method should be preferred to downhole seismic tests in obtaining shear wave velocity profiles.

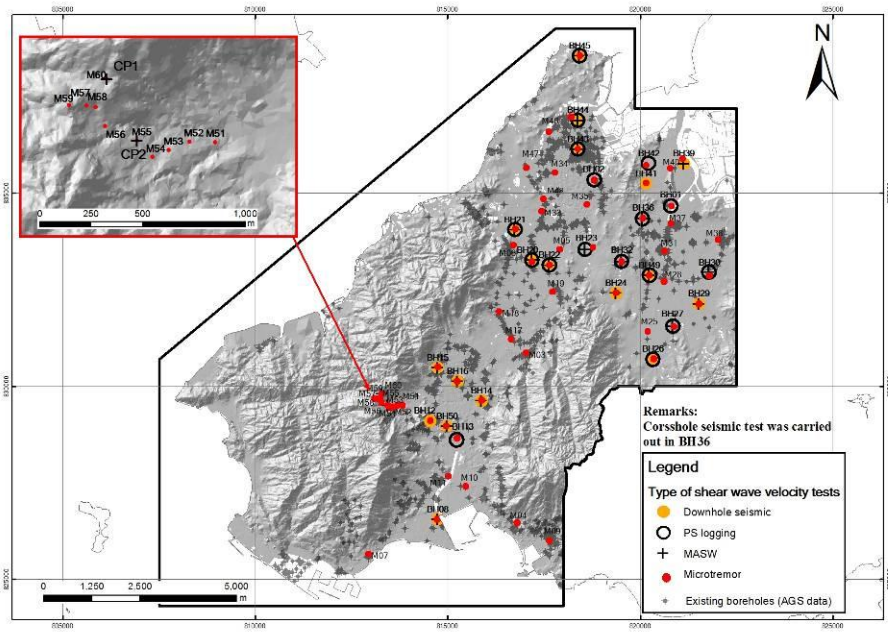


Figure 2. Geophysical field test locations

Table 1. Overall characterisation of the soils for all sites

All Sites	Number of sites		Depth (m)		Thickness (m)		SPT-N		Vs measurements (m/s)	
	with the considered soil material	tested with SPT	min	max	min	max	min	max	min	max
Fill	23	9	0	11.3	0	11.3	3	39	130	350
Marine/Estaurine deposit	5	5	1.5	11.3	2	8.2	3	21	150	200
Alluvium Sand	22	21	1.5	22	2	15.4	3	98	150	450
Alluvium Clay	7	7	1.5	16.8	0.9	8	3	34	200	400
In-situ sedimentary rock	14	14	4.6	146.5	4.6	131.1	5	> 100	160	632
In-situ Tuff	10	9	1.5	150	1	137.4	10	> 100	153	700
In-situ Granite	2	2	13.2	51.3	9.7	37.8	33	> 100	325	800

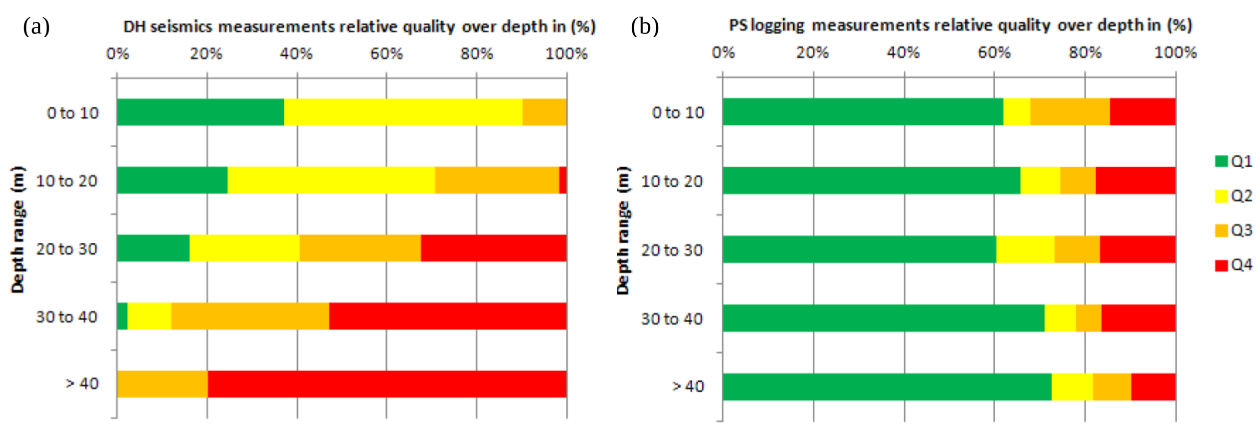


Figure 3. Downhole seismic vs. PS logging measurements relative quality with depth

b. Crosshole seismic & MASW

The results of V_S measurements obtained from crosshole seismic and MASW are consistent with the data from PS logging and downhole seismic tests. However, the MASW tests generally give reliable results only down to a depth of approximately 10 m below the ground surface.

2.2.2. Microtremor tests

Microtremor tests were carried out by the City University of Hong Kong as part of the study to explore the applicability and effectiveness of this non-destructive and economic means to determine the dominant period of a site. In Figure 4, the measured natural periods of the sites are compared to the calculated periods for the entire soil profile (see Figure 4a) and soil profile considered only down to where SPT N > 100 (see Figure 4b). The site period was calculated as:

$$T = \frac{4H^2}{\sum_i h_i V_{Si}}$$

where T = site period; H = thickness of the soil deposits and h_i and V_{Si}, the thickness and shear wave velocity for layer i respectively.

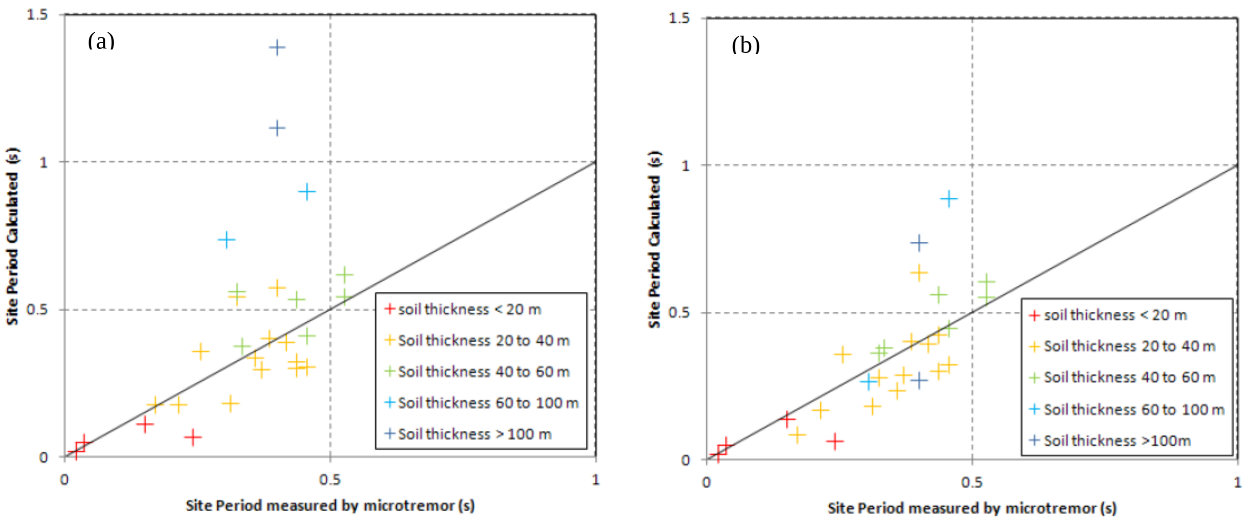


Figure 4. Comparison between measured and calculated site periods when considering (a) the entire profile, (b) down to where the SPT N value is > 100

The site period measurements match the calculated values better when considering the soil profile down to SPT N > 100. The microtremor test results thus appear to be dominated by the resonance of the relatively softer soils of the shallower strata whereas the deeper stiff soils (SPT N > 100) do not noticeably affect the dominant site period.

2.2.3. Laboratory geotechnical tests

a. Standard laboratory tests

A total of 78 soil samples and 25 rock samples were tested for bulk density. The soil densities vary from 1.7 t/m^3 to 2.2 t/m^3. A design value of 2.0 t/m^3 has been chosen for the fill, alluvium, colluvium and saprolite soils and 1.7 t/m^3 for marine and estuarine soils. For the bedrock, the density values were taken to be between 2.6 t/m^3 and 2.8 t/m^3 according to their level of weathering. Plasticity index tests gave an average PI of 26% for alluvial clay, 20% for Estuarine/Marine deposits and 19% for residual soils.

b. Cyclic triaxial tests

Six cyclic triaxial tests with on-sample strain measurement and shear-wave velocity measurements from internal bender element tests were carried out at the Hong Kong University of Science and Technology. The samples tested were completely decomposed metasiltstone (sandy clayey silt and clayey silt samples), alluvium (clayey fine to coarse sand/silty fine sand/ silty clay samples), and estuarine/marine deposits (clayey silt sample). The derived normalised shear modulus degradation curves plotted as G/G_0 versus shear strain amplitude are shown in Figure 5, along with the curves for sand fill and completely decomposed granite and volcanic rock used in the site response analysis, modified after Seed & Idriss (1970) and Leung et al. (2010). The cyclic triaxial test results show a noticeable difference in behaviour between completely decomposed metasiltstone described as clayey silt, and the sample described as sandy clayey silt, and these material types were therefore differentiated.

The range of conventional degradation curves from gravels to clays (EPRI, 1993) resulting from a broad European dataset are plotted as the background in Figure 5 for comparison purposes. The EPRI curves are consistent with the relatively low plasticity index of the Estuarine/Marine deposits and the completely decomposed metasiltstone samples tested in this study.

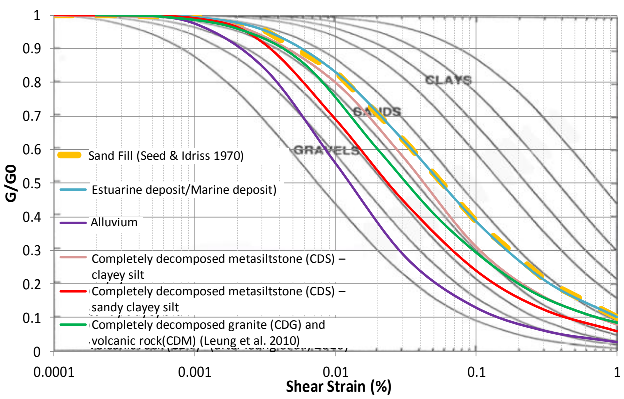


Figure 5. G/G_0 curves

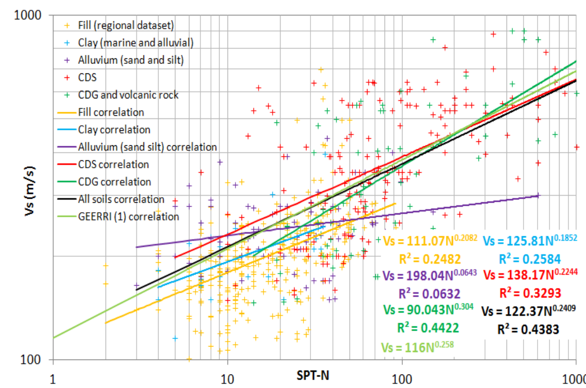


Figure 6. Measured V_S and SPT N correlations

3. SITE RESPONSE ANALYSES

3.1. Input

3.1.1. Soil properties

The soil profiles were defined in terms of soil types, shear wave velocity and small-strain shear modulus against depth. The bedrock shear wave velocity was assumed to be 1000 m/s. The shear wave velocity profile was derived from Q1 and Q2 in-situ measurements and the V_S-SPT N correlations that were computed as illustrated in Figure 6. It should be noted that for fill, the study dataset is limited and has been expanded with field data from Singapore and elsewhere in Hong Kong to derive the correlations. Additional datasets were considered as described by Pappin et al. (2008), Ng et al. (2000) and Veijayaratnam et al. (1993). In addition to the correlations in Figure 6, the following relationship recommended by GEERRI between V_S, SPT N and depth (Z in m) was also considered:

$$V_S = 75.67\ N^{0.1436}\ Z^{0.2563}\ \text{(m/s)}$$

The calculated V_S values correlated from SPT N values generally show good agreement with the in-situ measurements.

3.1.2. Ground motions

The derivation of the time histories is based on the results of probabilistic seismic hazard assessments recently completed by Arup and GEERRI and considered the attenuation models, de-aggregation plots and bedrock uniform hazard response spectra (UHRS) for ground motions having a 63%, 10% and 2% chance of being exceeded in the next 50 years. Figure 7 shows the average bedrock UHRS which were used as targets for the derivation of time histories. The magnitude-distance combinations representative of the different probable ground motions considered in the study are summarised in Table 2. The real earthquake records that were used to derive the time histories were chosen from the Pacific Earthquake Engineering Research (PEER) strong motion database, except the long period '2% chance of being exceeded in the next 50 years' ground motion, as the current PEER earthquake database is only available for earthquake distances less than 200 km.

Arup modified the artificial and selected recorded earthquake time histories in the time-domain in order to match the target UHRS closely, particularly at long periods, using the computer program RSPMATCH (Hancock et al., 2006). Separately, GEERRI generated time-histories using artificial Green's function simulations to produce a tri-linear shape of time history in order to spectrally match the target spectrum in the frequency-domain (ESE, 2005).

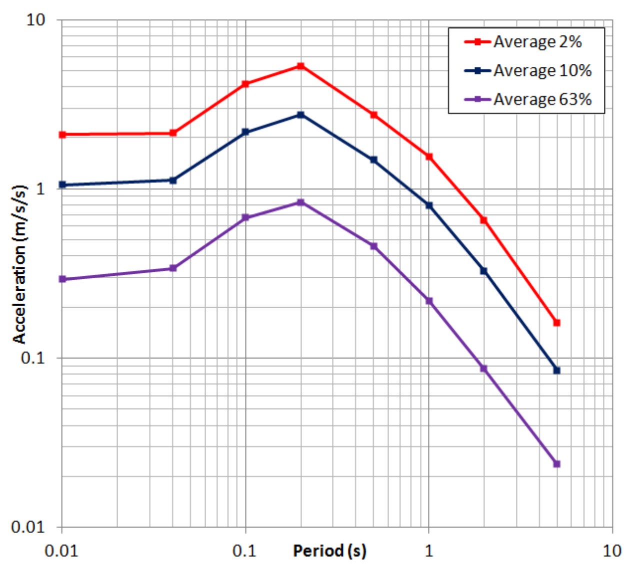


Figure 7. Average bedrock UHRS target spectra

Table 2. Earthquake scenario events

Probability of the ground motion in the next 50 years	Short period ground motion		Long period ground motion					
	0.2 s		1 s (near field event, r < 250 km)		1 s (for 2%, far field event, r > 250 km)		5 s	
	M	R (km)	M	R (km)	M	R (km)	M	R (km)
63%	5.5	50	6.5	150			6.5	150
10%	5.5	30	6.5	60			7	90
2%	5.5	10	7	60	8	250	7.5	90

3.2. Site Response Analyses Methodologies and Results

GEERRI used the site response computer program ESE (2005), which is an equivalent-linear method similar to SHAKE (Schnabel et al., 1972) and EERA (2000). Arup used *Oasys* SIREN to perform the site response analysis calculations using a fully non-linear method. Detailed calibration analyses undertaken using *Oasys* SIREN are described by Henderson et al. (1990) and Heidebrecht et al. (1990).

A systematic comparison between the results of Arup and GEERRI for the '10% chance of being exceeded in the next 50 years' ground motion was carried out for each borehole. The results of the site response analyses were presented in terms of spectral ratios and showed a good agreement between the two programs. The response spectra of the 27 boreholes analysed for site response were therefore classified into four groups according to measured site period as shown in Table 3. The design response spectra derived for each group are shown in Figure 8.

Table 3. Site period classification groups

Group	**Site Period (N > 100), T_{N100}**
Group 1	< 0.15 s
Group 2	0.15 – 0.30 s
Group 3	0.30 – 0.50 s
Group 4	0.50 – 1.00 s

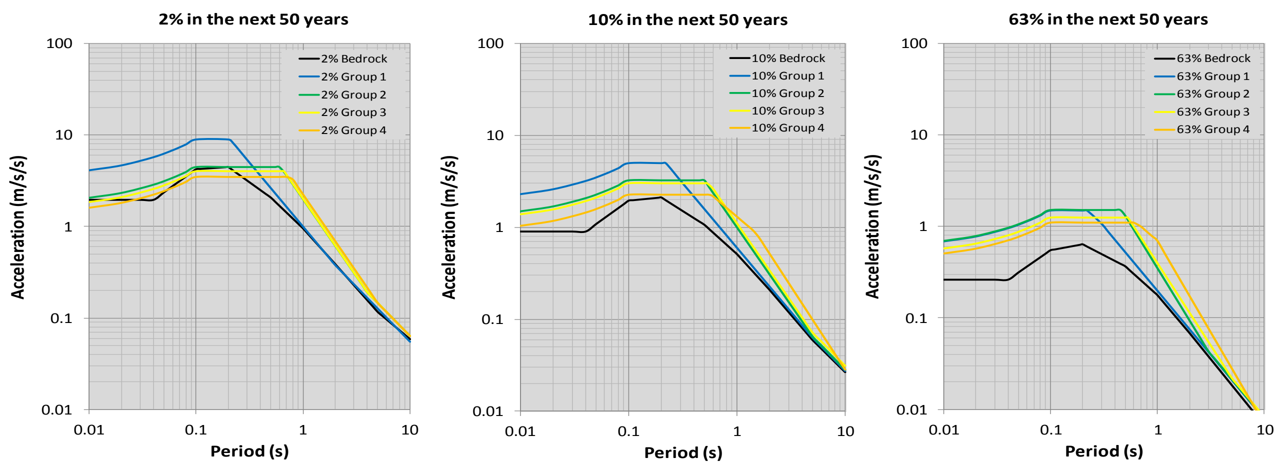


Figure 8. Design response spectra for Group 1 to Group 4 sites

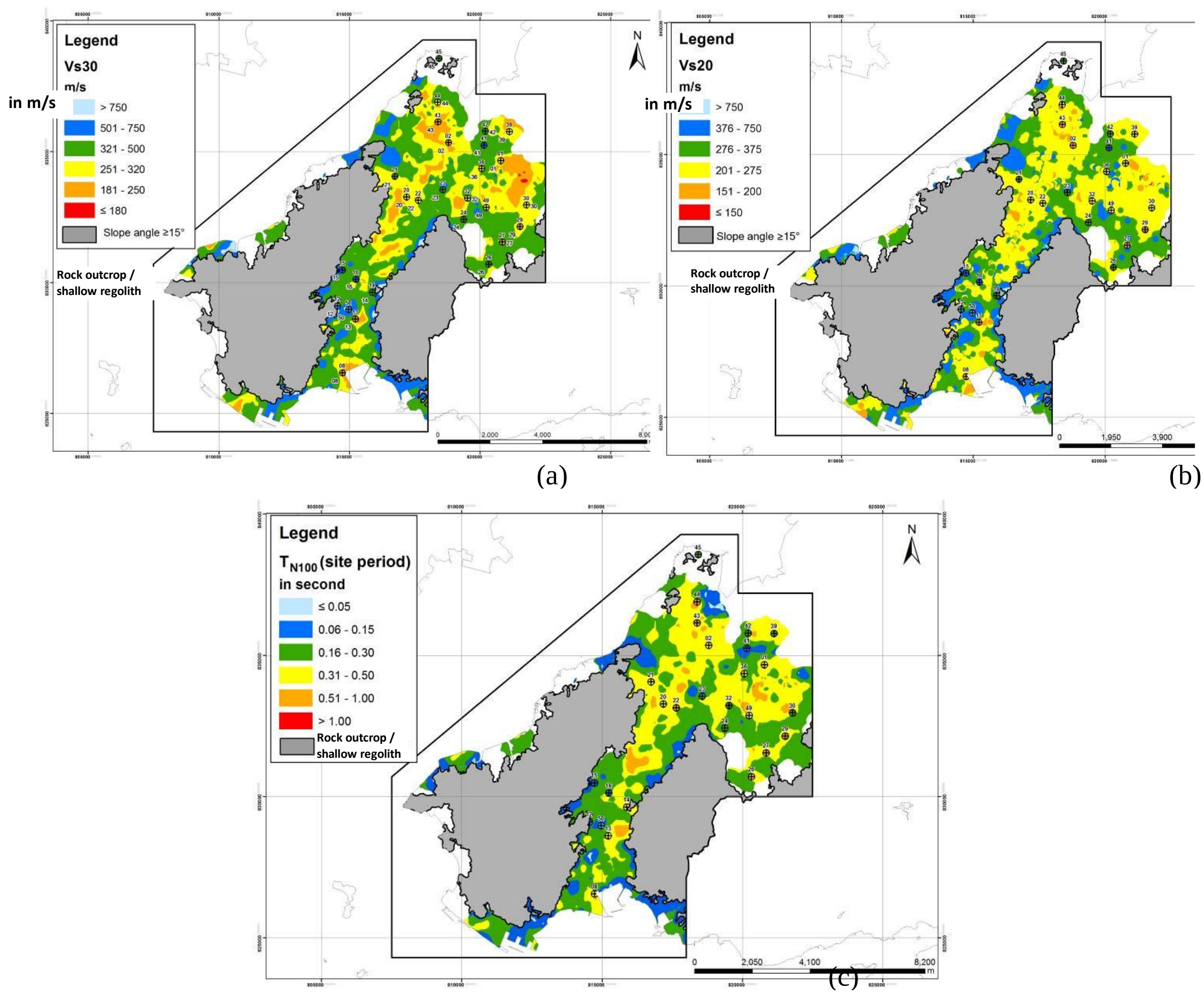
4. MICROZONATION MAPS

4.1. Site Classification

Eurocode 8 and US International Building Code (IBC, 2009) use similar classification based on an average shear wave velocity of soil depth to 30 m ($V_{S,30}$), while the Chinese code (GB50011-2010) uses $V_{s,20}$ instead. As discussed in Section 2.2.2, the site period measurements match the calculated values better when considering the soil profile down to SPT N > 100. Therefore, the recommended site classification is based on the site period down to a soil depth with SPT N > 100, as shown in Table 3.

4.2. Classification Maps

Information on more than 3000 boreholes from a digital database was used to develop the microzonation maps. The SPT N values of each borehole with their corresponding soil type were extracted, and the corresponding shear wave velocities calculated based on the V_S-SPT N correlations presented previously. $V_{S,30}$, $V_{S,20}$ and T_{N100} were then derived for each drillhole location. To generate the contours, the value of $V_{S,30}$, $V_{S,20}$ or T_{N100} are interpolated on each grid node in the study area using the Kriging method. The resulting microzonation maps are shown in Figure 9. Site periods measured by microtremor tests were found to be very consistent with the T_{N100} contours and it is therefore recommended to consider developing the systematic use of microtremor test as a non-intrusive and economical tool for future seismic microzonation studies.



Note: The area with rock outcrop / shallow regolith was not considered in the site response analyses.

Figure 9. Arup microzonation maps in terms of (a) $V_{S,30}$, (b) $V_{S,20}$, (c) T_{N100}

GEERRI also developed a seismic microzonation map based on the Chinese code (GB50011-2010) method, as shown in Figure 10. The study area is classified into 3 classes: Group I, II and III corresponding to rock, stiff soil and soft soil respectively. The distributions of similar soil conditions are generally consistent with Figure 9. The corresponding design site corner periods of each of the Chinese site classes are shown in Table 4. It can be seen that these increase with increasing levels of ground motion as expected.

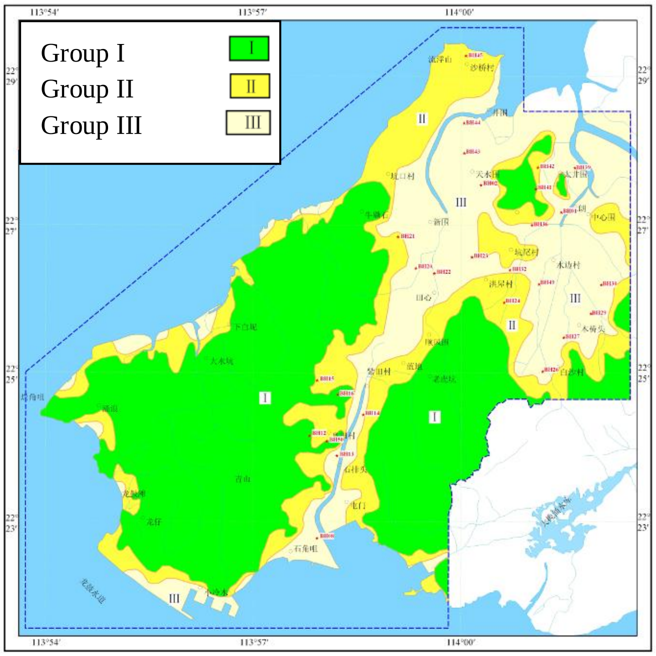


Figure 10. GEERRI Microzonation map using the Chinese soil classification method

Table 4. Design site corner periods (s) for the various classification Groups

Group	Chance of ground motion being exceeded in the next 50 years		
	63%	10%	2%
Group I	0.28	0.40	0.60
Group II	0.32	0.50	0.75
Group III	0.35	0.65	1.00

5. DISCUSSION

A number of site response microzonation maps: $V_{S,20}$, $V_{S,30}$ and T_{N100} have been developed. As discussed in Section 3, T_{N100} is considered to give the most consistent result when grouping the soil response spectra in site response analysis. In addition, the predominant period measured by microtremor tests show generally very good agreement with the map produced from T_{N100}. It is reasonable to consider soil below the depth with SPT N > 100 as very stiff soil which does not significantly affect seismic soil response. Also, using SPT N > 100 gives reasonable results even for deep boreholes in soil. For example, some boreholes show very deep weathering in Hong Kong and deep saprolite usually has significant depths of SPT N value greater than 100 but the responses from these stiff soils are not significant to the seismic site response.

6. CONCLUDING REMARKS

The ground surface response spectra produced by the site response analyses have been studied and classified such that a systematic seismic ground motion microzonation methodology can be applied to the whole study area. It also compares the resulting microzonation recommendations with those arrived at independently by GEERRI using conventional practice in applied in China. However, it is considered that the site response microzonation maps are not of adequate resolution and not sufficiently reliable in dividing the deeper soil areas into finer zones due to high uncertainties of the ground condition. Therefore, the microzonation maps should only be used for general planning purposes. For individual projects, reliable ground investigation data should always be obtained to enable a site classification to be assessed or site specific dynamic site response studies to be carried out.

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