Liquefaction Assessment in Hong Kong

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SUMMARY:
This paper presents a comprehensive liquefaction potential assessment 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 assessment and the results are presented as liquefaction microzonation maps. One-dimensional site response analyses have been carried out to calculate the earthquake-induced cyclic shear stresses for a suite of 27 soil profiles from boreholes in the study area. The dynamic soil properties were determined based on field and laboratory dynamic testing. Two input earthquake ground-motion levels corresponding to rock motion with a 10% and a 2% chance of being exceeded in the next 50 years respectively have been examined. The results are presented in terms of probability of liquefaction potential under these two earthquake ground-motion levels, calculated by the conventional SPT N value correlation methods. Published geological maps and detailed ground investigation information from over 3000 boreholes were then adopted in carrying out the microzonation assessment. The assessment generally shows that the chance of liquefaction in the study area for the '10% chance of being exceeded in the next 50 years' ground motion is very low. However, some soil layers are likely to liquefy when subjected to the extreme seismic ground motions having a '2% chance of being exceeded in the next 50 years'.

Another facet of this study is a direct comparison of the above findings with the liquefaction likelihood derived following the Chinese Seismic Code (GB50011-2010). Key observations of the comparison are presented and discussed.

Keywords: Microzonation, Site response, Liquefaction, Hong Kong

1. INTRODUCTION

The term liquefaction generally refers to the cyclic generation of large pore water pressures in saturated granular soils resulting in reduction of effective stresses, and leading to almost complete loss of soil shear strength. The variables that influence the onset of liquefaction include the presence of ground water, particle size distribution and in-situ relative density of the soil, effective confining stress and amplitude and duration of shaking. In soils with a high percentage of fine-grained particles, such as clays, the rate of build up of excess pore water pressures is much slower than that in sands and therefore liquefaction is much less probable. In very coarse-grained soils such as gravels, the excess pore water pressures are generally rapidly dissipated and again liquefaction is less probable. Generally sandy soils have the greatest susceptibility to liquefaction.

Liquefaction assessments are currently not required for general buildings in Hong Kong. Nevertheless, such assessments have been conducted for some major civil engineering projects. Pun (1992) studied the risk of liquefaction occurring in marine sand fills in Hong Kong based on the empirical SPT method (Seed et al., 1985) and concluded that extensive liquefaction of the marine sand fills was very unlikely, but possible at some local weak spots. Shen & Lee (1995) carried out a dynamic stability assessment on hydraulic sand of the reclamation sites in Hong Kong to develop guidelines for quality control of hydraulic fill placement. They carried out a 1-D site response analyses and used the simplified empirical method by Seed & Idriss (1967) to assess the liquefaction potential. Their results indicated that liquefaction was not likely to occur from an earthquake ground motion having a peak ground acceleration of about 10% g, arising from an earthquake of magnitude 7.

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. This paper presents a comprehensive liquefaction potential assessment for the ground conditions in the study area and the results are presented as liquefaction potential maps. One-dimensional site response analyses have been carried out to calculate the earthquake-induced cyclic shear stresses for a suite of 27 soil profiles from boreholes. The dynamic soil properties were determined from field and laboratory dynamic testing. Two input earthquake ground-motion levels corresponding to rock motion having a 10% and 2% chance of being exceeded in the next 50 years have been examined. The results are presented in terms of probability of liquefaction potential under these two earthquake ground-motion levels, as calculated by conventional SPT N value correlation methods. Published geological maps and detailed ground investigation information from over 3000 boreholes were then adopted in carrying out the microzonation assessment. Another facet of this study is a direct comparison of the calculated liquefaction probabilities with the liquefaction likelihood derived following the Chinese Seismic Code (GB50011-2010). Key observations of the comparison are presented and discussed.

2. DEFINITION OF SUSCEPTIBLE SOILS

Sandy soils are those most likely to liquefy under earthquake loading. In the study area, soils susceptible to liquefaction are reclamation fill, alluvial sands and silts, and sandy or silty marine deposits. Laboratory tests have been carried out to determine the fines and clay contents of the soils and the results are summarised in Table 1. Other soils in the study area, such as colluvium which typically comprises gravel, cobbles, boulders in a silt/clay matrix, and saprolite (completely to highly decomposed rocks), which retain the parent rock structure, are not considered to be liquefiable. The liquefaction assessments have been extended to a depth of 40 m below existing ground level. It is considered that below this depth, liquefaction is improbable and also unlikely to influence behaviour of facilities founded near to the surface. It should be noted that the maximum depth of liquefaction susceptibility analysis is up to 20 m below the existing ground level in the current Chinese Code for Seismic Design of Buildings (GB50011 – 2010).

Table 1. Fines and Clay Contents

Soil Type	Soil Description	Average Fines Content (%)	Average Clay Content (%)
		P.S. < 0.074 mm	P.S. < 0.005 mm
Debris Flow Deposit	Sandy SILT	34	10
Fill	SAND	11	6
	SILT	54	28
Alluvium	SILT	54	21
	Silty CLAY	76	51
	Sandy CLAY	46	32
	SAND	23	11
Marine / Estuarine	Sandy Clayey SILT	63	25
	Clayey SILT/ Silty CLAY	76	47

3. METHODOLOGY

Common engineering practice in the assessment of liquefaction potential is to use empirical relationships based upon field observations of liquefaction, or absence of liquefaction, in past earthquakes, and measured in-situ soil properties, such as the standard penetration test (SPT), cone penetration test (CPT), or in-situ shear-wave velocity (V_S). A widely adopted relationship is the SPT based correlation of Seed et al. (2001), which is presented in the following equation:

$$P_L = \Phi\left[-\frac{\left(N_{1,60} \cdot (1 + 0.004 \cdot FC) - 13.32 \cdot \ln(CSR) - 29.53 \cdot \ln(M_W) - 3.70 \cdot \ln(\sigma_v') + 0.05 \cdot FC + 33.73\right)}{2.7} \right]$$

where:

P_L = probability of liquefaction

Φ = standard cumulative normal distribution

$N_{1,60}$ = SPT N value corrected for overburden effects and energy. N_1 is corrected for overburden and $N_{1,60}$ is corrected for energy, equipment and procedure based on the following correction factors:

$$N_1 = \left(\frac{100}{\sigma_v'}\right)^{0.5} N$$

$$N_{1,60} = N_1 \cdot C_R \cdot C_S \cdot C_B \cdot C_E$$

C_R = correction for rod lengths shorter than 10 m
C_S = correction for non-standard SPT samplers
C_B = correction for borehole diameters greater than 115 mm
C_E = Correction for energy efficiency of SPT hammer

FC = percentage of fines content (finer than 0.074 mm)

M_W = moment magnitude of the earthquake for which the liquefaction probability is being assessed

σ_v' = vertical effective stress (kPa)

CSR = 'equivalent uniform cyclic shear stress ratio'. This has been evaluated by means of site-specific soil response analyses using *Oasys* SIREN. SIREN computes the peak shear stress (τ_{max}) at each soil element in the profile, and the 'equivalent uniform' CSR is assumed to be equal to 65% of the peak, where,

$$CSR = 0.65 \cdot \frac{\tau_{\max(SIREN)}}{\sigma_v'}$$

The following $N_{1,60}$ correction factors in Youd & Idriss (2001) have been adopted:

- C_R = 0.75 for a rod length < 3 m
  = 0.8 for a rod length = 3 to 4 m
  = 0.85 for a rod length = 4 to 6 m
  = 0.95 for a rod length = 6 to 10 m
  = 1.0 for a rod length > 10 m

  It has been nominally assumed that the rod length is measured from 1 m above ground level.
- C_S = 1.0
- C_B = 1.0
- C_E = 1.0 for standard automatic trip hammers used in Hong Kong.

The results of the site response analyses have been used to compute the profile of shear stress versus depth for each borehole analysed. The procedures are fully described by Pappin et al. (2012) and made use of the non-linear dynamic one-dimensional site response program *Oasys* SIREN. Input earthquake time-histories have been selected to represent de-aggregated magnitude and distance combinations for the three ground-motion levels based on the seismic hazard assessment for the study area completed recently by Arup (Pappin et al., 2012). The following ground-motion levels were analysed using *Oasys* SIREN to determine site response coefficients, which have been considered in terms of liquefaction potential:

- '10% chance of being exceeded in the next 50 years', near-field earthquake event at 60 km, $M_w = 6.5$
- '2% chance of being exceeded in the next 50 years,' near-field earthquake event at 60 km, Mw = 7.0
- '2% chance of being exceeded in the next 50 years', far-field earthquake event at 250 km, $M_w = 8.0$

The calculations of vertical effective stress have been carried out using the ground water level based on the borehole records, which is generally about 2 m below the existing ground surface. The assessment assumes that liquefaction will not occur above the ground water level.

3.1. Chinese Seismic Code Methodology

The Chinese Seismic Code for Seismic Design of Buildings (GB50011 – 2010) considers liquefaction unlikely to occur under the following soil conditions:

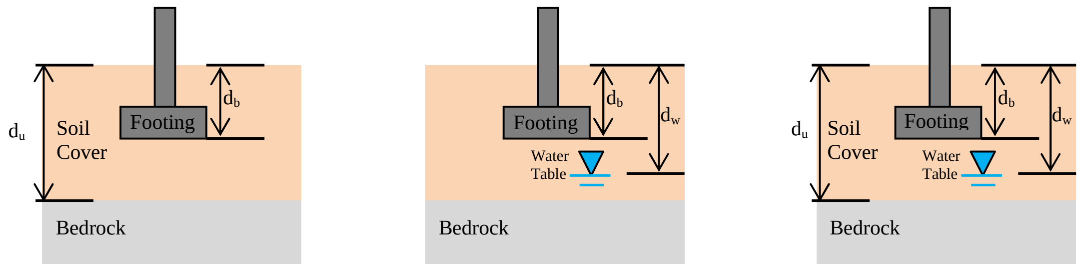
- when the geological age of soil condition corresponds to formation in the Late Quaternary Period or before, i.e. over 100,000 years before present, in earthquake Intensity 7 and Intensity 8 regions;
- soil comprising clay particles (< 0.005 mm particle diameter) of more than 8%, 13% and 16% in earthquake Intensities of 7, 8 and 9 regions respectively; and
- the covering soil and ground water table levels respect one of the following criteria, as illustrated in Figure 1:

(i) $d_u > d_0 + d_b - 2$ m;

(ii) $d_w > d_0 + d_b - 3$ m; and

(iii) $d_u + d_w > 1.5\, d_0 + 2\, d_b - 4.5$ m

where d_u is the thickness of the non-liquefiable covering soil without marine and silty clay (m)
d_0 is depth of the characteristic SPT N value (m), see Table 2
d_b is the depth of shallow footing, not exceeding 2 m
d_w is the depth of the highest recorded level of ground water table (m)



(i) $d_u > d_0 + d_b - 2$ m   (ii) $d_w > d_0 + d_b - 3$ m   (iii) $d_u + d_w > 1.5\, d_0 + 2\, d_b - 4.5$ m

Figure 1. Illustration of the non-liquefaction criteria for covering soil and level of ground water

Table 2. Depth of the characteristic SPT N value, d_0

Soil Type	Earthquake Intensity 7	Earthquake Intensity 8	Earthquake Intensity 9
Silt	6 m	7 m	8 m
Sand	7 m	8 m	9 m

The critical SPT N value for liquefaction, N_{cr} is calculated down to 20 m as follows:

$$N_{cr} = N_0 \beta [\ln(0.6d_s + 1.5) - 0.1d_w)] (3 / \rho_c)^{0.5}$$

where N_0 is the characteristic SPT N value for liquefaction
β is 0.8 for Hong Kong (Earthquake Design Group 1 as specified in the code)
d_s is the depth of SPT test layer (m)
d_w is the depth of ground water table (m)
ρ_c is the clay content (%).

The design N_0 value is based on the code-recommended N_0 range for different earthquake intensities. Table 3 summarises the recommended N_0 values based on the Chinese Seismic Code.

Table 3. Characteristic SPT N for liquefaction, N_0

Chance of being Exceeded in the next 50 years	Earthquake Intensity	Design Peak Ground Acceleration (g)	N_0
10%	7	0.10	7
2%	8	0.20	12

Layers of soil are identified to liquefy if their measured uncorrected N value is smaller than the calculated N_{CR}. If this occurs for one or more layers, the following equation is used to calculate the Liquefaction Index, I_{lE} according to the Chinese Seismic Code as follows:

$$I_{lE} = \sum_{i=1}^{n} \left(1 - \frac{N_i}{N_{CRi}}\right) d_i W_i$$

where I_{lE} is the Liquefaction Index
n is the number of measured SPT N value
N_i is the measured uncorrected SPT N value
N_{CRi} is the Critical SPT N value for liquefaction
d_i is the thickness of representative SPT N layer, can be taken as the average thickness between the SPT N values at the top and bottom layers
W_i is the depth coefficient, when the depth is less than 5 m it is taken as 10 and when the depth is 20 m it is taken to be zero and between 5 m to 20 m the value is taken as having a linear reduction with depth.

Three levels of Liquefaction Index are classified in the Chinese Seismic Code below:

- Slight liquefaction potential $0 < I_{lE} \le 6$
- Moderate liquefaction potential $6 < I_{lE} \le 18$
- Severe liquefaction potential $I_{lE} > 18$.

4. LIQUEFACTION ASSESSMENT RESULTS

Figure 2 shows an example of the results of the liquefaction assessment using Seed et al. (2001) and the Chinese Seismic Code (GB50011-2010) method subject to '10% chance of being exceeded in the next 50 years' ground motion (peak ground acceleration of 0.1 g in rock) for Hong Kong based on the site-specific seismic hazard assessment (Pappin et al, 2012) and Intensity 7 respectively. The results for the '2% chance of being exceeded in the next 50 years' ground motion (peak ground acceleration of 0.2 g in rock) and Intensity 8 are also shown. When the liquefaction probability from Seed et al. (2001) exceeds 50% or the Chinese Seismic Code, N_{CR} to N ratio is greater than 1, it is considered that the soil layer will liquefy.

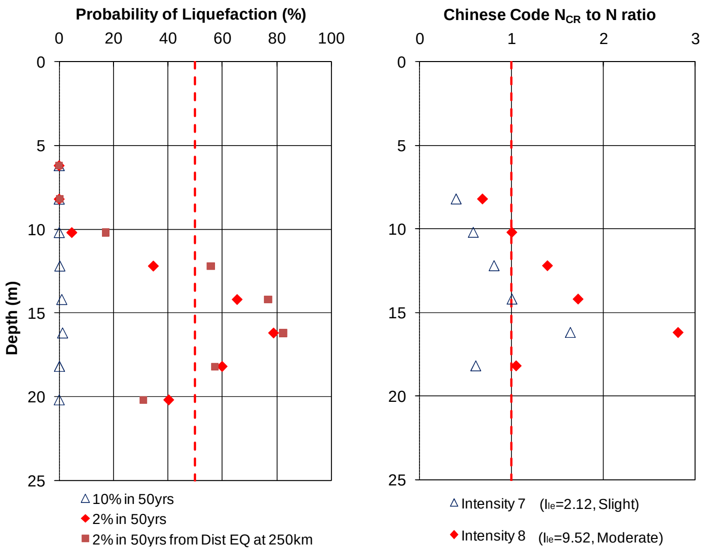


Figure 2. Liquefaction chart for borehole no. BH01

The calculated maximum liquefaction probability (Seed et al., 2001) of any single layer and the Liquefaction Index I_{le} (Chinese Seismic Code, GB50011-2010) for the boreholes are summarised in Table 4. In general, the Seed et al. (2001) and the Chinese Seismic Code methods have similar findings on the level of liquefaction potential. The key factors causing the difference of the results are the fines content used by Seed et al. (2001) and the clay content used by the Chinese Seismic Code. This explains the zero liquefaction potential calculated by the Chinese Seismic Code for boreholes BH24, BH39 and BH42. In Seed et al. (2001), there are no absolute limits to define the susceptibility of soil for the liquefaction analysis. In the Chinese Seismic Code, however, soil having clay content greater than 10% and 13% is considered to be not liquefiable in earthquake Intensity 7 and Intensity 8 respectively. To enable comparison of the results of the Chinese Code and Seed et al. (2001), the Chinese Seismic Code (GB50011-2010) assumption that earthquake Intensity 7 and Intensity 8 are equivalent to peak ground accelerations of 0.1 g and 0.2 g respectively.

Table 4. Summary of liquefaction analysis for boreholes showing any liquefaction potential

BH No.	Seed et al. (2001)			Chinese Seismic Code GB50011-2010			
	Maximum Liquefaction Probability (%)			Intensity 7		Intensity 8	
	10% in 50 years	2% in 50 years	2% in 50 years at 250 km	I_{le}	Liquefaction Class	I_{le}	Liquefaction Class
BH01	1	79	82	2.1	Slight	11.5	Moderate
BH02	0	11	18	-	-	-	-
BH08	0	63	81	-	-	10.0	Moderate
BH20	0	1	1	-	-	-	-
BH22	6	24	82	2.6	Slight	6.1	Moderate
BH23	0	0	0	-	-	-	-
BH24 *	0	76	40	-	-	-	-
BH26	0	27	27	-	-	5.6	Slight
BH36	0	0	1	-	-	-	-
BH39 *	0	15	50	-	-	-	-
BH42 *	1	42	65	-	-	-	-
BH44	1	29	47	8.4	Moderate	19.5	Severe

* denotes no liquefaction according to the Chinese Seismic Code based on the clay content larger than 10% and 13% for earthquake Intensity 7 and Intensity 8 respectively.

4.1. Liquefaction Zoning

The available digital borehole data including SPT N values have been used to analyse the liquefaction potential for ground motions having a 10% and 2% chance of being exceeded in the next 50 years. This comprised about 2000 boreholes with sandy soils. The liquefaction probability of each borehole is calculated using the Seed et al. (2001) method. In the analysis, the ground water table is assumed to be 1.5 m below the existing ground for simplicity and is chosen based on the ground investigation work in this project, which was carried out during summer when a few rainstorms occurred. The maximum depth of liquefaction is considered to be 40 m below the existing ground. Also, only alluvial sand and silty sand are considered in the liquefaction analysis. Although some of the fill contains loose sand and may also have a chance of liquefaction, it is considered that the soil materials of fill can be highly variable and localised. Therefore, a site-specific liquefaction analysis should be considered for an area with significant fill reclamation and hence such material has not been analysed in this regional study.

The results from the *Oasys* SIREN analyses have been used to estimate the shear stress at various depths. Figure 3 shows the curves of best estimate maximum shear stress against depth for the '10% chance of being exceeded in the next 50 years' ground motion. Figures 4 and 5 also show the best estimate maximum shear stress against depth for the near-field and far-field ground motions having a '2% chance of being exceeded in the next 50 years'.

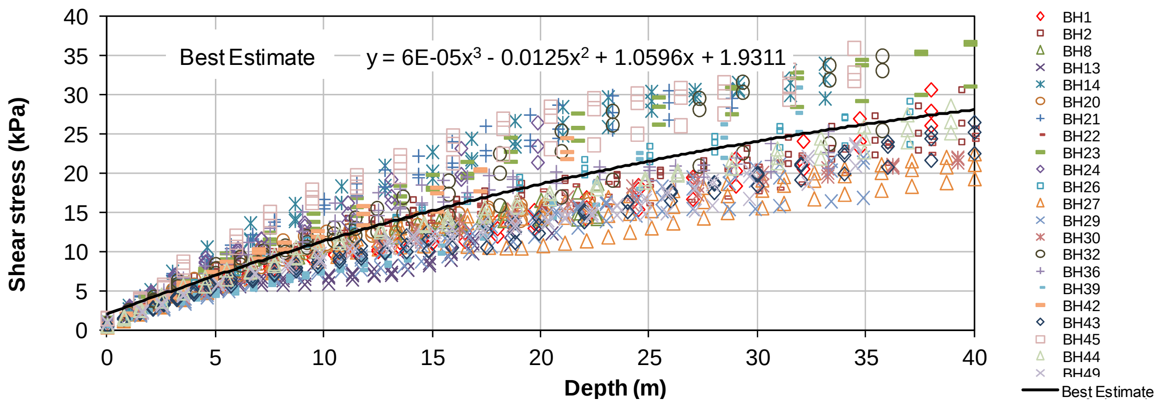


Figure 3. Maximum shear stress against depth for all boreholes for '10% chance of being exceeded in the next 50 years' ground motion

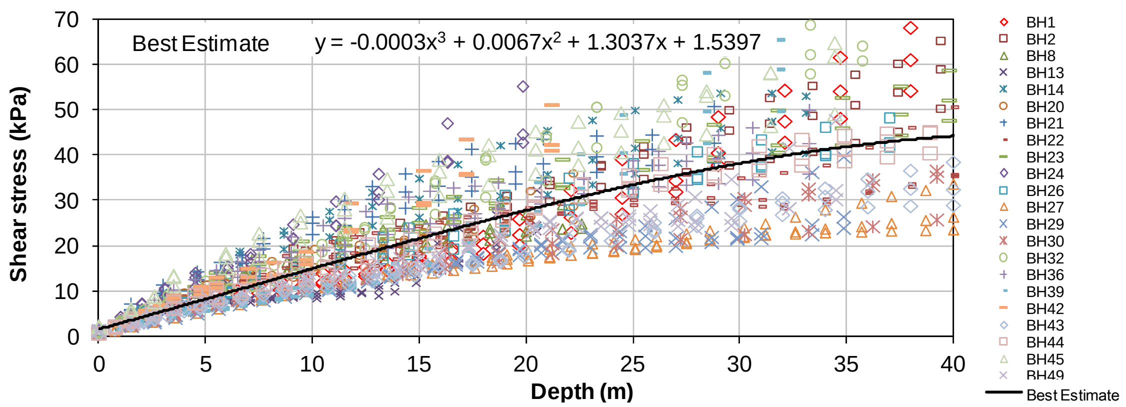


Figure 4. Maximum shear stress against depth for all boreholes for '2% chance of being exceeded in the next 50 years' near-field ground motion

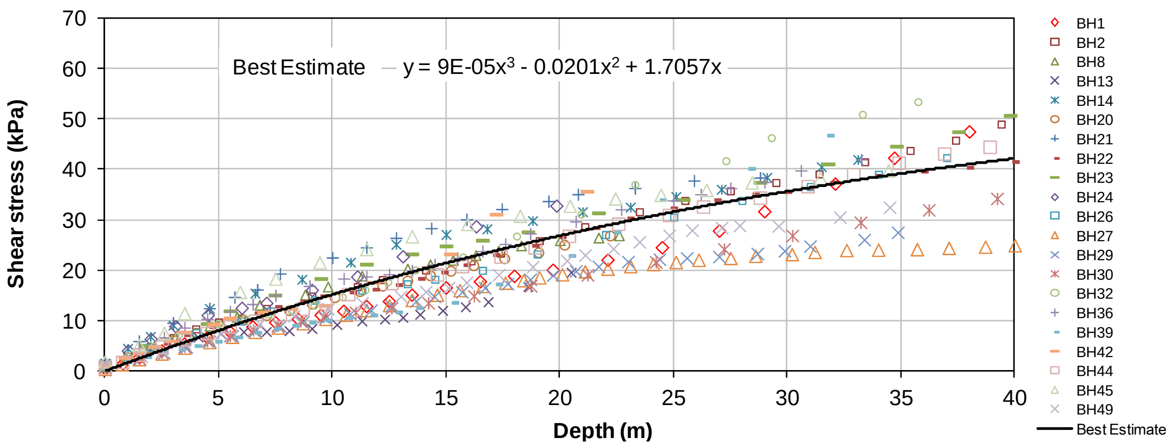
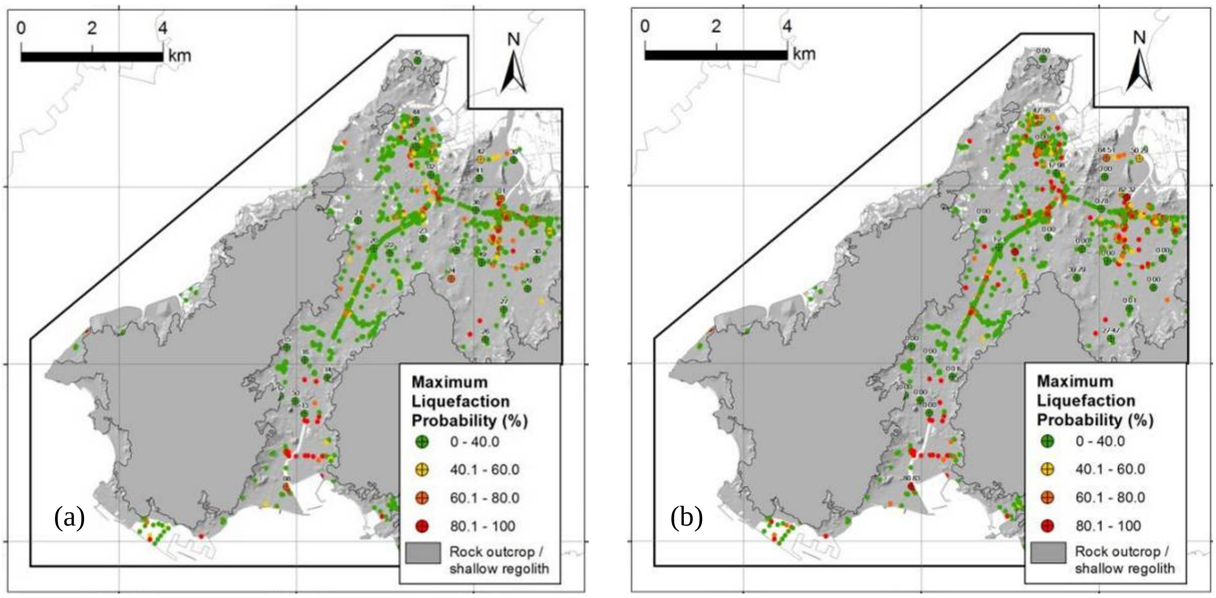


Figure 5. Maximum shear stress against depth for all boreholes for '2% chance of being exceeded in the next 50 years' far-field ground motion

The results of liquefaction potential assessment shows that the maximum probability of liquefaction for the '10% chance of being exceeded in the next 50 years' ground motion is less than 10% even if the upper estimates of maximum shear stress are applied. However, when the ground motion having only a '2% chance of being exceeded in the next 50 years' is considered, a significant number of boreholes show liquefaction probability exceeding 50% for at least one soil layer, which means that the liquefaction potential should be considered to be at least moderate.



Note: Area with rock outcrop / shallow regolith is not considered in the liquefaction assessment

Figure 6. Liquefaction probability of each borehole based on best estimate design lines for '2% chance of being exceeded in the next 50 years' (a) near-field and (b) far-field earthquake ground motions

The liquefaction probability of each borehole for the '2% chance of being exceeded in the next 50 years' ground motions are presented in Figures 6a and 6b for the best estimate maximum shear stress at various depths for the near-field and far-field earthquake events respectively. Liquefaction contours were then generated from these maps (Figures 6a and 6b) and divided into four zones of probabilities as shown in Figures 7a and 7b. The results are based on the maximum liquefaction probability of any soil layer.

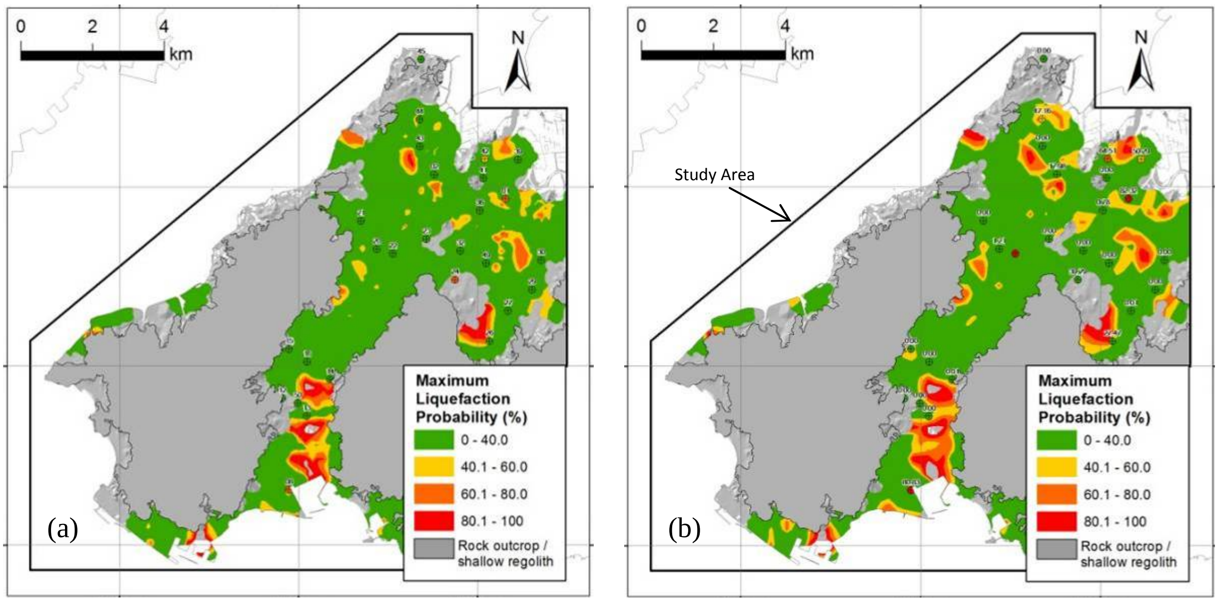


Figure 7. Contours of liquefaction probability based on best estimate design lines for '2% chance of being exceeded in the next 50 years' (a) near-field and (b) far-field earthquake ground motions

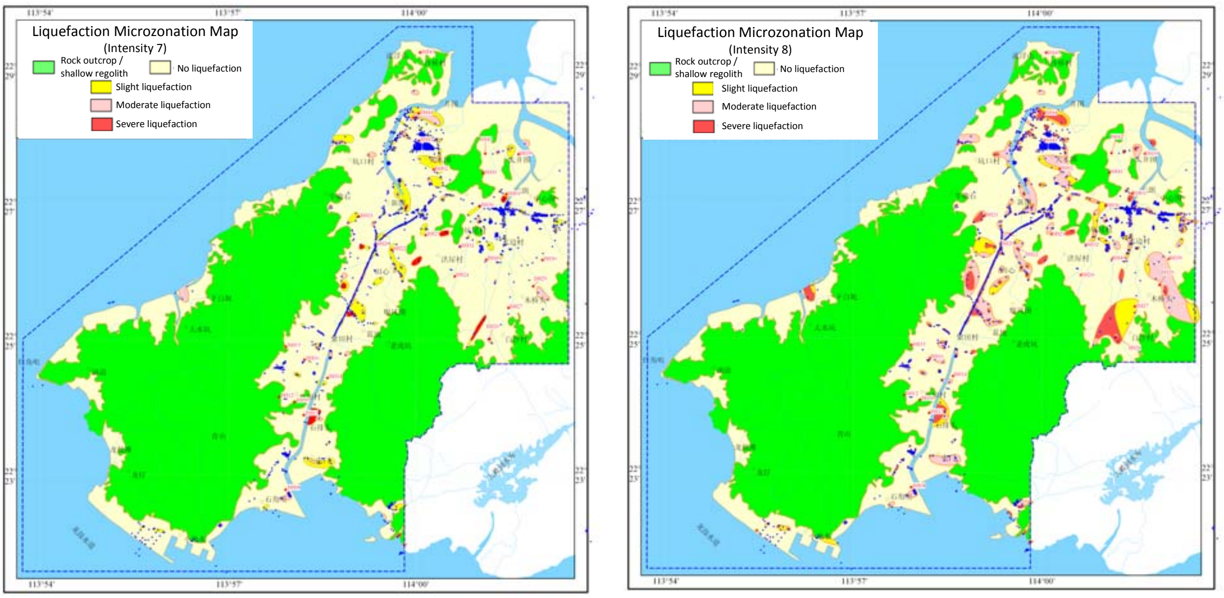


Figure 8. Contours of liquefaction probability based on the Chinese Seismic Code (GB50011-2010) for (a) earthquake Intensity 7 and (b) Intensity 8 ground motions

Based on the Chinese Seismic Code (GB50011-2010), liquefaction index microzonation maps for earthquake Intensity 7 and Intensity 8 respectively have also been produced independently by GEERRI and these are shown in Figure 8. Earthquake Intensities 7 and 8 are respectively approximately equivalent to ground motions having a 10% and 2% chance of being exceeded in the next 50 years, according to the Chinese Seismic Code (GB50011-2010). The calculations show that the chance of liquefaction derived using the Chinese Seismic Code is higher than that derived using Seed et al. (2001) for Intensity 7 and the '10% chance of being exceeded in the next 50 years' ground motion respectively. The results of both methods however, are comparable for the Intensity 8 and the '2% chance of being exceeded in the next 50 years' ground motion. It must be emphasised that the empirical method based on Seed et al. (2001) has only considered the maximum liquefaction potential of any soil layer within the borehole profile whereas the Chinese Seismic Code takes into account the effects of liquefaction for different thicknesses of the various soil layer within the profile.

5. CONCLUSIONS

The results of ground investigation and site response analysis have been used to assess the liquefaction potential in a pilot study area of the North-West New Territory region of Hong Kong. The study has adopted the Seed et al. (2001) empirical method based on SPT N values to assess the probability of liquefaction potential, while an independent liquefaction assessment based on the current Chinese Seismic Code GB50011-2010 has also been carried out. In general, the Seed et al. (2001) and Chinese Code methods show similar findings on the level of liquefaction potential for individual boreholes. Liquefaction index microzonation maps for earthquake Intensity 7 and Intensity 8 using the Chinese Seismic Code method are also produced. In Hong Kong, earthquake Intensity 7 and Intensity 8 are approximately equivalent to seismic ground motions having a 10% and 2% chance of being exceeded in the next 50 years respectively. The comparison shows that the Chinese Seismic Code gives a much higher probability of liquefaction from ground motions having a '10% chance of being exceeded in the next 50 years' but gives a similar result to Seed et al. (2001) for the more extreme '2% chance of being exceeded in the next 50 years' ground motions.

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