Determination of Small Strain Soil Properties in Hong Kong by Geophysics Testing

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ABSTRACT:

Geophysics testing techniques are commonly adopted to obtain in-situ small strain shear stiffness for seismic response analysis. The measured soil shear wave velocity can be used to determine the natural site period. A comprehensive field study has been carried out to determine the small strain soil properties in the North-west region of Hong Kong by using different geophysics testing techniques, such as down-hole seismic, PS suspension logging, cross-hole seismic, microtremor tests and multiple channel analysis of surface wave (MASW).

In this paper, the geophysics testing methods used in the study are introduced. The merits and drawbacks of the different techniques as applied to various ground conditions, including data quality and site constraints, are discussed. Based on the measured site periods, site classification and the corresponding design ground surface response spectra are determined by reference to the Australian Standard AS1170.4 and the International Building Code (IBC). The response spectra are compared with the results of the one-dimensional site response analysis carried out using computer program *Oasys* SIREN.

Keywords: Geophysics test, Site classification, Site response

1. INTRODUCTION

A pilot seismic microzonation study in the North-west New Territories of Hong Kong was completed by Arup (2012), supported by the Guangdong Engineering Earthquake Resistance Research Institute (GEERRI), for the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department in Hong Kong. In the study, 27 vertical boreholes consisted of various types of geophysics tests were carried out in the study area to investigate the soil dynamic properties. At some locations, more than one type of geophysics tests were carried out to determine the soil shear wave velocity (V_S) profiles for comparison purposes. In this paper, the adopted geophysics tests are introduced and their limitations discussed. The measured soil V_S profiles are used to determine the site classifications by reference to the Australian Standard AS1170.4 and International Building Code (IBC). This is to check if different code methods would result in changes of the site classes. Site-specific response spectrum analyses are also carried out to compare the period dependant spectral ratios with those inferred by the codes.

2. IN-SITU GEOPHYSICS TESTS

Geophysics tests were carried out in 27 vertical boreholes within the study area (see Figure 1). The following five types of geophysics techniques had been carried out (Fugro, 2009) at various site locations:

- Down-hole seismic (19 nos.)
- PS suspension logging (17 nos.)
- Cross-hole seismic (1 no.)
- Multi-analysis of Surface Wave (MASW) (20 nos.)
- Microtremor (60 nos.)

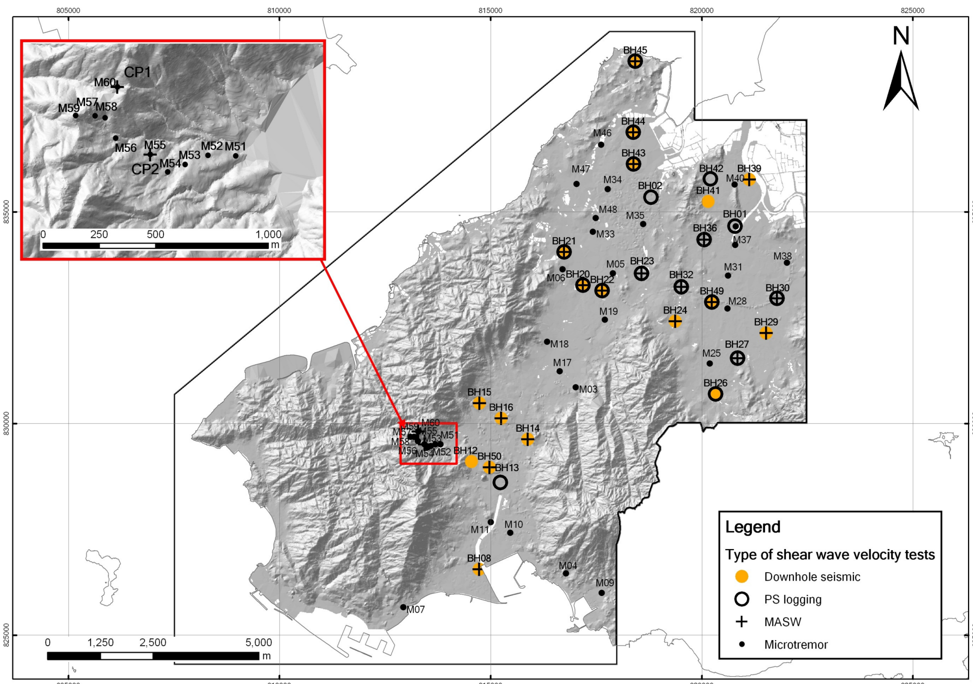

Figure 1 Geophysical field test locations

Eight site locations were selected in this study and they are generally covered with 1.5 m to 5.5 m thick fill, underlain by 1.5 m to 12 m thick estuarine deposit or alluvium, followed by 16 m to 100 m thick highly to completely decomposed granitic, volcanic or sedimentary rocks. The depths to bedrock range from 24 m to 120 m. The merits and drawbacks of the different geophysics techniques as applied to various ground conditions, including data quality and site constraints, are discussed in the following sections.

2.1 DOWN-HOLE SEISMIC TEST

Down-hole seismic test requires a vertical borehole with a diameter of 90 mm PVC pipe installed within the borehole. Grouting is used to fill the gap between the borehole and the PVC pipe, since shear waves cannot travel in fluid medium. A seismic source is generated by hammering a rigid block fixed on the ground surface (Figure 2a) and the resulting shear wave is detected by a geophone within the vertical borehole at various depths (Figure 2b). By changing source polarisation, the arrival time of shear wave could be identified. The soil V_S profile is calculated from the arrival time and wave travelling distance. This testing method is limited by the travelling distance of the generated source. Also, when the measurement is located below a rock layer, only a weak signal of shear wave is received due to high stiffness of rock mass and hence, a low quality of data may be resulted. More discussion on the data quality will be presented in Section 3.

Figure 2a Equipment of down-hole seismic test

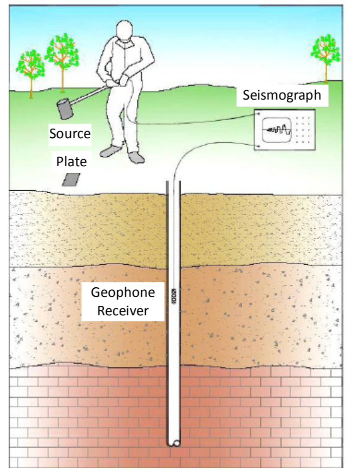

Figure 2b Set-up of down-hole seismic test (Fugro, 2009)

2.2 CROSS-HOLE SEISMIC TEST

The set-up of cross-hole seismic test is similar to down-hole seismic test but the generated shear wave is travelled in a horizontal direction rather than a vertical direction. Normally, two vertical boreholes about 10 m apart are required (Figure 3a) and a seismic source and a geophone receiver are installed at the same depth in each borehole (Figure 3b). This method can produce higher accuracy of measurements as compared to down-hole seismic test because the quality of data is not affected by signal problem due to increase of the measuring depths. However, at least two boreholes are required and the soil stratum has to be generally consistent in horizontal layer between the two boreholes in order to obtain good quality results.

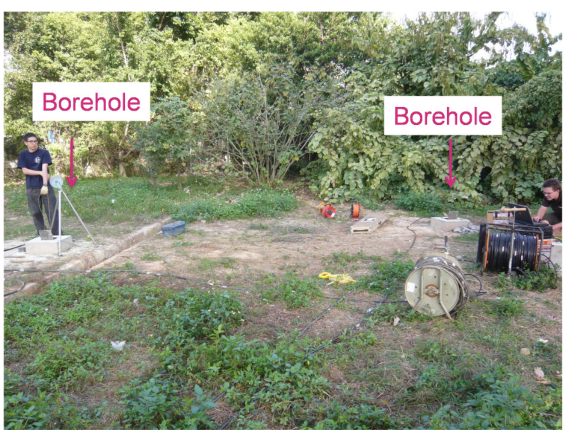

Figure 3a Equipment of cross-hole seismic test

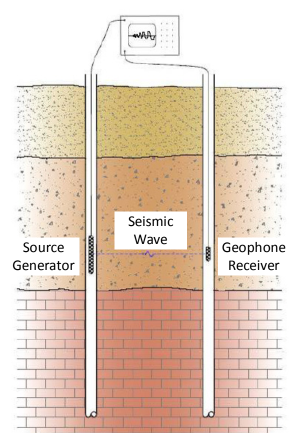

Figure 3b Set-up of cross-hole seismic test (Fugro, 2009)

2.3 PS SUSPENSION LOGGING TEST

An OYO PS Suspension Logging system was adopted in this study. In this test, seismic waves are generated at the base of the instrument lowering in a single vertical borehole (Figure 4a). The arrival waves are recorded by two geophone receivers at the top part of the instrument (see Figure 4b). The geophone receiver and the source inducer are separated by a fixed vertical distance. The source generates a P wave to the adjacent borehole wall and consequentially an upward shear wave is produced and it travels along the borehole wall. Soil V_S at a specific depth is calculated by the difference in arrival time between two geophone receivers at a fixed distance. However, the measurements must be carried out within an uncased borehole filled with water or other fluid. Sometimes, it is difficult to fill up the borehole, if the ground water level is low and permeability of the soils/rocks is high. In areas of loose material (e.g. sands and gravels) where collapse of borehole is likely to occur, the quality of the measurements cannot be attained. To overcome this problem, it is necessary to carry out the test incrementally by portions without removing the whole casing in the borehole. However, the drill rig is required to standby during the measurement and this can affect the process of the ground investigation works. Also, serious hole collapse or highly fractured rock stratum can cause irregular borehole wall surface which can lead to unsatisfactory data quality.

Figure 4a Instrument of PS suspension logging test

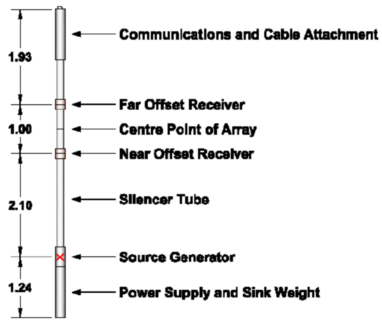

Figure 4b Set-up of PS suspension logging test (Fugro, 2009)

2.4 MULTI-CHANNEL ANALYSIS OF SURFACE WAVE (MASW)

MASW requires a seismic source using drop weight / hammer generated on the ground surface and a series of parallel geophones are installed along the ground surface to receive the surface waves (Figure 5a). The soil V_S profile is determined indirectly by interpreting the resulting Rayleigh wave dispersion curves deduced from the surface waves (Figure 5b). An estimated V_S profile is calculated with assumed values of Poisson's Ratio and density of soil. This is a quick and convenient method as no borehole is required. However, it is not a direct measurement of V_S and the measured results should be interpreted with care. In addition, the measurement depth is limited by the energy of the seismic source and was found to vary between 5 m to 20 m below the ground surface.

Figure 5a Instrument of MASW

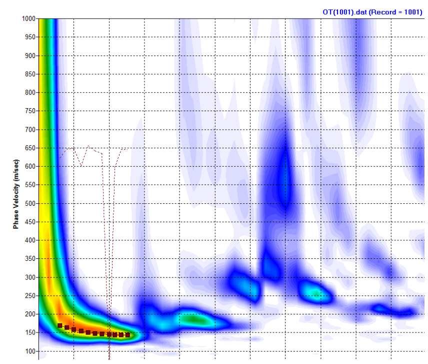

Figure 5b Dispersion curve of MASW

2.5 MICROTREMOR MEASUREMENT

The instrument of microtremor measures the tri-axial ambient vibrations of the ground caused by background noises (Figure 6). Nakamura (1989) indicated that horizontal to vertical (H/V) peak ratio corresponds to the natural site period and amplification factor. The background noises at each location were measured for at least 15 minutes. The microtremor is a non-destructive method for determining the dominant period of a site. However, it cannot be used to measure the soil V_S. Also, if there are several inter-bedded hard strata, it will affect the accuracy for determining the site period.

Figure 6 Set-up of microtremor instruments

3. DATA QUALITY OF DOWN-HOLE AND PS LOGGING TESTS

The constraints and limitations of the geophysics methods described above would affect the quality of the recorded shear waveforms and cause difficulties in identifying the first arrival time of the shear wave. As the pick for first arrival time is usually determined by manual operation, the accuracy of V_S would therefore be highly dependent on judgement of interpretation for the signal data based on the measured wave characteristics and quality. To reflect the confident level of the measured data, the data are ranked according to their level of quality from Q1 (best) to Q4 (worst).

Figure 7 shows the time traces of the down-hole seismic wave along the depth from one of the boreholes (BH49) as an example. The picks of the first arrival time of the shear waveforms along the depths are presented by a red line in Figure 7. In general, the quality of shear waveforms, i.e. sharpness and clearness of the polarisation in two directions, reduces from Q1 to Q4 with depth due to lower seismic penetration energy and dispersion by wave reflection. The descriptions of the quality ranking are presented in Figure 7. In addition, the first arrival time is difficult to be determined when the wave is recorded below the bedrock. The seismic waves reflected at the surface of hard stratum (bedrock) would interfere with the signals received by the geophones.

Figure 8 shows the general quality ranking of seismic waveforms of the PS suspension logging tests from Q1 to Q4. In Q1 and Q2 data, at least one shot of generated wave source (top left and right pictures in Figure 8) can be correlated to the two receivers and V_S can be calculated. Q1 data have clearer wave signals than Q2 data. Q3 data require further processing by overlaying of the waveforms obtained from the far and near receivers in order to recognise the same polarized shear waveform (see Figure 9a). However, no similar wave pattern at arrival can be determined from both left and right shots of the generated shear wave sources in the Q4 data. V_S can only be calculated using the first arrival of either one from the near or far receivers, as shown in Figure 9b.

Q3 and Q4 data of the PS Suspension Logging were usually found in loose soil stratum in the study area, where hole collapse occurred. The hole collapse created irregular borehole wall that directly affected the quality of seismic wave transmitted along the borehole wall. Since there are limited number of cross-hole seismic and MASW tests, the quality of data are not classified into different ranking in this study.

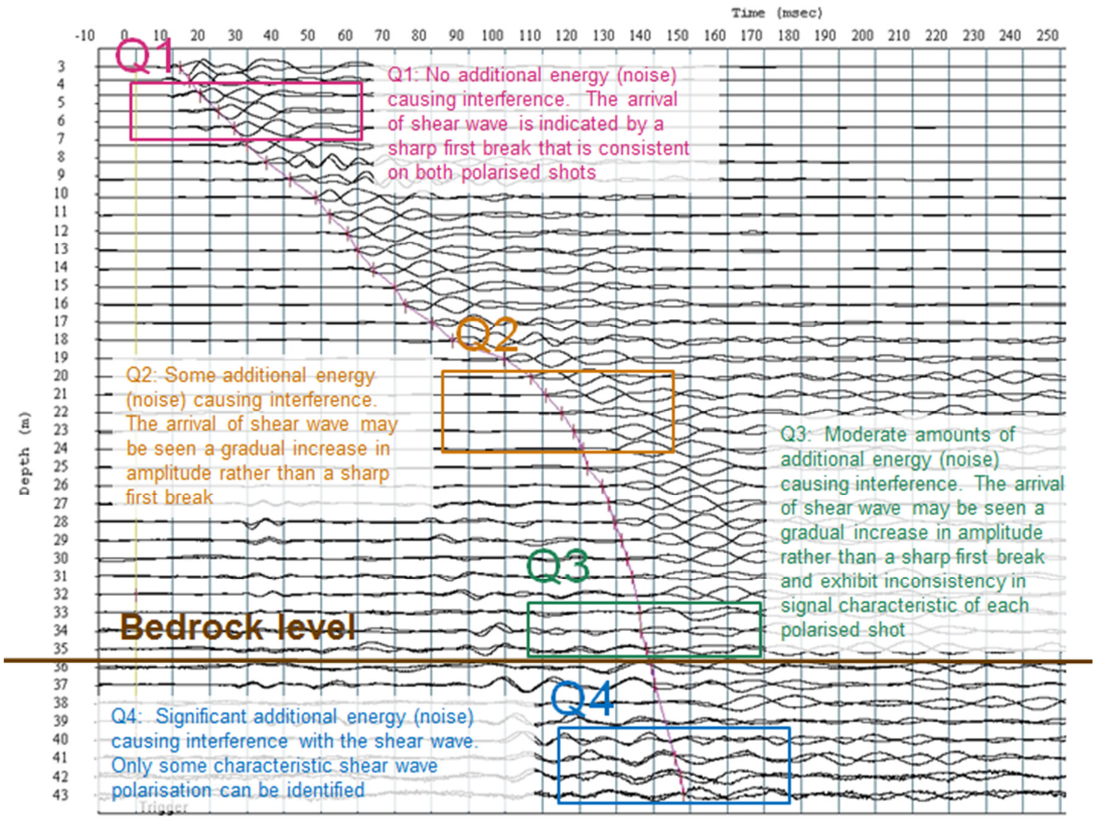

Figure 7 Quality of seismic waveforms from the down-hole seismic test in BH49

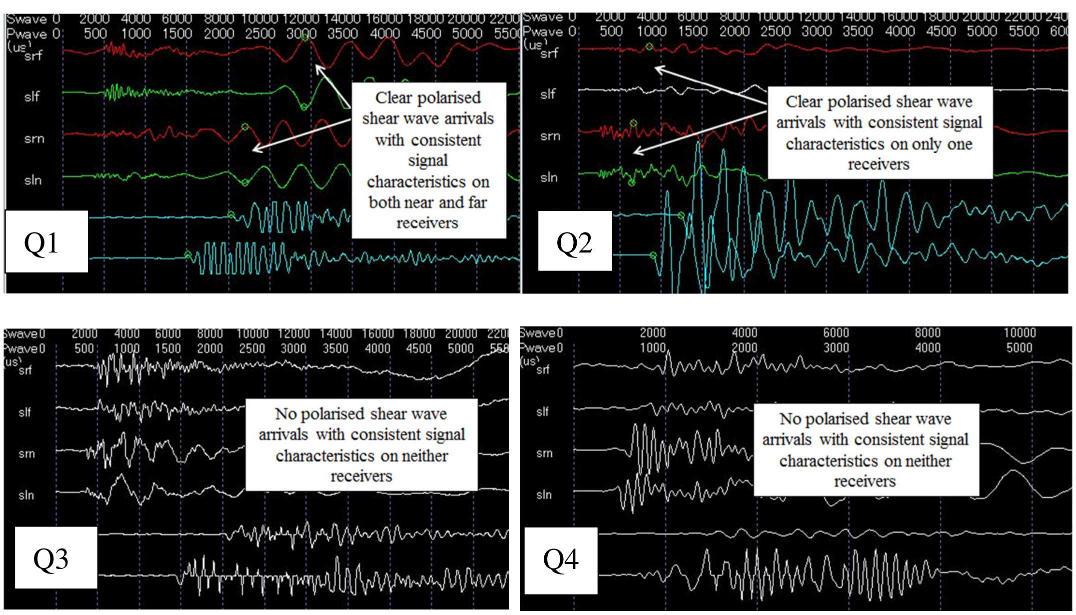

Figure 8 Quality of seismic waveforms from the PS suspension logging

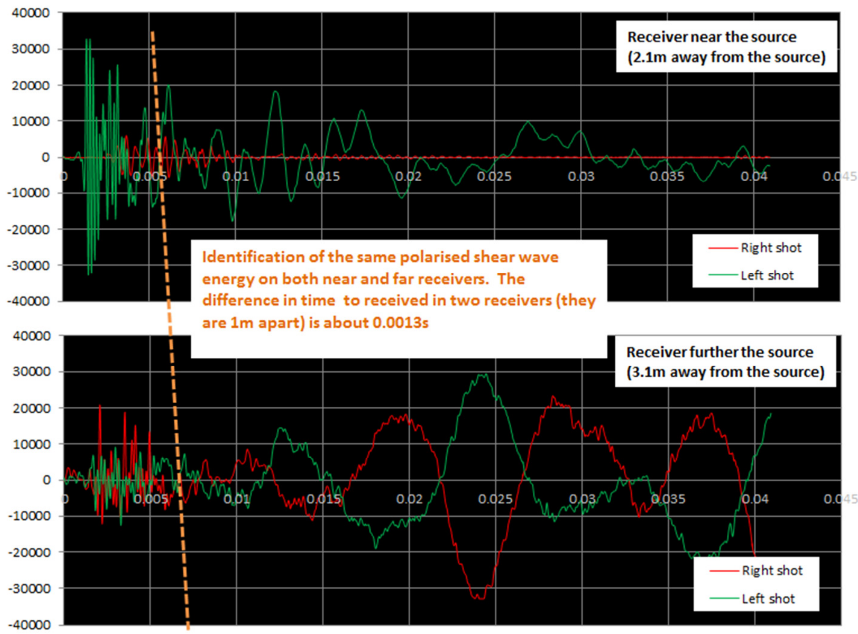

Figure 9a Further processing for Q3 a data in PS suspension logging

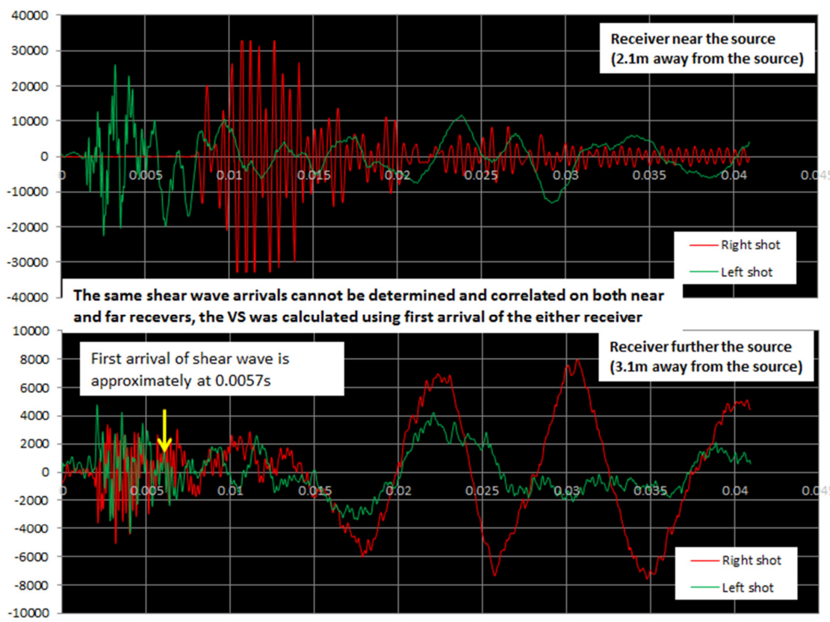

Figure 9b Data interpretation for Q4 data in PS suspension logging

4. COMPARISON OF SITE CLASSIFICATION BY DIFFERENT GEOPHYSICS TESTS

Eight testing locations were selected for comparison of the determination of site classifications. Down-hole seismic, PS suspension logging and microtremor tests were conducted in all these selected locations. Cross-hole seismic tests were also carried out in one of these locations (borehole BH36). MASW were performed in all locations except borehole BH26.

Conventionally, in-situ measured soil V_S profile is the preferred parameter to determine the site class by the international standards. In AS1170.4, a site is classified by the site natural period which is calculated from a simple wave equation of $4H/V_S$, where H is the soil depth above the bedrock. In IBC, an average value of V_S down to a depth of 30 m (V_{S30}) is used for the site classification.

The data obtained from different geophysics measurements at the selected locations were used to classify the sites according to the procedures presented in AS1170.4 and IBC. The best estimate V_S profile was derived using the high quality in-situ measurements as defined by Q1 and Q2, which was explained in Section 3 above (example in Figure 10). The results of site periods and V_{S30} values at the selected borehole locations are summarised in Table 1 and Table 2 respectively.

Table 1 Comparison of site period and classes

	Depth to Rock (m)	Site Period (AS1170.4) (s)								Measured Site Period (s)	
		Best Estimate		Downhole		PS logging		Crosshole		Microtremor	
BH20	23.9	0.41	Class C	0.46	Class C	0.48	Class C	N/A	N/A	0.44	Class C
BH21	33.3	0.37	Class C	0.51	Class C	0.39	Class C	N/A	N/A	0.46	Class C
BH22	43.7	0.7	Class D	0.67	Class D	0.72	Class D	N/A	N/A	0.44	Class C
BH26	>120	1.27	Class D	Note 1				N/A	N/A	0.4	Class C
BH36	35	0.5	Class C	0.5	Class C	0.51	Class C	0.46	Class C	0.39	Class C
BH44	47.1	0.63	Class D	0.77	Class D	0.65	Class D	N/A	N/A	0.53	Class C
BH45	38	0.39	Class C	0.33	Class C	0.36	Class C	N/A	N/A	0.32	Class C
BH49	48.3	0.66	Class D	0.62	Class D	0.48	Class C	N/A	N/A	0.46	Class C

Notes:
1. Shallow soil with site period less than or equal to 0.6 second is classified as Class C.
2. Deep or soft soil with site period greater than 0.6 second is classified as Class D.

Table 2 Comparison of V_{S30} using IBC

	Depth to Rock (m)	V_{S30} (IBC 2012)							
		Best Estimate		Downhole		PS logging		Crosshole	
BH20	23.9	231	Class D	206	Class D	186	Class D	N/A	N/A
BH21	33.3	339	Class D	241	Class D	313	Class D	N/A	N/A
BH22	43.7	215	Class D	234	Class D	213	Class D	N/A	N/A
BH26	>120	305	Class D	265	Class D	Note 2		N/A	N/A
BH36	35.0	269	Class D	260	Class D	246	Class D	275	Class D
BH44	47.1	272	Class D	199	Class D	264	Class D	N/A	N/A
BH45	38.0	348	Class D	395	Class C	324	Class C	N/A	N/A
BH49	9.0	222	Class D	227	Class D	356	Class D	N/A	N/A

Notes:

1. Very dense soil with V_{S30} in between 360 m/s and 760 m/s is classified as Class C.
2. Stiff soil with V_{S30} in between 180 m/s and 360 m/s is classified as Class D.

In general, the results of site classifications using measurements of different geophysics methods are consistent, except for borehole locations of BH45 and BH49. At the borehole location of BH45, there are more data of Q3 in the down-hole measurements than the PS suspension logging measurements (Figures 10 and 11). The reason for the above lower quality data was the delay of the grouting operation. The site records showed that the grouting to fill-up the gap between the PVC pipe and the borehole wall was carried out few days after the completion of the drilling, and as such the hole might have collapsed prior to the grouting work.

Figure 10 also shows relatively high V_S values were measured in PS suspension logging tests between the elevations of 2 mPD to -10 mPD. The seismic traces as shown in Figure 12 indicate that the first arrival time is unable to be determined at such elevations. According to the site records, serious borehole collapse occurred at borehole BH49 when the casing was being extracted at the levels of the cavity infill strata in marble and the alluvium stratum. The borehole wall was significantly disturbed and this might have resulted in much more Q3 and Q4 data. Therefore, there was a high uncertainty in picking the first arrival time for the V_S calculations.

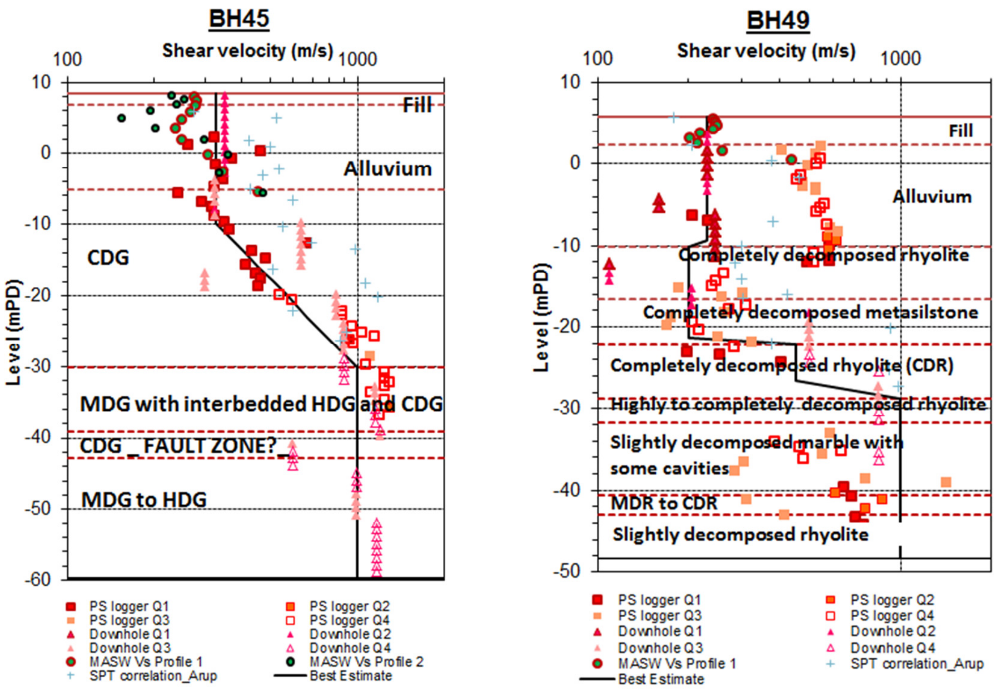

Figure 10 V_S profiles for BH45 and BH49

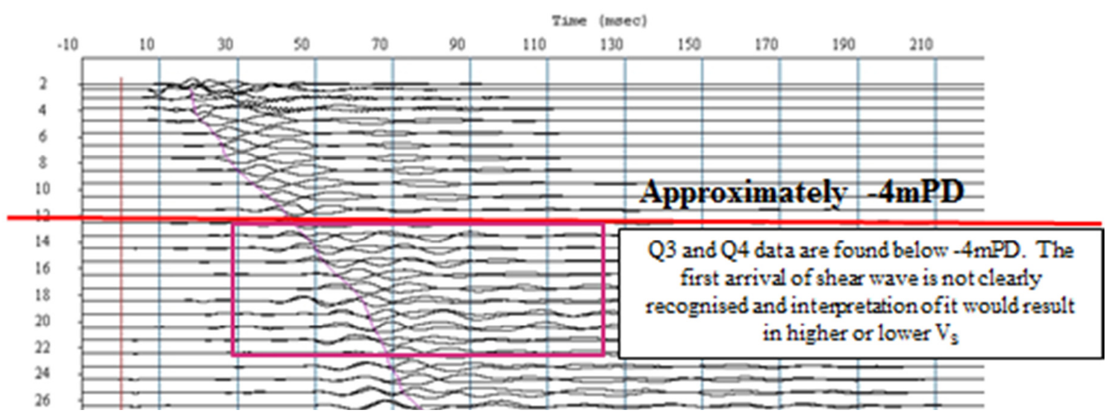

Figure 11 Seismic waveforms of the down-hole seismic test in BH45

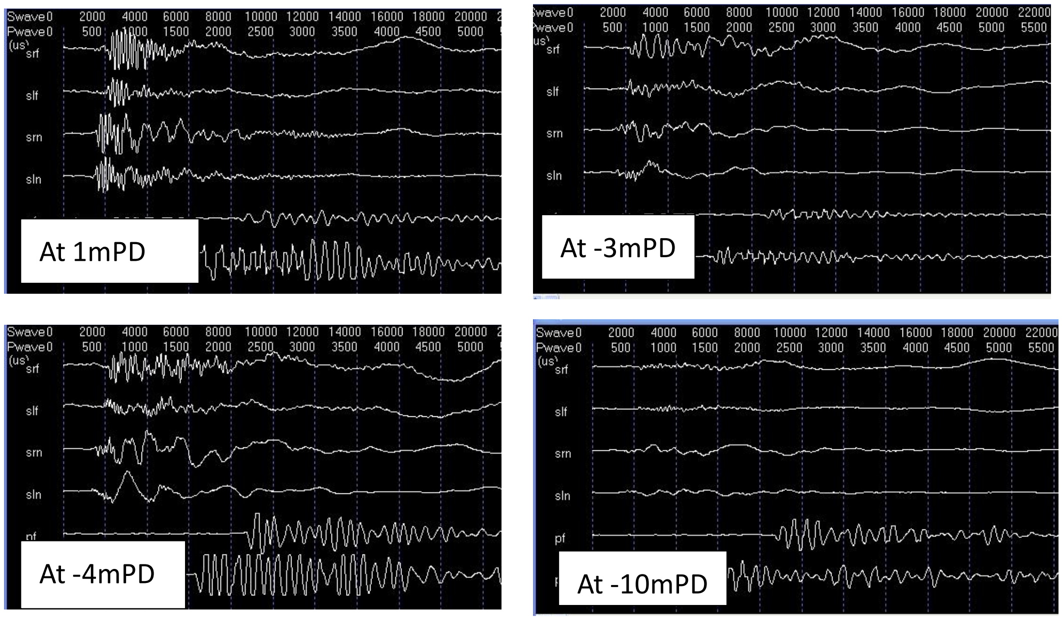

Figure 12 Waveforms of the PS suspension logging test at the level between 2mPD to -10mPD in BH49.

Site periods were calculated by the above equation of $4H/V_S$ by the down-hole and PS suspension logging tests and the results are summarised in Table 3. The calculated site periods are compared with the measurements of the MASW. The comparison shows that the site period up to the lowest level of MASW measurements among the other geophysics tests are similar, which implies that all these geophysics methods can give consistent results of V_S.

Table 3 Site period comparison with MASW

No.	Lowest depth of measurement of MASW (m)	Site period calculated to the bottom depth of MASW (s)		
		MASW	Down-hole	PS suspension logging
BH20	11.8	0.25	0.25	0.31
BH21	9.1	0.13	0.16	0.15
BH22	19.3	0.38	0.36	0.36
BH36	10.0	0.18	0.19	0.18
BH44	14.2	0.30	0.39	0.16
BH45	14.0	0.20	0.17	0.17
BH49	5.1	0.08	0.09	0.04

5. SPECTRAL RATIO COMPARISON FROM SITE RESPONSE ANALYSIS

Site response analyses were carried out for the selected 8 locations using program *Oasys* SIREN, which is a 1-dimensional non-linear finite difference program. Detailed calibration analyses undertaken using *Oasys* SIREN were described by Henderson et al. (1990) and Heidebrecht et al. (1990). The best estimate V_S profiles were adopted in the site response analyses. Suitable earthquake records were adjusted to match the target uniform horizontal response spectrum (UHRS) of the Hong Kong ground motion, having a 2% probability of being exceeded in the next 50 year. The UHRS has been determined from a PSHA study in Hong Kong by Pappin et al. (2012). The input bedrock shear wave velocity ranges between 1,000 m/s and 1,500 m/s. The bedrock is modelled as a wave transmitting boundary and further details of the modelling can be found in Pappin et al. (2012).

Spectral ratios were obtained from the site response analyses and compared with those derived from IBC and AS1170.4 using their procedures. Figures 13 and 14 show that all the calculated ground surface response spectra from the site response analyses are enveloped by Class D response spectra derived from IBC and AS1170.4. Stiff soil with V_{S30} in between 180 m/s and 360 m/s and the site period greater than 0.6 second are classified as Class D in IBC and AS1170.4 respectively. The detailed descriptions of the site classification can be found in IBC (2012) and AS1170.4 (2007). All the selected 8 sites were resulted in Class D by the IBC procedures, as shown in Table 2. However, there is a variation of site classes between Class C and Class D by using AS1170.4, as shown in Table 1. Very dense soil with V_{S30} in between 360 m/s and 760 m/s and the site period less than 0.6 second are classified as Class C in IBC and AS1170.4 respectively. Among the eight selected boreholes, BH20, BH21, BH36 and BH45 consist of relatively stiff soil as classified in Class C by AS1170.4. Although the peak spectral ratios of these four boreholes are relatively low, they still cannot be enveloped by the Class C response spectrum of AS1170.4.

The measured periods by the microtremor tests are also presented in Figures 13 and 14. The measured periods are consistently lower than the calculated peak periods of each borehole by the site response analyses. This can be explained that the calculated peak periods in the site response analyses are based on the non-linear shear stiffness degradation which results in lower V_S (i.e. Site Period = $4H/V_S$).

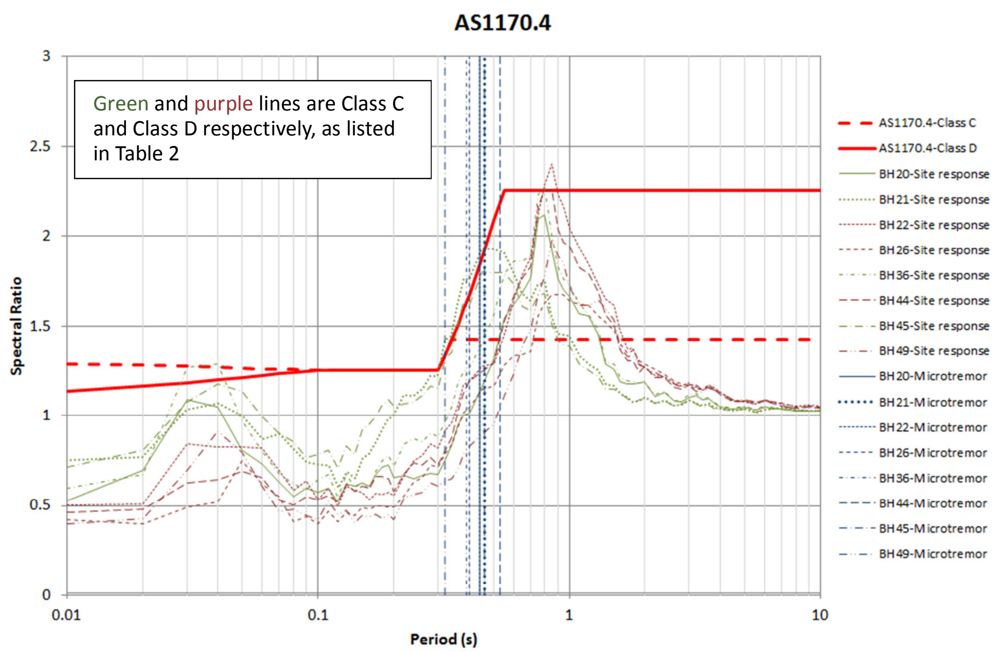

Figure 13 Spectral ratio comparison to AS1170.4 (2007)

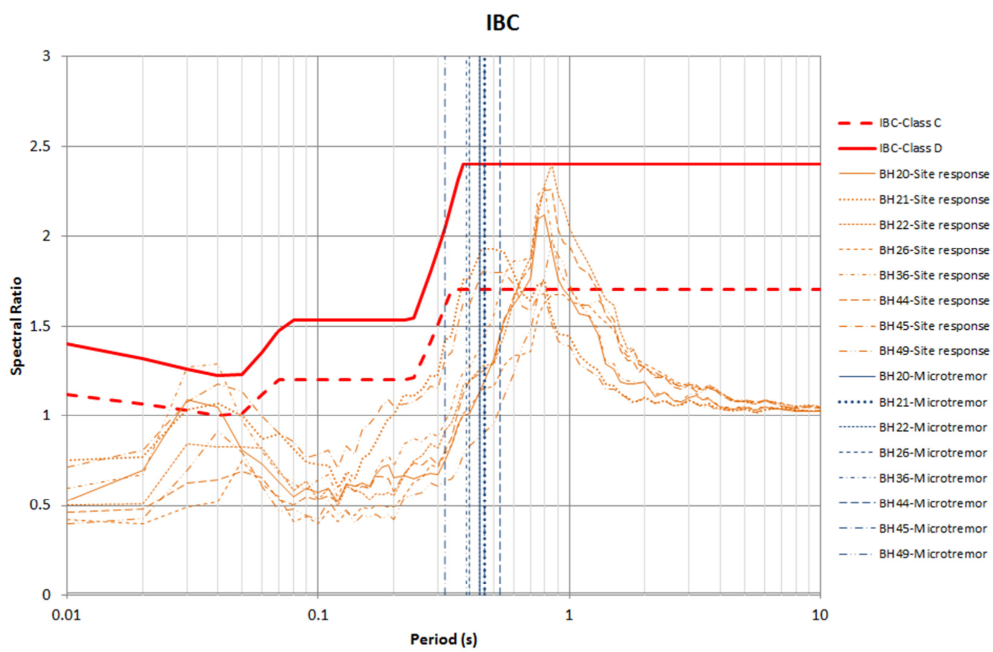

Figure 14 Spectral ratio comparison to IBC (2012)

6. DISCUSSION AND CONCLUSIONS

This study aimed to compare various geophysics techniques for measuring insitu shear wave velocity (down-hole seismic, PS suspension logging, cross-hole seismic and MASW tests) and whether they would lead to a different site classification. The merits and drawbacks of the different techniques as applied to various ground conditions, including data quality and site constraints, are discussed. To conduct the comparison of site classification, the procedures of AS1170.4 and IBC were adopted for the selected sites. The results show that the determined site classes were generally consistent by using different geophysics test methods, except in some situations where the ground was disturbed during formation of the boreholes.

The quality of the data is for the borehole tests are affected by the source energy and reflection of borehole wall surface or inter-bedded hard strata. Data quality can significantly reduce in a collapsed borehole with loose soil stratum. The irregularity of the borehole wall could alter the shear waveform causing difficulty in determining the first arrive time pick for the V_S calculation. Quality of the grouting should be monitored to ensure that the gap between the PVC casing and the borehole is filled in properly. In addition, the quality of data decreases with increasing depth, hence it is not recommended to carry out down-hole seismic test in very deep boreholes.

MASW can only estimate V_S for a shallow depth of ground profile, unless a very large seismic source can be used. It cannot provide reliable soil V_S profile, if the soil depth is more than about 10 m. However, within its depth limit, MASW gives similar V_S measurements as compared with other geophysics methods. MASW can be therefore a convenient non-destructive method to supplement the other destructive geophysics methods at shallow depths. Finally, it is important to consider the site constraints and local geology (e.g. inter-bedded hard strata) to ensure that test data can be acquired with the best quality.

The eight selected sites are all classified to be Class D according to the procedures of IBC and the calculated ground surface response spectra are enveloped by the Class D spectrum of IBC. If the sites are classified according to AS1170.4 four of them become Class C. The results of 1-D site response analyses show that the Class C spectral envelope of AS1170.4 may underestimate the peak site response of several site conditions.

7. ACKNOWLEDGEMENTS

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