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In-situ measurement of shear wave velocities at two soft soil sites in Singapore

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ABSTRACT: In-situ measurement of shear wave velocities provides information on soil stiffness at very low strain, typically less than 10^{-3}%. It is now widely recognised that low strain stiffness should be determined as part of the site investigation for seismic problems. However depending on the measurement method, there are some differences in the wave velocities. In-situ measurement of shear wave velocities using the down-hole technique and continuous surface wave technique were performed at two soft soil sites in Singapore. In the down-hole technique, a single borehole, a horizontally polarised surface source and a down-hole geophone were used. The continuous surface wave technique uses a continuous vibrating source placed on the ground surface. Surface waves of various frequencies from 5 to 100 Hz were generated and the waves were picked up by a series of geophones placed collinear with the source. The surface wave test measures the Rayleigh wave velocities. The down-hole tests were able to provide information to a great depth whereas the surface wave tests were only able to provide information down to a depth of about 12 m. The measured shear wave velocities found from the down-hole test and computed shear wave velocities found in the surface wave tests show differences of about ±10%. The difference is not due to the assumed Poisson's ratio used in the computation of the shear wave velocities from the Rayleigh wave velocities alone, but is also attributed to the differences in wave source.

1 INTRODUCTION

The response of soil to strain is highly non-linear. At very low strain levels, less than 10^{-3}%, the soil response is linear which allows the use of elastic theory. At intermediate strain levels, 10^{-3}% to 10^{-1}%, the soil response becomes non-linear. At high strain levels, greater than 10^{-1}%, the soil response remains non-linear and will start to experience plastic deformation and may eventually reach an unstable condition (Mathews et al. 1996, Luna and Jadi 2000). Geophysical methods are becoming increasingly popular in site investigation to complement conventional site investigation methods (McCann and Green 1996). The soil properties determined using geophysical methods correspond to very small strain levels and these properties are usually termed as dynamic soil properties. The compression and shear wave velocities of the soil are commonly determined in geophysical measurements. The bulk modulus, shear modulus, Poisson's ratio and Young's modulus of the soil can be determined from the compression and shear wave velocities. The computed stiffness is an in-situ measurement and thus avoids the usual problems of laboratory tests such as sampling disturbance, unrepresentative sampling, sample-size effect and stress condition (Anderson and Woods 1975). For saturated soils, the compression wave velocity is usually not measured as the compression wave velocity is that of water and is not indicative of the stiffness of the soil.

Geophysical methods may be divided into two broad categories: subsurface and surface methods (Ado and Robertson 1992, Menzies 2000). Examples of subsurface methods are down-hole survey, up-hole surveys, seismic cone and cross-hole surveys. Examples of surface methods are refraction surveys, reflection surveys and surface wave methods. The subsurface methods usually require one or more boreholes, whereas surface methods are non-intrusive. The measured shear wave velocities of soils differ depending on the geophysical investigation method used. In this paper, two geophysical methods, down-hole and continuous surface wave, were employed at two soft soil sites in Singapore. The results from these geophysical investigations are presented and compared.

2 DESCRIPTION OF GEOPHYSICAL METHODS

2.1 Down-hole method

In the seismic down-hole test, only one borehole is required (Figure 1). The components in the down-hole test set-up consist of an impulse source, a down-hole receiver, recorder and trigger. The receiver (borehole packer with bi-directional geophones) is fixed in the borehole at the required depth. The impulse source is provided by a hammer blow either directly (P wave) or parallel (S wave) to the ground surface usually through a wooden plank weighed down by a set of dead weights. The trigger consisting of geophones are fixed to the impulse source. The down-hole test can be performed with a string of receivers or a single receiver at various depths. The down-hole tests reported in this paper were performed using a single receiver. The test was performed twice at each depth. For the S-wave test, a wooden plank was struck at each end in turn so each S-wave generated is the reverse of the other. The receiver signals are superimposed and if a discrepancy is found in the arrival times between the two signals, the test is repeated again. For the S-waves, arrival time is identified as the beginning of the reversal of the signal. Details of the down-hole test can be found in Hoar and Stokoe (1978). The corrected arrival time, t, of the P or S wave is computed as

$$t = \frac{d}{L} T \qquad (1)$$

where L is the distance from the source to the receiver given by $\sqrt{x^2 + d^2}$, x is the horizontal distance from the source to the top of the borehole, d is the depth of the receiver and T is the measured first arrival time. By plotting d versus t, the wave velocity is given by the slope of the line.

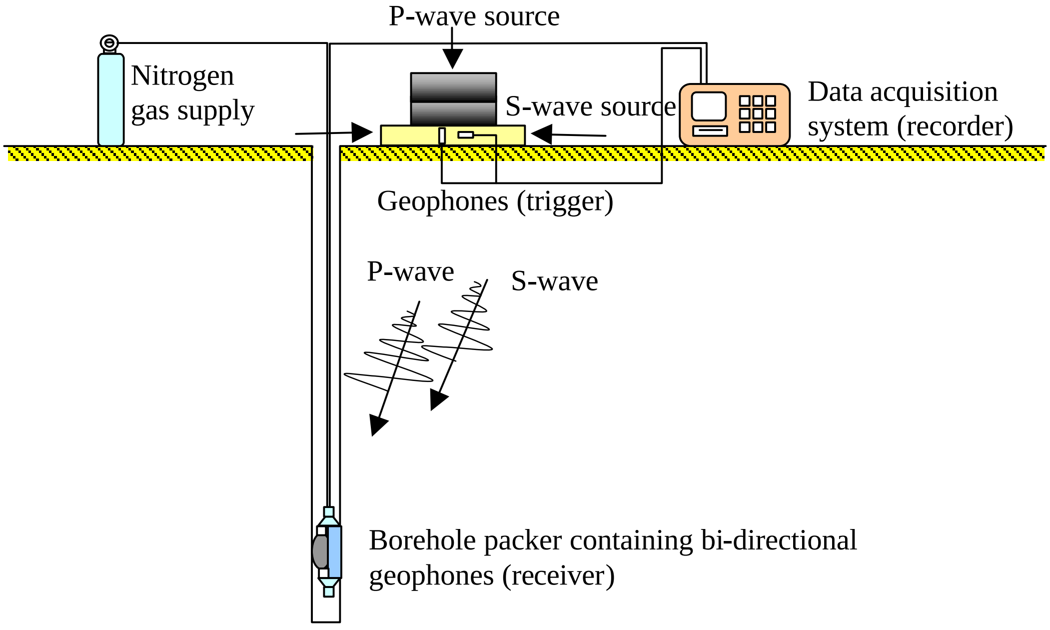


Figure 1. Schematic of down-hole method.

2.2 Surface wave method

Surface or Rayleigh waves are generated near the boundary of an elastic half-space. Rayleigh waves attenuate rapidly with depth, usually within one wavelength. Therefore, Rayleigh waves of different wavelengths penetrate the ground to different depths. For a uniform, isotropic elastic half-space, Rayleigh waves travel at a velocity independent of its wavelength. In a layered half-space, the Rayleigh wave velocity will depend on the wavelength as a long wavelength (low frequency) Rayleigh wave would penetrate the ground deeper and be influenced by the deeper material than a Rayleigh wave with short wavelength (high frequency). Two types of energy source are used in the surface test: impact sources such as a hammer or explosion source, or a continuous source such as mass vibrator. Impact sources are commonly used with spectral analysis of surface wave (SASW) (Stokoe and Nazarian 1985) whereas the continuous source gives rise to the continuous surface wave (CSW) method (Mathews et al. 1996). The test set-ups for both the SASW and CSW methods are similar: an energy source, geophones and a recorder.

In the SASW method, the Rayleigh waves are generated by an impact source providing frequencies in the range of 3 to 200 Hz which are picked up by a pair of geophones and recorded on the recorder (Mathews et al. 1996, Ganji et al. 1998). The signals then are able to produce the cross power spectrum, through undergoing Fourier transformation. For each frequency f, the Rayleigh wave velocity, V_r, is computed using the following equation:

$$V_r = \frac{2\pi f \Delta x}{\Delta\phi} \tag{2}$$

where Δx is the distance between the geophones and $\Delta\phi$ is the phase difference. A plot of the Rayleigh wave velocity versus wavelength gives the dispersion curve. The Rayleigh wave velocity-depth profile is then obtained through inversion of the dispersion curve. From elastic theory, shear wave velocity and Rayleigh wave velocity is related by

$$V_s = pV_r \tag{3}$$

where p is a function of Poisson’s ratio ν.

In the CSW method, the Rayleigh waves are generated by a vibrating mass which cycles through a range of frequency from a few Hz to few tens of Hz (Mathews et al. 1996, Menzies 2000). The energy of the Rayleigh waves depends on the size of the vibrating mass. The Rayleigh waves are detected by a series of geophones and recorded on the recorder. The signals are Fourier transformed and the phase angle, ϕ, for that frequency, f, is then obtained. By plotting the phase angle against distance of the geophones from the source, the wavelength λ can be determined as:

$$\lambda = \frac{2\pi\Delta x}{(2\pi n + \Delta\phi)} \tag{4}$$

where n is the number of Rayleigh waves between the geophones. Usually, the spacing of the geophones, Δx, is less than the wavelength of the Rayleigh wave, λ, and therefore, n is zero. The wavelength is thus given by the slope of the phase angle versus geophones distance plot multiplied by 2π. The Rayleigh wave velocity is then given by:

$$V_r = f\lambda \tag{5}$$

The dispersion curve is given by a plot of V_r versus λ. The Rayleigh wave velocity profile is obtained by inversion of the dispersion curve. In this paper, the CSW method was employed using a CSW system from GDS Instruments Ltd. A schematic of the CSW test set-up is shown in Figure 2. The vibrating mass weighing 64 kg applies a regulated and predominantly vertically polarised disturbance to the ground surface. The vibrating mass, producing Rayleigh waves at frequencies from 5 to 100 Hz, is controlled by a personal computer through a controller unit and a vibrator drive unit. The surface waves are detected by six geophones (4.5 Hz or 2 Hz) placed collinear with the vibrating mass.

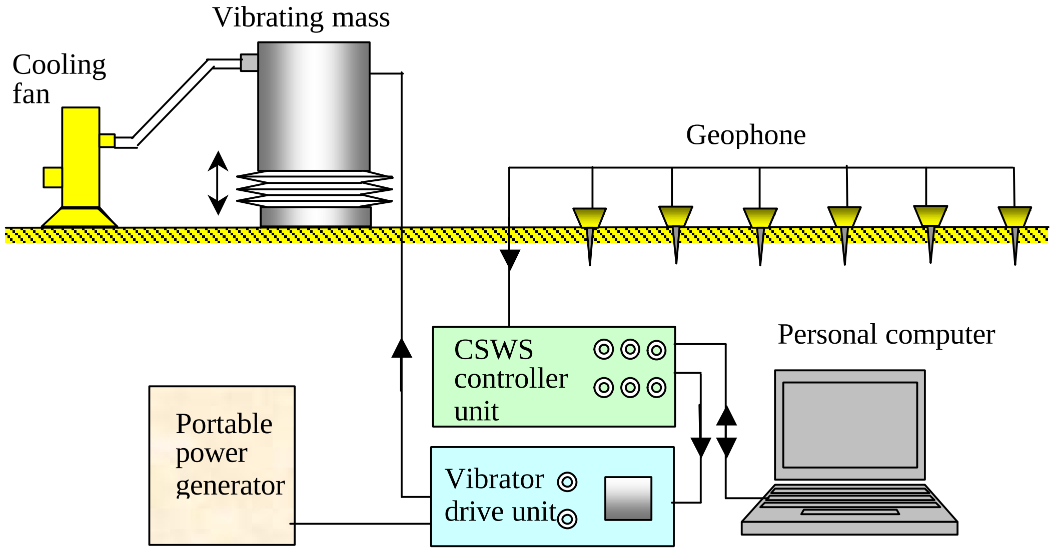


Figure 2. Schematic of CSWS test set-up

3 SOFT SOIL SITES

In Singapore, recent sediments occupied about 25% of the total land area (PWD 1976). The recent sediment deposits typically consist of a fill followed by a marine clay deposit of three distinct layers: an upper marine clay layer which is several metres to several tens of metres, an intermediate clay layer typically of a few metres and a lower marine clay layer that is several metres to several tens of metres. Geophysical tests were conducted at two sites, denoted as Site B and Site K in this paper, which are located in areas of the recent sediment deposits. The two sites are about five kilometres apart. Representative properties of the soil layers at the two sites are summarised in Table 1.

Table 1. Soil stratification and index properties of soft soil sites.

Soil Strata	**Site B**					**Site K**				
	H (m)*	**LL**	**PL**	**w (%)**	r **(Mg/m^3)**	**H (m)**	**LL**	**PL**	**W (%)**	r **(Mg/m^3)**
Fill	5.0	-	-	~20	~1.9	6.5	-	-	15-21	~1.95
Upper Marine Clay	11.0	~92	~24	60-70	~1.65	13.0	~90	~25	55-60	~1.66
Intermediate Clay	2.0	~59	~34	~40	~1.85	2.0	~55	~21	~25	~1.90
Lower Marine Clay	13.5	~86	~22	50-55	~1.70	9.0	~60	~22	46-52	~1.69

* H = Thickness of layer

4 TEST RESULTS AND DISCUSSIONS

4.1 Down-hole tests

Down-hole tests were performed at both Site B and Site K with a single geophone receiver in a cased borehole. The geophone receiver was lowered at 1 m depth intervals. The plots of depth versus travel time are shown in Figure 3. With the aid of the borehole logs, best-fit straight lines were fitted to the various soil strata and the P and S wave velocities were determined from the slopes of the straight lines. A summary of the P and S wave velocities for the various strata is given in Table 2. The P wave velocity indicates that the fill is not fully saturated at Site B. For Site K, the P wave velocities are the same for the fill and upper marine clay. However, the soil layers can be discerned through the S wave velocities.

Table 2. Summary of P and S wave velocities from down-hole tests.

Soil Strata	Site B		Site K	
	V_p (m/s)	V_s (m/s)	V_p (m/s)	V_s (m/s)
Fill	1127	105	1514	133
Upper Marine Clay	1570	131	1514	122
Intermediate Clay	1524	180	1667	207
Lower Marine Clay	1585	159	1561	151

4.2 CSW tests

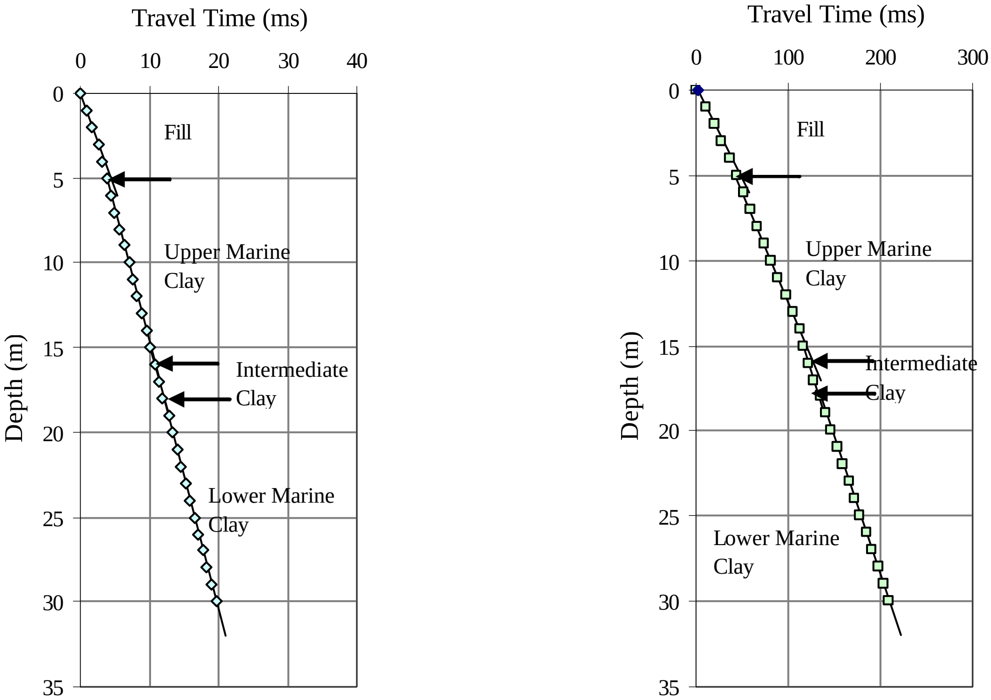
CSW tests were conducted by placing six 4.5 Hz geophones at 0.5 m intervals collinear with the vibrating mass which is positioned at 1 m from the nearest geophone. An initial sweep using frequency from 5 to 100 Hz at 5 Hz intervals was conducted. As the number of points in the dispersion curve was few and far between in the low frequency range, a more refined run was usually conducted for the low frequency range at smaller frequency intervals. The 2 Hz geophones were also used to pick up the lower frequency Rayleigh waves. However, the 2 Hz geophones were found to be very sensitive to ambient noise even when the tests were performed in the early hours of the morning after midnight. Only marginal improvement was noticed in the dispersion curve when the 2 Hz geophones were used. At each site, the line of geophones was rotated about the vibrating mass at angles of 90^o. Four tests were conducted at Site B and three tests were conducted at Site K. The test configurations were indicated in Figure 4. The dispersion curves for Site B and Site K are shown in Figure 4. At short wavelengths (< 5 m), Site B shows a noticeable scatter in the dispersion curves. This is due to refraction and reflection of the Rayleigh wave at the ground surface boundary. Such scatter is also noticeable at the soil layer boundaries. The dispersion curves of both Site B and Site K show two different Rayleigh wave velocity layers with the dispersion curves of Site K giving a clearer distinction of the two layers.

The inversion of the dispersion curve to a shear velocity-depth profile can be done at different levels of sophistication. At the simplest level, the wavelength-depth method can be used to provide a quick assessment (Mathews et al. 1996, Tokimatsu 1997). In the wavelength-depth method, λ/z is assumed to be constant. Value of $\lambda/z = 2$ is commonly used (Jones 1958, Heukolom and Foster 1962, Ballard and McLean 1975, Abbis 1981). Gazetas (1982) recommended that $\lambda/z = 4$ should be used at sites where stiffness increases with depth and $\lambda/z = 2$ should be used at homogeneous sites. An average value of $\lambda/z = 3$ was recommended as a suitable compromise (Gazetas 1982). Applying $\lambda/z = 2$ to the dispersion curves of Site B and Site K gave good estimate of the thickness of the fill at 5 m and 6 m, respectively. Based on $\lambda/z = 2$, the penetration depth of the surface waves was only about 12 m for Site B and 13 m for Site K. It is also possible to use linear inversion models (Lai and Rix 1998, Honjo et al. 1998, Ganji et al. 1998, Xia et al. 1999) and finite element models (Anand et al. 2001) to obtain a multi-layered soil that produces a dispersion curve that matches the measured dispersion curves.

However, this is beyond the scope of the current paper and will not be discussed.

4.3 **Comparison of Shear Wave Velocities**

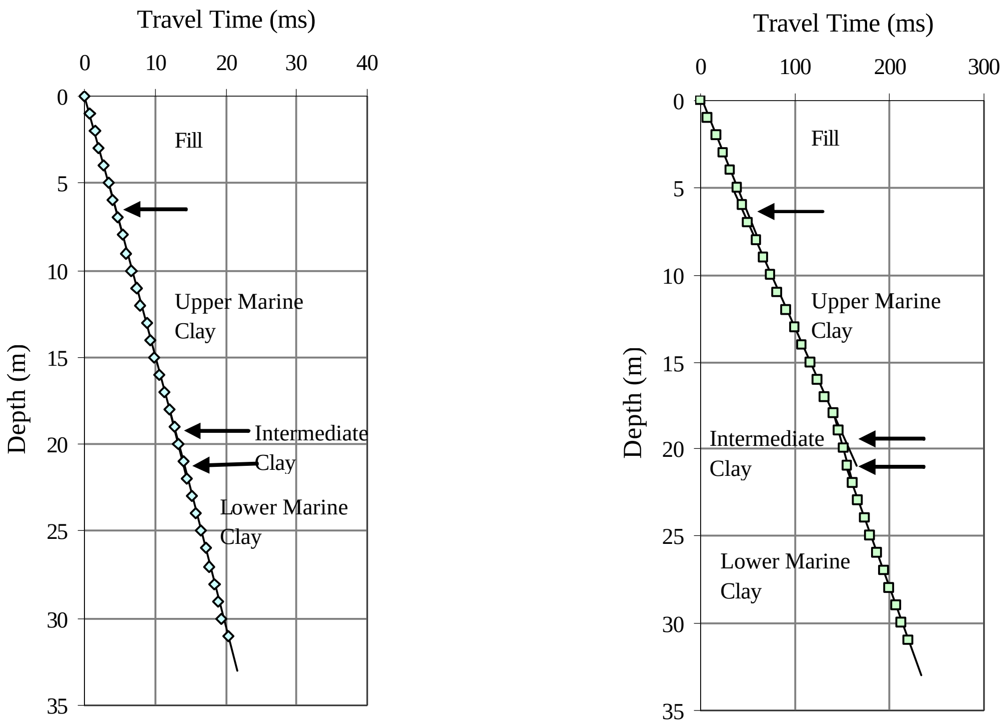
As the penetration depth of the surface waves was only about 12 m, comparison of the shear wave velocities can only be made for the fill and the upper marine clay. To compare the wave velocities measured, the Rayleigh wave velocities are converted to the shear wave velocities using Equation 3. For both the fill and the upper marine clay, the Poisson’s ratio is taken as 0.5 (i.e. p = 1.047). The comparison is summarised in Table 3. The difference in shear wave velocity is about +9% for the fill and -4% for the upper marine clay.



(i) P wave

(ii) S wave

(a) Site B



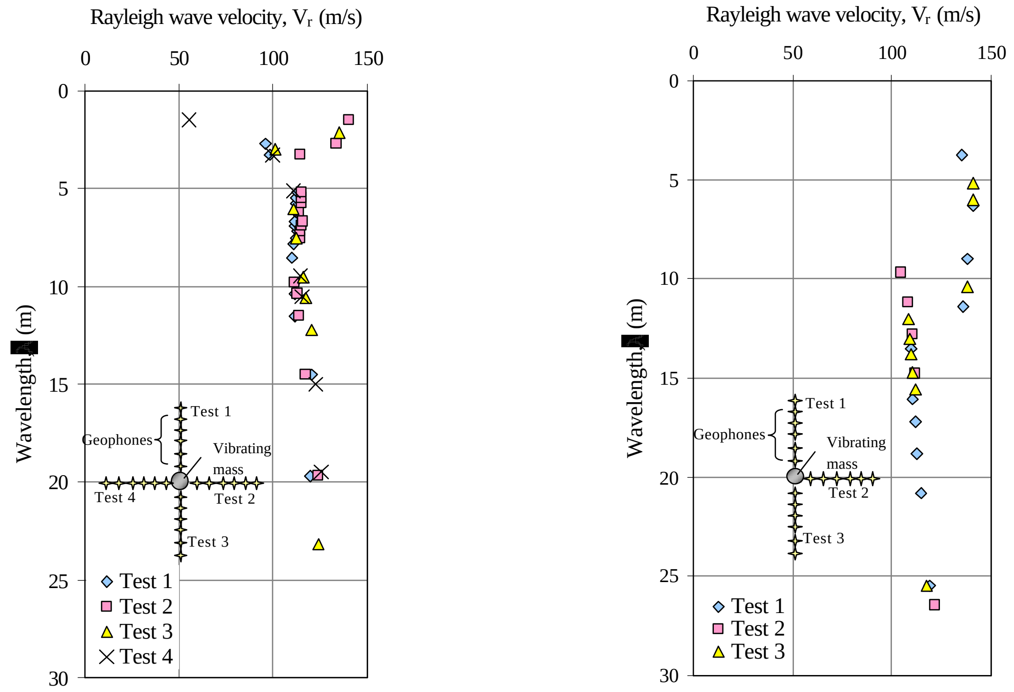
(i) P wave

(ii) S wave

(b) Site K

Figure 3. P and S waves' travel time versus depth from down-hole tests.

The difference does not decrease much if other values of Poisson's ratio were used. For the fill, the difference in shear wave velocity increases if a Poisson's value of less than 0.5 is used. Addo & Robertson (1992) showed a greater difference in shear wave velocities measured using seismic CPT (essentially a down-hole method) and the SASW method. Addo & Robertson used an average p value of 1.1 to obtain shear wave velocities from the Rayleigh wave velocities. A likely cause of the differences is that the disturbance waves were horizontally polarised in the down-hole tests and were vertically polarised in the surface wave tests.



(a) Site B (b) Site K

Figure 4. Dispersion curves for Site B and Site K from CSW tests.

Table 3. Comparison of shear wave velocities.

Soil strata	**Site B, V_s (m/s)**		**Site K, V_s (m/s)**	
	Down-hole test	**CSW test**	**Down-hole test**	**CSW test**
Fill	105	117	133	144
Upper Marine Clay	131	128	122	117

5 CONCLUSION

Two geophysical methods, down-hole and CSW, were employed at two soft soil sites in Singapore and their results were compared. The application of the surface wave method to the soft soil sites is straightforward as the site geology is well known and the results can be easily interpreted. The usual advocate for the use of surface wave method is that it is non-intrusive and thus can be performed more economically and in less time. However, the surface wave method is limited by the penetration depth of the Rayleigh wave which was found to be about 12 m for the soft soil sites. Furthermore, an estimate of the soil Poisson’s ratio is required in the determination of shear wave velocities which may account for a discrepancy of about 5% when compared with shear wave velocities from the down-hole tests. Nevertheless, some additional differences in the shear wave velocities are still present which may be attributed to the different wave sources. The difference in shear wave velocities from different geophysical methods should perhaps be treated as the uncertainty similar to other site investigation tests.

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REFERENCES:

Abbis, C.P. 1981. Shear wave measurements of the elasticity of the ground. *Geotechnique*, Vol 31(1) 91-104.

Addo, K. & Robertson, P.K. 1992. Shear wave velocity using Rayleigh waves. *Can. Geotech. J.*, Vol 29(4), 558-568.

Anderson, D.G. & Woods, R.D. 1975. Comparison of field and laboratory shear moduli. *Proc. Conf. on In-situ Measurement of Soil Properties*, Specialty Conf. of the Geotechnical Engrg Div., ASCE, Rayleigh, North Carolina, June 1975, Vol. 1, 121-150.

Anand, S., Leong, E.C. & Cheong, H.K. 2001. The use of a continuous wave measurement system for in situ characterisation of soil. In P.P. Rahardjo & T. Lunne (eds), Proc. Intern. Conf. on In Situ Measurement of Soil Properties and Case Histories, 139-144.

Ballard, R.F. & McLean, F.G. 1975. Seismic field methods for in-situ moduli. *Proc. Conf. on in situ measurement of soil properties.* Specialty Conf. Engng Div. ASCE, Rayleigh, North Carolina, Vol 1, 121-150

Ganji, V., Gucunski, N. & Nazarian, S. 1998. Automated inversion procedure for spectral analysis of surface waves. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol 124(8) 757-770.

Gazetas, G. 1982. Vibrational characteristics of soil deposits with variable velocity. *J. Num. Anal. Meth. Geomech.*, Vol 6, 1-20.

Heukolom, W. & Foster, C.R. 1962. Dynamic testing of pavements. *Trans. ASCE*, Vol 127(1) 425-456.

Hoar, R.J. & Sokoe, K.H., II 1978. Generation and measurement of shear waves in situ. *Dynamic Geotechnical Testing,* ASTM STP 654, American Society for Testing and Materials. 3-29.

Honjo, Y., Iwamoto, S., Sugimoto, M., Onimaru, S. & Yoshizawa, M. 1998. Inverse analysis of dynamic soil properties based on seismometer array records using the extended Bayesian method. *Soils and Foundation,* Vol 38(1) 131-143.

Jones, R.B. 1958. In-situ measurement of dynamic properties of soil by vibration methods. *Geotechnique*, Vol 8(1), 1-21.

Lai, C.G. & Rix, G.J. 1998. Simultaneous inversion of Rayleigh wave velocity and attenuation for near surface characterization. In P.K. Robertson & P.W. Mayne (eds), Proc. of First Intern. Conf. on Site Characterization-ISC'98, Atlanta, Georgia, USA, 19-22 April, 1999, Rotterdam: Balkema, 503-508.

Luna, R. & Jadi, H. 2000. Determination of dynamic soil properties using geophysical methods. *Proceeding of the First Intern. Conf. on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure, St. Louis, MO December2000.*

Mathews, M.C., Hope, V.S. & Clayton, C.R.I. (1996). The use of surface waves in the determination of ground stiffness profiles. *Proc. Instn Civ. Engrs Geotech. Engng*, Vol 119, 84-95.

McCann, D.M. & Green, C.A. (1996). Geophysical surveying methods in a site investigation programme. In C. Craig (ed.), *Advances in Site Investigation Practice; Proc. Intern. Conf., London, 30-31 March 1995*. Thomas Telford, 687-700.

Menzies, B.K. 2001. Near-surface site characterisation by ground stiffness profiling using surface wave geophysics. In K.R. Saxena and V.M. Sharma (eds.), *Instrumentation in Geotechnical Engineering. H.C.Verma Commemorative Volume*. Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, Calcultta, 43-71.

PWD 1976. *Geology of the Republic of Singapore*. Public Works Department, Singapore.

Stokoe, K.H. & Nazarian, S. 1985. Use of Rayleigh waves in liquefaction studies. In R.D. Woods (ed), *Measurement and Use of Shear Wave Velocity*, ASCE, New York, 1-17.

Tokimatsu, K. 1997. Geotechnical site characterization using surface waves. In K. Ishihara (ed), *Proc. of IS-Tokyo'95, The First Intern. Conf. on Earthquake Geotechnical Engineering*, Tokyo, 14-16 November 1995, Rotterdam: Balkema, 1333-1368.

Xia, J., Miller, R.D. & Park, C.B. 1999. Estimation of near-surface shear wave velocity by inversion of Rayleigh waves. Geophysics, Vol 64(3) 691-700.