

Estimate of Small Stiffness and Damping Ratio in Residual Soil Using Spectral Analysis of Surface Wave Method

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Abstract. Research in the important parameters for modeling the dynamic behavior of soils has led to rapid development of the small strain stiffness and damping ratio for use in the seismic method. It is because, the experimental determination of the damping ratio is problematic, especially for hard soils sample. Many researchers have proved that the surface wave method is a reliable tool to determine shear wave velocity and damping ratio profiles at a site with very small strains level. Surface wave methods based on Rayleigh waves propagation and the resulting attenuation curve can become erroneous when higher modes contribute to the soil's response. In this study, two approaches has been used to determine the shear strain amplitude and damping ratio of residual soils at small strain level using Spectral Analysis of Surface Wave (SASW) method. One is to derive shear strain amplitude from the frequency-response curve and the other is to derive damping ratio from travel-time data. Then, the results are compared to the conventional method.

1 Introduction

In many geotechnical engineering applications, the level of strains in the soil is small [9, 11], especially when dealing with normal functionality of the structures. Within the range of small strain (10-4% or less), [17], the mechanical behavior of the ground can be properly modeled by means of viscoelasticity [3]. Depending on the history of loading, soil may compact or dilate, its stiffness may depend on the magnitude of stress levels, soil deformations are time-dependent, etc. In fact, soil behavior is considered to be truly elastic in the range of small strain.

Specifically, the shear modulus and damping ratio profiles at a site can be determined by means of Rayleigh waves propagation [14], by assuming a layered half-space with horizontal, mono-phase, homogeneous and isotropic layers. Rayleigh waves propagate on the free surface of a medium and during propagation they are subjected to dispersion and attenuation. Generally, viscoelasticity dispersion and attenuation phenomena are correlated [8], so that shear modulus and damping ratio are coupled dynamic properties of the soil. Nevertheless, at very small deformations uncoupling dispersion and attenuation phenomena may represent a good approximation of soil behavior.

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2 Basic Theory of Seismic Method

In current practice of geotechnical testing, the measurement of low-strain dynamic properties of soils can be performed with a variety of techniques using in-situ or laboratory tests. Surface wave measurements has been used to investigate the attenuation and damping ratio of a layered soil deposit [13]. In their studies, an attenuation curve was constructed from the observed spatial attenuation of Rayleigh wave amplitudes and then was inverted to obtain the material shear damping ratio. The strain levels can be categorized into three groups: the very small strain level, where the stiffness modulus is constant in the elastic range; the small strain level, where the stiffness modulus varies non-linearly with the strain; and large strain level, where the soil is close to failure and the soil stiffness is relatively small [2, 5, 10, 15]. The significance of small strain non-linear behavior of soils in deep excavations also was examined [7].

2.1 Strain amplitudes of soil deposit

A review of literature revealed that there are a number of factors affecting the estimation of soil stiffness at small strain level. These factors are not only related to natural and soil inherent structures but also to its geological history. Initial shear modulus can be defined as shear modulus at infinitely small strain amplitude. It is therefore necessary to obtain strain amplitude in soil deposits when the SASW test is to be conducted. The strain amplitude, γ is defined as the ratio of peak particle velocity, v , to shear wave velocity, V_s :

$$\gamma = (v/V_s) \quad (1)$$

At small strain conditions, particle motion resulting from propagation of shear waves is non-destructive. As γ increases, the shear modulus will decrease from the maximum small strain value, G_0 . In-situ test have commonly been assumed to be small strain and the measurement of V_s will be directly related to the G_0 [16]. The appropriate strain must be known, as well as the appropriate modulus reduction with increasing strain.

2.2 Damping ratio and shear stress of soil

The G_0 is an important soil parameter related to the predictions of the ground movements and field data interpretations. The increase of the internal disorder in the material and hence increase of the dissipative properties [9], in terms of material damping. In soil dynamics and earthquake engineering, the G_{max} and the damping, D ratio are important parameters in soil characterization. Through the relationship of damping and shear strain [1, 12], the characteristic of normal or shear strain can be determined by using following equation:

$$D = (D_{max}/1 + \ln(1 + (e - 1)(\gamma_r/2\gamma))) \quad (2)$$

where D_{max} is maximum damping, 33%, D is damping at corresponding strain level and γ is the shear strain at measured damping. An elastic model is not able to describe energy dissipation and hence a viscoelastic model must be used. The dissipative phenomena take place at very low cyclic strain in soils and must be taken into consideration. Soil dynamics tests under cyclic loading, both in normal triaxial or shear test have shown common hysteretic behavior. The skeleton or the backbone curve of the hysteresis is known to follow the form of curve [4]. This curve can be expressed in the form of hyperbolic stress-strain soil model which the shear stress, τ of soil can be defined using the following equation:

$$\tau = (G_0\gamma/(1 + (\gamma/\gamma_r))) \quad (3)$$

where G_0 is shear modulus at small strain (less than about $10^{-4}\%$), γ is shear strain under loading and γ_r is the characteristics of shear strain.

3 Research Method

In this study, determination of importance parameters of residuals soils was performed by using the following procedure: (1) measuring V_s at the field and (2) estimating the variation of G_0 and D of soil corresponding γ level, based on interpretation from WinSASW 3.2.12 software.

3.1 SASW field testing

The field measurements were conducted using a seismograph and three vertical geophones having a natural frequency of 1Hz and geophone calibration factor is 400V/m/s. The test site was a residual soil with meta-sedimentary origin where 27 stories commercial building is to be build located at Damansara, Selangor. The configuration of field measurements was set up using Common Array Profiling (CAP) [6]. Four different seismic impact sources were used to generate energy over a broad frequency range. The location of Spectral Analysis and Surface Wave (SASW) test performed at the nearest point of Standard Penetration Test (SPT) and Instrumented Pile Load (IPLT) has shown in Figure 1.

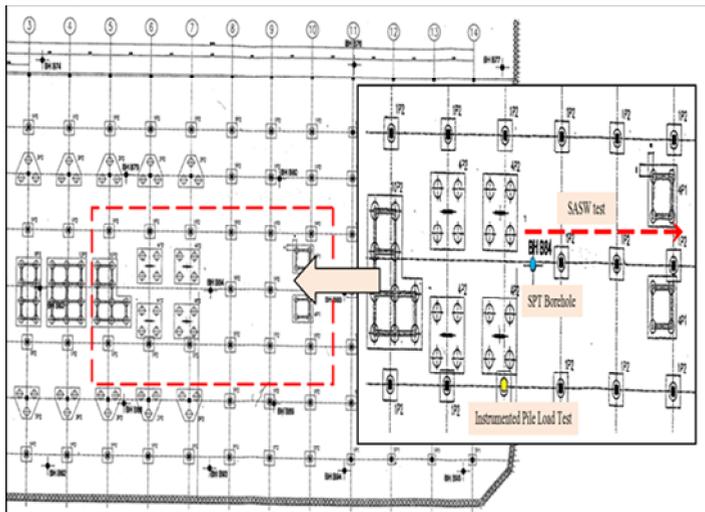


Figure 1. Site map with marked testing locations (N.T.S drawing).

3.2 Data analysis and interpretation

The SASW data was obtained using the National Instrument USB6289 data acquisition system with the WinSASW 3.2.12 and analysis software to determine V_s . This paper summarized a procedure for estimating the shear strain amplitude and damping ratio of soils at small-strain level from SASW method. The shear strain amplitude estimated from travel-time data as shown in Figure 2(a) and damping of soil measured from frequency-response curve as shown in Figure 2(b). In addition, the result obtained at a site with the two approaches are compared to the conventional method.

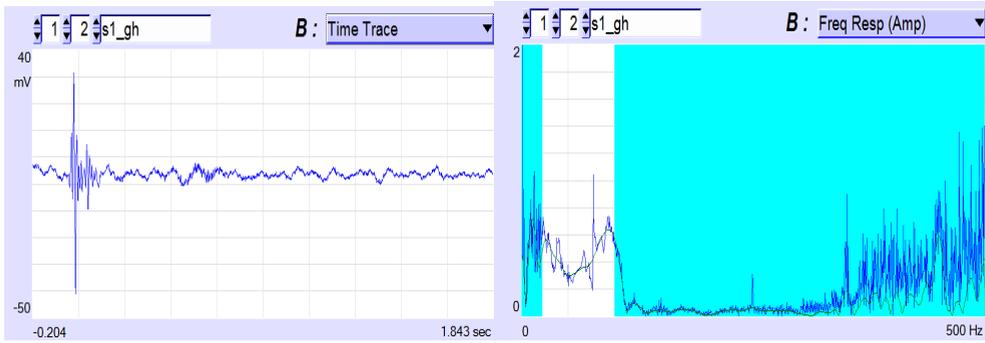


Figure 2. Data analysis for (a) travel-time curve and (b) frequency-response curve in determining strain amplitude and damping of soil.

4 Results and Discussion

The SPT and SASW test results identified numerous soil layers at the site indicate over 20.30 meters of medium dense silty sand, stiff sandy clay and silt which is a residual soil and has underlain by weathered rock deposit of granite as provided in Figure 3. Direct comparison of the shear wave velocity, V_s and normalized shear wave velocity, V_{s1} profiles is illustrated in Figure 4(a). The V_s profile is roughly divided into three sections, V_s is about 218m/s, 257m/s and 516m/s at 0~6.45m, 6.45~7.60m and below 7.6m which encountered the rock formation respectively. The V_{s1} performed after consider the overburden pressure of the soil layer.

GL at 0.0m		GWL at 3.88m	
Soil excavation 13.31m depth from ground level			
Silty SAND with some gravel			Soil Layer 1
Medium stiff, Sandy CLAY			Soil Layer 2
		VWWSG at 1.5m	Soil Layer 3
Stiff, Sandy SILT			Soil Layer 4
		VWWSG at 4.6m	Soil Layer 5
Sandy SILT with little gravel			Soil Layer 6
		Bored Pile	
Highly Weathered, GRANITE, Weak		VWWSG at 7.7m	Soil Layer 7
		VWWSG at 9.2m	Soil Layer 8
Moderately Weathered, GRANITE, Medium Strong		VWWSG at 10.7m	Soil Layer 9

Figure 3. The soil profile of the test site.

The dynamic strain level caused by the shear waves can be estimated based on attenuation response on the soil by conducting SASW testing. In this study, the peak particle velocity can be defined by the interpretation of travel-time data that obtained from WinSASW software. Furthermore, the results of shear strain amplitudes for all sources can be determined using Equation (1) as presented in Figure 4(b). Meanwhile, in order to measure the damping from the signal spectrum recorded from SASW test, the half-power bandwidth method has been used for the interpretation of frequency-response curve using Equation (2). The results of damping based on this interpretation has shown in Figure 4(c).

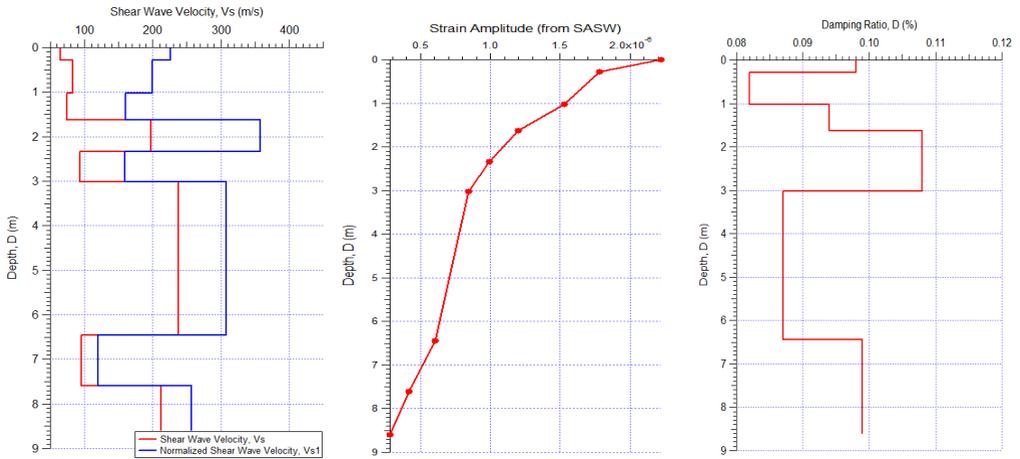


Figure 4. Profile of (a) shear wave velocity, (b) strain amplitude and (c) damping for the test site using SASW method.

In general, prediction on characteristic of strain amplitudes and damping in SASW method will decreases with depth of soil. In this study, analysis of the performed SASW field data shows that the strain amplitudes caused by several assorted hammer as seismic source are generally less than $10^{-4}\%$. Summary of the shear wave velocity, shear strain amplitudes and damping as tabulated in the Table 1 below.

Table 1. Summary of the result for the test site.

Layer	Depth, z (m)	Shear Wave Velocity, V_s (m/s)	Shear Modulus, G_0 (kN/m^2)	Shear Strain Amplitudes, γ		Damping, D (%)	Shear Stress of Soil, τ (kN)
				SASW Test ($\times 10^{-6}$)	IPLT Test ($\times 10^{-4}$)		
1	0	64.48	6494.2	3.5	4.6	9.8	242.46
2	0.28	83.33	5373.9	2.4	4.6	8.2	275.29
3	1.08	74.68	3368.1	2.06	4.52	9.4	88.15
4	1.63	197.09	21516.7	1.56	4.46	10.8	258.84
5	2.34	93.04	3536.4	1.29	4.41	10.8	35.31
6	3.02	237.99	16672.2	1.10	4.3	8.7	313.93
7	6.45	95.46	2019.6	0.78	3.77	9.9	17.02
8	7.6	212.22	11323.9	0.54	3.36	9.5	66.69
9	8.57	647.32	71235.8	0.34	2.7	9.5	261.96

From this study, the result shows that as shear strain increases, the shear modulus will decreased. The appropriate shear strain must be known, as well as the appropriate modulus reduction with increasing strain. Shear stress, τ of the soil have been determined using Equation (3) and the result has been tabulated in Table 1 above. The shear stress for a different types of soil affected by the dynamics properties of soils such as shear wave velocity, shear modulus, strain amplitudes and damping.

5 Conclusions

As a conclusion, it can be summarized that the effects of shear strain amplitudes on shear modulus and damping can significantly influenced the predicted shear stress of soil. Thus, shear strain amplitudes should be considered when selecting shear modulus and damping for geotechnical engineering design.

It is also shown that the characterization of the physical properties of the soil structure in terms of the shear strain amplitudes and the damping of soil layer can be satisfactorily obtained using frequency-response and travel-time curve from SASW data analysis. In addition, this method has the advantage of being fast, practical and non-destructive tool for engineers in measuring shear modulus and damping at very small strain conditions compared to the conventional method. Implication of the results and future research directions are also presented.

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