Sampling disturbance evaluation based on the shear wave velocity measured in laboratory and field tests

Xiaoqiang Gu
Department of Geotechnical Engineering & Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai, China, guxiaoqiang@tongji.edu.cn

Wenlan Jiang[1], Jiangu Qian[2], Maosong Huang[3]
Department of Geotechnical Engineering & Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, Shanghai, China, 1732230@tongji.edu.cn[1], qianjiangu@tongji.edu.cn[2],mshuang@tongji.edu.cn[3]

Pangyong Shen
Shanghai Chengtou Water Group Co., LTD, Shanghai, China, qcsshenpy@163.com

ABSTRACT: The shear wave velocity of soil play an important role in many geotechnical problems such as site characterization, ground seismic response analysis and liquefaction potential evaluation. Due to sample disturbance, it is well believed that the results of field measurement and laboratory measurement are different. In this study, the shear wave velocity of typical soils in Shanghai are measured by field suspension logging method and laboratory resonant column test. The results are compared and the disturbance of sampling is quantified by the ratio of the shear wave velocity in the field to that in the laboratory. It is found that the shear wave velocity in the laboratory is significantly lower than that in the field and such decrease depends on the magnitude of shear wave velocity. It indicates that the sampling disturbance based on the shear wave velocity is significant and therefore special attention should be paid if the shear wave velocity is critical in a geotechnical problem.

Keywords: sampling disturbance; shear wave velocity; resonant column; suspension logging

1. Introduction

The shear wave velocity of soil play an important role in many geotechnical problems such as site characterization, ground seismic response analysis and liquefaction potential evaluation [1-2]. The shear wave velocity of the soil is directly related to the soil small strain shear stiffness, a intrinsic soil property.

The soil shear wave velocity can be measured either in the laboratory or in the field. In laboratory, the shear wave velocity can be measured by resonant column apparatus [3-4], bender element [5-6] or quasi-static loading with high resolution local strain measurement [7-8]. In the field, the shear wave velocity can be measured by cross hole method, down-hole method or surface wave analyses [9]. In laboratory, the samples are obtained from the field during site investigation and consolidated to stresses at the field. Then, the shear wave velocity was measured and it is generally treated as the field values. Therefore, the key challenge is the difference between the laboratory tests and field tests or the effect of sample disturbance.

The source of sample disturbance can be mainly divided into two sources: the stress relief and the mechanical disturbance [10]. The stress relief describe the total stress applied on the sample become zero when it was removed from the ground. During this stress relief, the soil structure may be changed and the bonding between particles may be damaged, which may not be fully recovered during the consolidation in laboratory. The mechanical disturbance refers to the disturbance caused during the drilling process, the penetration of sampler, sampler retrieval to the ground, sample transportation, sample extrusion from the tube, sample trimming and other processes to prepare the sample.

Generally, sample disturbance can not be eliminated and its effect on different soil properties (e.g. density, compressibility, or shear strength) may be different. Hence, it is very important to evaluate the effect of sample disturbance on the soil properties. Lunne et al. [11] investigated the effect of sampler type on the soil disturbance and the studied soil properties included soil compressibility by oedometer, soil undrained shear strength by triaxial and shear wave velocity by bender element. Lunne et al. [11] also proposed to a compressibility index $\Delta e/e_0$ to quantify the sample disturbance, where Δe is the change of void ratio when the specimen is consolidated to the field overburden stress and e_0 is the initial void ratio. It should be noted that they took the measurements of block sample as the reference, but the soil compressibility in the field is unknown. Strictly, the soil properties can be directly measured in the field should be taken as the reference. Keeping this in mind, the shear wave velocity should be an convenient index for sample disturbance evaluation. Sasitharan et al. [12], Chiara and Stokoe [13], Landon et al. [14], Ferreira et al. [10] used the shear wave velocity to quantify the sample disturbance and the results were compared with those from the compressibility in oedometer tests. Nevertheless, in majority of these studies, the shear wave velocity in the laboratory was measured at unconfined stress states or the field shear wave velocity was not measured.

In this study, the shear wave velocities V_s of soil specimens collected in Shanghai during the site investigation were measured by resonant column tests and empirical equation for predicting the small strain shear stiffness was proposed. Meanwhile, the shear wave velocity measurements by suspension logging in 12 boreholes during the site investigation of three projects in Shanghai were also analyzed and empirical equations were also proposed. By comparing the shear wave velocity or small strain shear stiffness in the laboratory and in the field, the effect of sampling disturbance can be evaluated.

2. Laboratory resonant column tests

2.1. Resonant column apparatus

The resonant column (RC) apparatus used in this study is of a Stokoe type with bottom-fixed and top-free configuration, as schematically shown in Fig. 1. It is equipped with an electromagnetic driving head with precision wound coils and internally mounted, counter balanced accelerometers. The dimensions of tested specimen are 50 mm in diameter and 100 mm in height, respectively. The confining pressure is applied by compressed air and water bath is adopted to ensure the saturation. The cell pressure capacity is 1.0 MPa. The axial deformation of the specimen during consolidation is measured by an internal high-resolution LVDT. Furthermore, bender elements (BE) and slow rate torsional shear (TS) functions are also incorporated in this RC apparatus.

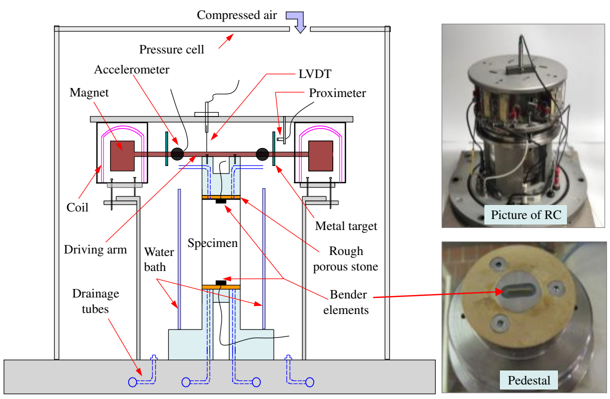


Figure 1. Schematic illustration and picture of the resonant column apparatus with bender elements.

2.2. Tested soil samples

The tested intact samples were collected during the site investigations of 10 projects in Shanghai, which is located in the east coastal line of China. Shanghai is covered by deep depositional materials up to 300-400m. The number of tested samples is 83 in total and the soil type include clay, slit and sand. The 38 clay samples were collected from the depth of 1.0-91.0m. The water content, void ratio and plasticity index of these clay specimens are in the range of 22.5-47.8%, 0.641-1.319 and 11.9-19.7, respectively. The number of silt specimens is 15 and the sampling depth is in the range of 2.0-67.6m. The water content and void ratio of these silt samples are in the range of 21.1-36.2% and 0.595-0.988, respectively. The 40 sand specimens include medium sand, fine sand and silty sand and the sampling depth is in the range of 32.0-99.0m. The water content and void ratio of these sand samples are in the range of 10.5-27.7% and 0.379-0.870, respectively.

The specimen was trimmed into the tested dimensions first and the was consolidated to the field vertical effective stress. After consolidation, resonant column tests were carried out to measure the dynamic shear modulus at different shear strain levels. In a RC test , the shear wave velocity V_s and the associated dynamic shear modulus G can be calculated by [9]

$$V_s = \frac{2\pi f_t L}{\beta} \tag{1}$$

$$G = \rho (V_s)^2 \tag{2}$$

where f_t is the resonant frequency in torsional excitation, ρ is the mass density involving in the wave propagation, L is the specimen length, and β is a parameter that can be determined by

$$\beta \tan \beta = \frac{I}{I_0} \tag{3}$$

where I is the mass polar moment of inertia of the specimen and I_0 is the mass polar moment of inertia of the components above the specimen.

In RC tests, the modulus reduction curve (i.e. the decrease of dynamic shear modulus with increasing shear strain) can be obtained. When the input excitation voltage and therefore the resulted shear strain is small (i.e. less than 5×10^{-6}), the shear modulus is termed as the small strain or the maximum shear modulus G_0. In this study, we focus on the small strain shear modulus G_0 and the results of modulus reduction curves can be found in Gu et al. [15].

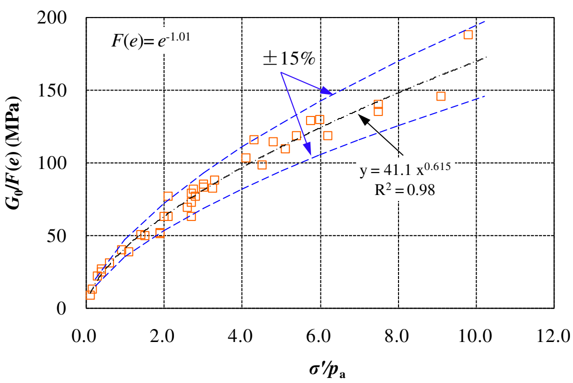
2.3. RC test results

Both theoretical considerations and experimental results have showed that the small strain shear modulus of soils mainly depends on void ratio e (or soil density) and effective confining pressure σ′, and can be expressed by the following general form [3]:

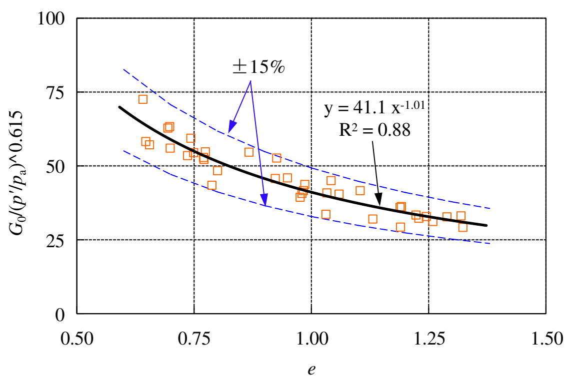
$$G_0 = AF(e)(\frac{\sigma'}{p_a})^n \quad (4)$$

where A is a constant reflecting soil type, grain properties and fabric, p_a is a reference stress, n is the stress exponent reflecting the effect of the confining pressure and $F(e)$ is a void ratio function reflecting the effect of soil density. Here, a void ratio function $F(e) = e^{-x}$ [16] is used.

Figs. 2-4 show the G_0 values of clay, silt and sand obtained in RC tests, together with the fitting results, respectively. As seen in these figures, the G_0 value of each soil increases with increasing effective stress and decreasing void ratio as expected. The G_0 value can be well fitted by Eq. (4) and generally the difference between the measurement and prediction of the G_0 values does not exceed 15%. The stress exponent n is somewhat higher than the commonly used 0.5, which is obtained based on the clean sand, especially for the clay and sand. Moreover, the sand is less sensitive to the void ratio compared to the clay and silt. Generally, for the same void ratio and effective confining pressure, the G_0 value of sand is higher than that of clay, and the silt is in the middle.

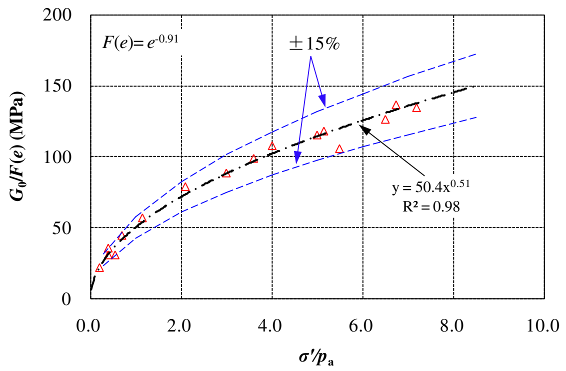


(a)

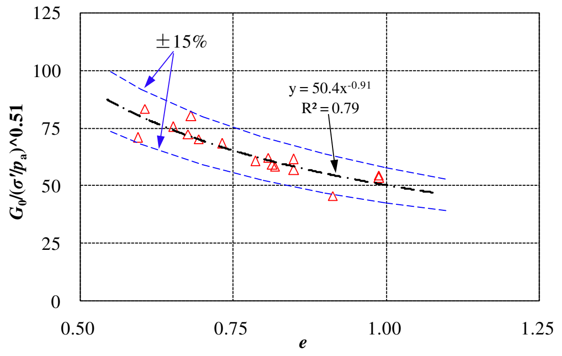


(b)

Figure 2. The G_0 of clay obtained by laboratory resonant column.

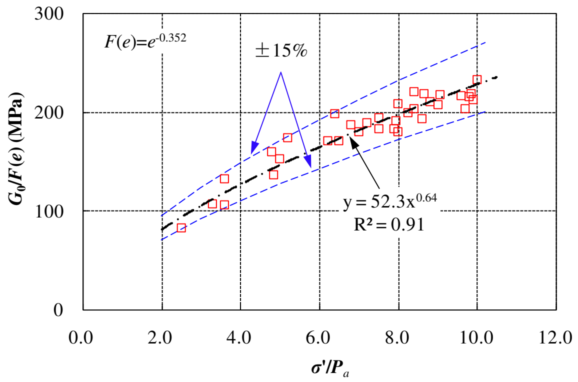


(a)

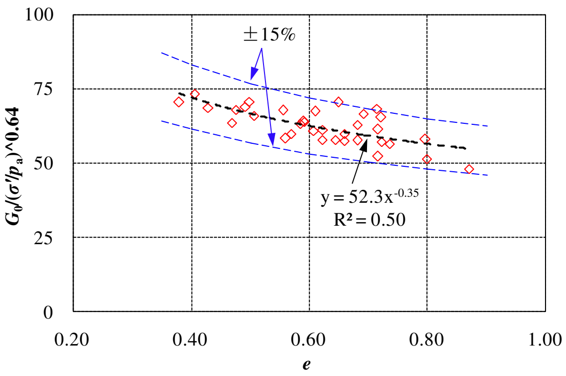


(b)

Figure 3. The G_0 of slit obtained by laboratory resonant column.



(a)



(b)

Figure 4. The G_0 of sand obtained by laboratory resonant column.

3. Field suspension logging tests

3.1. Test sites and equipment

The shear wave velocity measurements were carried out during the site investigation of three important projects in Shanghai, including the 632m-high Shanghai Tower (ST), the Suzhou river deep sewage tunnel (DST) and the hard X-ray tunnel (HXT). Shear wave measurements were carried out in two boreholes up to 185 in ST, in two boreholes up to 150m in DST, and in 8 boreholes up to 125m in HXT, respectively. The shear wave velocity was measured by suspension logging with a interval of 1.0m, as shown in Fig. 5. At each depth, the shear wave velocity was measured, while the soil type and the physical properties (e.g. water content, unit weight and void ratio) can be determined according to the borehole sampling. The coefficient of lateral earth pressure at rest K_0 of the soil was measured and the mean effective stress was used to analyze the shear wave velocity in Eq. (4).

3.2. Results of field suspension logging tests

Figs. 6-8 show the G_0 values of clay, silt and sand obtained in field suspension logging tests as well as the fitting results by Eq. (4), respectively. As seen in these figures, the G_0 value of each soil increases with increasing effective stress and decreasing void ratio as expected. However, the stress component for each soil in the field is somewhat higher than that in the laboratory. Similarly as the results in laboratory, the G_0 value of sand in the field is also less sensitive to the void ratio compared to the clay and silt. Meanwhile, compared to the results in laboratory, the G_0 values are much scattered, especially for the clay. Generally, for the same void ratio and effective confining pressure, the G_0 value of sand is also much higher than that of clay, and the silt is in the middle. Moreover, for the same void ratio and effective confining pressure, the G_0 value in the field is much higher than those in the laboratory, indicating that the sample disturbance reduce the small strain shear stiffness.

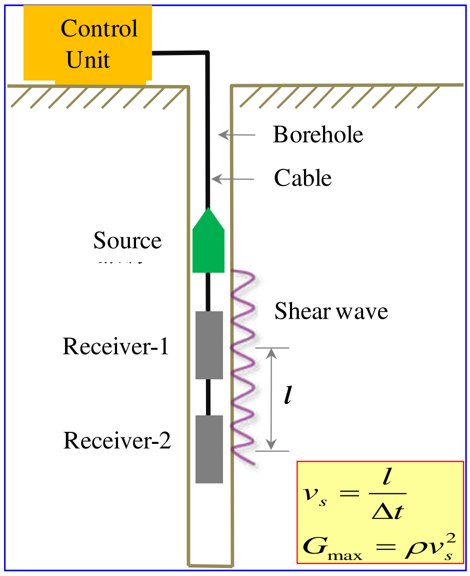


Figure 5. The schematic of suspension logging test.

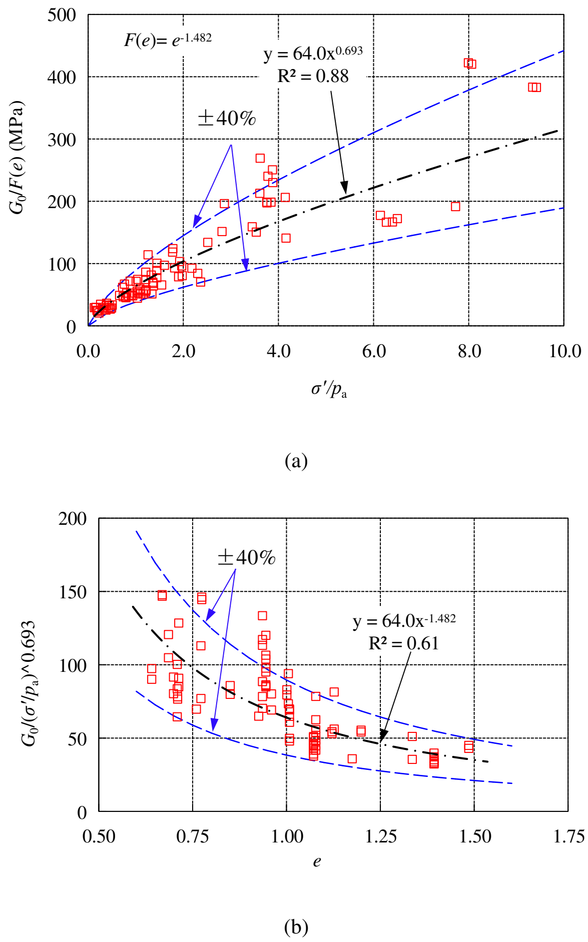


Figure 6. The G_0 of clay obtained by field suspension logging test.

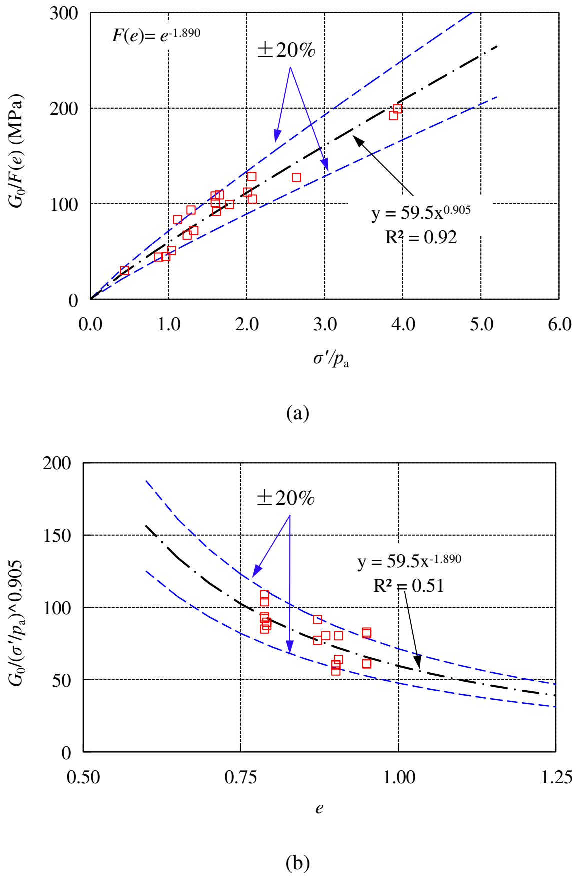


Figure 7. The G_0 of silt obtained by field suspension logging test.

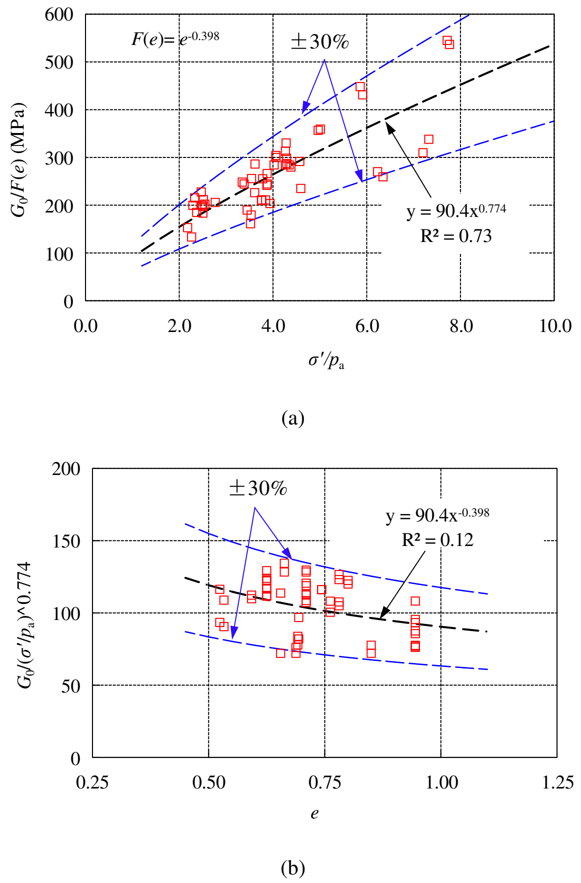


Figure 8. The G_0 of sand obtained by field suspension logging test.

4. Sampling disturbance evaluation

Fig. 9 compared the small strain shear modulus from the laboratory resonant column tests and from the field suspension logging. In Fig. 9, G_{0F} is the direct measurement in the field, while G_{0L} is the G_0 calculated based on the fitting results in laboratory according to the void ratio and mean effective stress of the specimen. As seen in Fig. 9, G_{0F} is much higher than the G_{0L}, indicating the sampling disturbance. The average value of G_{0F} about 1.78 times of G_{0L}.

To quantify the sampling disturbance on the small strain shear stiffness, the ratio of the G_0 in laboratory G_{0L} to that in the field G_{0F} was plotted against the G_{0F} in Fig. 10, together with the results by Kokusho [17]. As seen in Fig. 10, the ratio G_{0L}/G_{0F} generally is smaller than one, indicating that the sampling disturbance reduces the small strain shear stiffness. Meanwhile, the ratio G_{0L}/G_{0F} decreases as G_{0F} increases, which means that the sampling disturbance is more significant when G_{0F} is larger. This phenomenon is expected since G_{0F} is usually larger at deeper depth, which corresponds to a stronger stress relief effect and therefore larger sampling disturbance. It is interesting to note that the ratio G_{0L}/G_{0F} in this study is quite close to the average value in Kokusho [17]. The average value of G_{0L}/G_{0F} of typical Shanghai soil approximately decreases from 0.75 to 0.40 when G_{0F} increases from 20MPa to 600MPa. The results indicate that special attention should be paid to the sampling disturbance on the soil shear wave velocity or small strain shear stiffness, especially the small strain shear stiffness is crucial in the project.

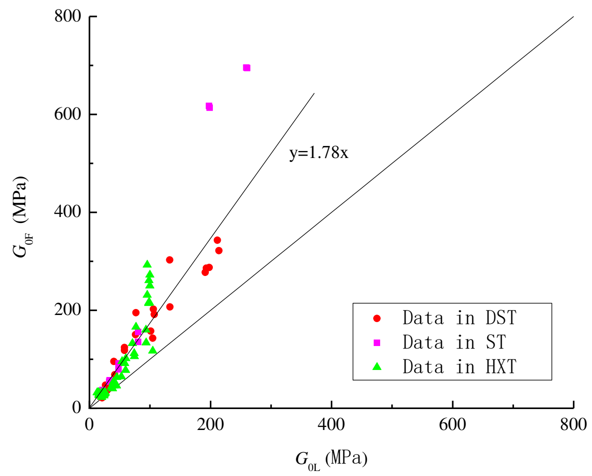


Figure 9. The evaluation of sampling disturbance by G_{0L}/G_{0F}.

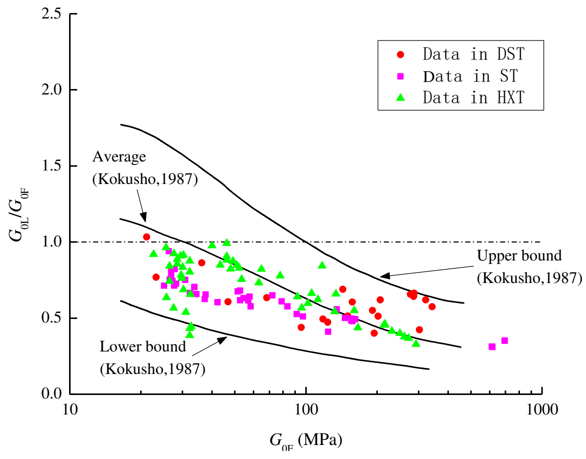


Figure 10. The evaluation of sampling disturbance by G_{0L}/G_{0F}.

5. Conclusions

In this study, the shear wave velocities and the associated small strain shear modulus of typical Shanghai soils were measured by resonant column tests in the laboratory and suspension logging tests in the field. The small strain shear modulus of the soils obtained in the laboratory and in the field are analyzed and compared to each other. The major findings in the paper can be summarized as follows:

a) The soil small strain shear stiffness increases with increasing mean effective stress and decreasing void ratio both in the laboratory and in the field. The stress component of the natural soils as well as the scattering of the data in the field is higher than that in the laboratory. For the same effective stress and void ratio, the shear modulus of sand is higher than that of clay, while the silt is in the middle.

b) The small strain shear modulus in the laboratory is considerably smaller than those in the field, indicating the effect of sampling disturbance. The degree of sampling disturbance can be evaluated by the stiffness ratio G_{0L}/G_{0F}. For typical Shanghai soils, the average value of G_{0L}/G_{0F} approximately decreases from 0.75 to 0.40 when G_{0F} increases from 20MPa to 600MPa. The results reveal that special attention should be paid to the sampling disturbance on the soil shear wave velocity or small strain shear stiffness, especially when the small strain shear stiffness is crucial in the project.

Acknowledgement

The work presented in this paper is supported by National Natural Science Foundation of China (Grant nos. 51738010, 51822809) and Fund for Research on the Monitoring Technology and the Analytical Model of the Shanghai Deep Drainage System. These supports are gratefully acknowledged.

References

[1] Yang, J., Yan, X. R. “Site response to multi-directional earthquake loading: a practical procedure”, Soil Dynamics and Earthquake Engineering, 29(4), pp. 710-721, 2009. https://doi.org/10.1016/j.soildyn.2008.07.008

[2] Andrus, R. D., Stokoe, K. H. II. “Liquefaction resistance of soils from shear-wave velocity”, Journal of Geotechnical and Geoenvironmental Engineering, 126(11), pp. 1015-1025, 2000. https://doi.org/10.1061/(ASCE)1090-0241(2000)126:11(1015)

[3] Hardin, B. O., Richart, F. E. “Elastic wave velocities in granular soils”, Journal of Soil Mechanics and Foundations Division, 89(SM1), pp. 33-65, 1963.

[4] Yang, J., Gu, X. Q. “Shear stiffness of granular material at small strain: does it depend on grain size?”, Géotechnique, 63(2), pp. 165-179, 2013. https://doi.org/10.1680/geot.11.P.083

[5] Gu, X. Q., Yang, J., Huang, M. S. “Laboratory measurements of small strain properties of dry sands by bender element”, Soils and Foundations, 53(5), pp. 735-745, 2013. https://doi.org/10.1016/j.sandf.2013.08.011

[6] Gu, X. Q., Yang, J., Huang, M. S., Gao, G. Y. “Bender element tests in dry and saturated sand: signal interpretation and result comparison”, Soils and Foundations, 55(5), pp. 952-963, 2015. https://doi.org/10.1016/j.sandf.2015.09.002

[7] Hoque, E., Tatsuoka, F. “Effects of stress ratio on small-strain stiffness during triaxial shearing”, Géotechnique, 54(7), pp. 429-439, 2004. https://doi.org/10.1680/geot.2004.54.7.429

[8] Ezaoui, A., Di Benedetto, H. “Experimental measurements of the global anisotropic elastic behavior of dry Hostun sand during triaxial tests, and the effect of sample preparation”, Géotechnique, 59(7), pp. 621-635, 2009. https://doi.org/10.1680/geot.7.00042

[9] Richart, F. E., Hall, J. R., Woods, R. D. “Vibrations of soils and foundations”, 1st ed., Prentice-Hall, Englewood Cliffs, New Jersey, United States of America, 1970.

[10] Ferreira, C., Viana Da Fonseca, A., Nash, D. F. T. “Shear wave velocities for sample quality assessment on a residual soil”, Soils and Foundations, 51(4), pp. 683-692, 2011. https://doi.org/10.3208/sandf.51.683

[11] Lunne, T., Berre, T., Strandvik, S. “Sample disturbance effects in soft low plastic Norwegian clay”, In: Almeida (eds) Recent Developments in Soil and Pavement Mechanics, Rio de Janeiro, Brazil, 1997, pp. 81-102.

[12] Sasitharan, S., Robertson, P. K., Sego, D. C. “Sample disturbance from shear wave velocity measurements”, Canadian Geotechnical Journal, 31(1), pp. 119-124, 1994. https://doi.org/10.1139/t94-013

[13] Chiara, N., Stokoe, K. H. “Sample disturbance in resonant column test measurement of small-strain shear-wave velocity”, In: Ling, H. I., Callisto, L., Leshchinsky, D., Koseki, J. (eds) Soil Stress-Strain Behavior: Measurement, Modeling and Analysis. Solid Mechanics and Its Applications, 1st ed., Springer, Dordrecht, Netherlands, 2007, pp. 605-613. https://doi.org/10.1007/978-1-4020-6146-2_41

[14] Landon, M. M., DeGroot, D. J., Sheahan, T. C. “Nondestructive sample quality assessment of a soft clay using shear wave velocity”, Journal of Geotechnical and Geoenvironmental Engineering, 133(4), pp. 424-432, 2007. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:4(424)

[15] Gu, X. Q., Lu, L. T., Yang, J., Wu, X. F. “Laboratory Measurements of the Dynamic Properties of Shanghai Clay”, In: Bian, X. C., Chen, Y. M., Ye, X. W. (eds) Environmental Vibrations and

Transportation Geodynamics, 1st ed., Springer, Singapore, 2018, pp. 585-592. https://doi.org/10.1007/978-981-10-4508-0_54

[16] Lo Presti, D. C. F., Jamiolkowski, M., Pallara, O., Cavallaro, A., Pedroni, S. “Shear modulus and damping of soils”, Géotechnique, 47(3), pp. 603–617, 1997. https://doi.org/10.1680/geot.1997.47.3.603

[17] Kokusho, T. “In situ dynamic soil properties and their evaluation”, In: The 8th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Kyoto, Japan, 1987, pp. 215-235.