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A proposed method to determine in-situ shear modulus and shear strain decay curves in different structured soil

Ran An [1,2], *Lingwei* Kong[1, 2*], *Aiguo* Guo[1, 2], and *Xianwei* Zhang[1, 2]

[1]State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: This paper illustrates the application of the self-boring pressuremeter test and the seismic dilatometer test to acquire the in-situ decay curves of stiffness with shear strain level (*G*-*γ* decay curves) of three types of structural soil, which are granite residual soil, structural soft soil and expansive soft rock. The proposed approach in combines the functions of SBPT and SDMT to provide the high standard of accuracy for the small-strain stiffness (from SDMT) and the major attenuation stage of stiffness (from SBPT). Using the proposed mathematical model can properly describe the tendency in typical in-situ *G*-*γ* decay curves based on the data of tests. To analyse the suitability of the proposed approach, the *G*-*γ* curve obtain from the resonant column test of granite residual soil is also employed to compare with the in-situ curves. The shear modulus *G* obtained from laboratory tests is found to be smaller and the stiffness attenuation rate is found to be faster than the curve of the in-situ test, which reflects the process of sampling, transporting and preparation of soil samples could cause unrecoverable damages in soil.

1 Introduction

Stiffness analysis in the small-strain deformation stage is one of the most important subjects of soil dynamic analysis [1]. The small-strain deformation of soil generally refers to the deformation stage with shear strain $\gamma < 10^{-5}$. Moreover, the small-strain shear modulus G_{max} is widely used in seismic response analysis, foundation design and safety evaluation of underground constructions. Jardine considered the small-strain deformation stage is mainly under the elastic deformation and the shear modulus upper limit (G_{max}) of soil is regard as an important parameter to characterize the soil stiffness [2]. The soil deformation of practical engineering often exceeds the scope of small-strain stage and the shear modulus (*G*) decreases with the increase of shear strain (*γ*). In order to predict the soil deformation and settlement, the application of shear modulus VS shear strain curve (*G*-*γ* decay curve) is applied as an effective method to describe the stiffness characteristics varies with the increase of deformation.

Currently, the *G*-*γ* decay curves of the soil depend largely on the resonant column test (RCT), of which the stability and reliability has been proved in practice [3]. The most representative description of dynamic shear stress-shear strain relation includes Hardin-Drnevich equation and Ramberg-Osgood equation [4,5]. In order to overcome the problem that Hardin-Drnevich equation is too simple and Ramberg-Osgood equation has too many parameters, Ken Stokoe proposed a simple and effective mathematical model of the *G*-*γ* decay curve of soil. These mathematical models which based on laboratory tests are of great significance for the study of soil dynamics [6]. However, the results of laboratory tests are inevitable to be affected by factors such as sampling disturbance and stress release of soil [7]. As an effective tool to study mechanical properties of soil, in-situ tests are particularly important in studying the structural soil which is susceptible to external disturbance [8]. The results of in-situ tests in structural soil are more reliable than laboratory tests [9].

According to the previous research results, the *G*-*γ* curves of soil is non-linear which can be divided into two typical stages: the small-strain stage ($\gamma < 10^{-5}$) and the major attenuation stage ($\gamma=10^{-4}\sim10^{-1}$) [10]. This paper is aimed at investigating the possible application of the self-boring pressuremeter test (SBPT) and the seismic dilatometer test (SDMT) for determining the completed decay curves of in-situ stiffness with shear strain, which is more suitable to describe the stiffness attenuation law with a reasonably high accuracy than laboratory tests.

2 Sites and methods

2.1 Testing sites

The following paragraphs present the results of in-situ tests carried out at three different testing sites covered with structural soil in China: granite residual soil of Shenzhen City, structural soft soil in Leizhou Peninsula and expansive soft rock in the northeast areas. And they contain a strong structural characteristic which is highly

* Corresponding author: lwkong@whrsm.ac.cn

Table 1. The basic physical properties of soils

Soil type	Density (g/cm^3)	Void ratio	Water content(%)	ω_L (%)	ω_P (%)	I_L	Permeability coefficient (cm/s)	Strength parameters C/kPa φ/°
GRS	1.94	0.71	26.2	56.24	22.56	34	1. 95×10^{-4}	52.4 16.2
SSC	1.98	0.74	26.7	58.89	27.27	32	1.79×10^{-4}	35.5 13.0
ESR	2.02	0.62	24.4	60.46	24.72	36	2.42×10^{-4}	37.3 15.2

sensitive to external disturbance. The elementary properties of the testing soil are presented in the Table1.

2.2 In-situ tests

The Cambridge three-arm self- boring pressuremeter (SBPT)and Marchetti seismic diameter (SDMT)were used for testing. SBPT provides a higher precision compared to the conventional Maynard pressuremeters and has the ability to drill in advance based on its own hydraulic injection system. Therefore, SBPT can greatly reduce the error from stress release during the process of drilling [11]. SDMT was the combination of the mechanical flat dilatometer (DMT) and the seismic module for measuring the shear wave velocity *vs*. According to the theory of elasticity, the small-strain shear modulus G_0 can be determined based on shear wave velocity *vs*. Marchetti [12]. established a reliable relationship between initial shear modulus G_0 and seismic wave velocity v_s, as shown in formula (1).

$$G_0 = \rho v^2 \tag{1}$$

where, ρ_0 is the natural density of soil, obtained by the laboratory test; v_S is the seismic shear wave velocity, obtained by the SDMT.

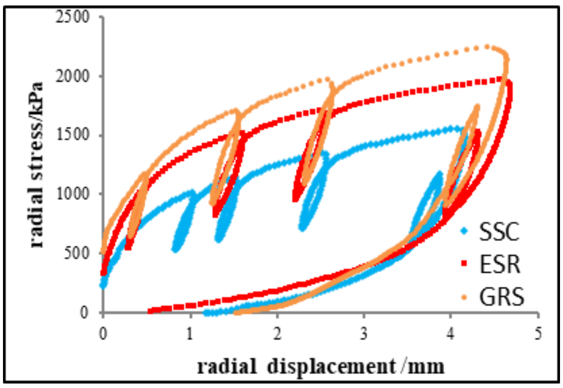

Fig. 1 The Stress-deformation curves of SBPT

Table 2. The stiffness calculation parameters

Soil type	Density ρ(g/cm^3)	Soil depth(m)	v_s(m/s)	G_0(GPa)
GRS	1.94	13m	236	108.1
SSR	1.98	14m	196	76.1
ESR	2.02	15 m	169	57.7

3 The in-situ G-Γ curves

Previous research results indicate that the in-situ initial shear modulus G of soil in the main attenuation stage (γ=10^{-4}~10^{-1}) can be accurately obtained by using SBPT [2]. To determine the attenuation law of soil stiffness during elastic and elastoplastic deformation period, this paper adopts the nonlinear analysis method recommended by Bolton and Whittle [13], which is based on the cavity expansion theory in geomechanics. The solving process is as follows:

1) From SBPT the curves of radial stress and displacement can be obtained directly, the curves are shown in the Fig.1. There are four hysteresis loops in each curve and every hysteresis loop represents a certain deformation stage. And the vertical and horizontal coordinates in loading section of hysteretic loops from Fig.1 are portrayed in the dual-logarithmic coordinates system with radial stress P_c as vertical coordinate and shear strain γ *as* horizontal coordinate, the results are shown in Fig.2.
2) Bolton and Whittle [13] found that P_c and γ in the hysteretic loops show linear relationships in the dual-logarithmic coordinate system and the relationship can be described by equation (2). Take GRS as an example, the linear relationship between P and r is shown in figure 2.

$$\ln P_c = \ln \eta + \beta \ln \gamma_c \tag{2}$$

where P_c is the radial stress, γ_c is the shear strain, β and η are undetermined coefficient, ln η and β are the intercept and slope of the fitting lines.

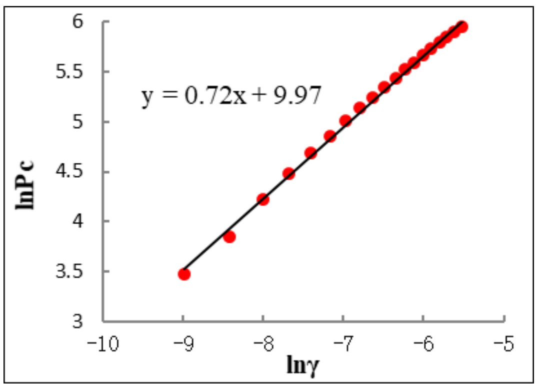

Fig. 2 The linear relations between Pc and γ

3) According to the method of solving tangential shear modulus G_t by Muir Wood [14], the value of shear modulus can be determined by formula (3)

$$G_t = \alpha\beta\gamma_c^{\beta-1} \tag{3}$$

where Gt is tangent shear modulus, α and β are called intercept parameters and elasticity indices. α can be determined by formula (4)

$$\alpha = \eta\beta \tag{4}$$

During the process of SBPT, elastic deformation of soil occurs in the first hysteresis loop (Loop1). It can be considered that the *G-γ* decay curve of this section is in the stage of the initial state. Therefore, the data of *Pc* and *γ* from Loop1 can reflect the undisturbed state of soil. The *G-γ* decay curves in small deformation (γ=10^{-4}~10^{-1}) obtained by SBPT are shown in Fig.3. It can be seen that the overall trends of all curves show evident declines while the values of shear modulus in the curves of various soils differ from each other.

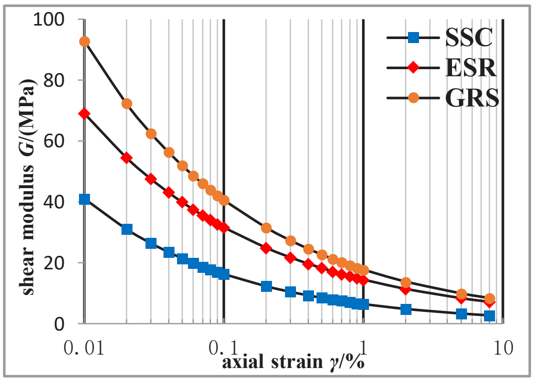

Fig. 3 The major decay stage of *G-γ* curves from SBPT

The shear modulus G_{max} of soil under small strain refers to the shear modulus when the shear strain $\gamma \leq 10^{-5}$. In this paper, the initial shear modulus G_0 obtained by SDMT is introduced into the solution of in-situ *G-γ* decay curves. From the theory of elasticity, the shear modulus *G* is almost constant when the shear strain $\gamma \leq 10^{-5}$. Therefore, the shear modulus remains as G_0 in the in-situ *G-γ* curves when the shear strain $\gamma = \gamma \leq 10^{-5}$. Referring to the shape of *G-γ* curves obtained by resonance column tests, the interval of the abscissa（*γ*） of in-situ *G-γ* curves is set as 10^{-6}~10^{-1}. The stage of $\gamma = 10^{-6}$~10^{-5} in curves can be regarded as an elastic deformation stage so as the value of *G* in the stage remains as G_0. In consequence, the complete in-situ *G-γ* decay curves of various structural soils are obtained by connecting the elastic deformation stage from SDMT and the main attenuation stage from SBPT with a smooth transition curve, as shown in the Fig.4.

It can be seen from Fig.4 that the in-situ *G-γ* curves obtained by the proposed method in this paper are exponential recession curves. The mathematical model of the stiffness under the small strain which obtained by Ken Stokoe can be used to describe the in-situ *G-γ* curves of structural soil [15]. The equation of mathematical model is shown by formula (5).

$$G = \frac{G_0}{1+(\gamma/\gamma_r)^c} \tag{5}$$

where the *c* in the formula is the curvature parameter of the in-situ *G-γ* curve, γ_r is the reference shear strain. In the formula, *c* and γ_r are fitting parameters which can be determined according to the testing curves of various types of soil.

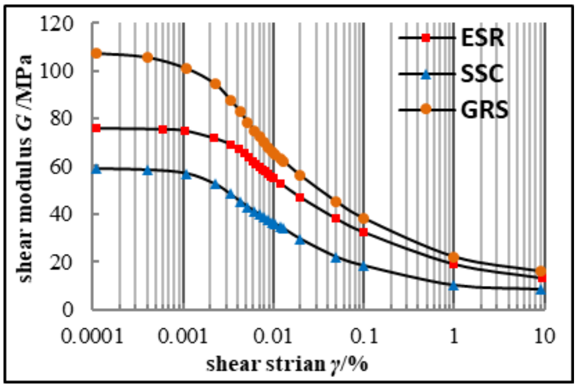

Fig. 4 The complete in-situ *G–γ* decay curves

The laboratory *G-γ* decay curves for granite residual soil were measured in triaxial tests with local strain measurement and bender elements. In order to compare the stiffness attenuation curves obtained by RCT and in-situ tests, the RCT curve and the in-situ curve are both portrayed in Fig.5. It can be seen in the Fig.5 that the model of Ken Stokoe can describe the variation trend of shear modulus *G* of granite residual soil with shear strain *γ* in the insitu and RCT curves, feasibly and precisely.

From the two curves, the stiffness parameter of in-situ curve is 2.1 to 3.6 times of the RCT curve with largest differences observed at the large strain level (γ＞1%) and smallest difference at the initial deformation stage (γ＜0.001%). Also, it is observed that different testing methods can cause significant discrepancy in the shape of *G-γ* curves. Although the overall trends of two curves are similar, the curvature of RCT curves (γ=10^{-4}~10^{-1}) are larger than that of in-situ testing curve. The result of this paper shows that laboratory testing results underestimate the non-linear soil stiffness.

In the study of soil dynamics, the attenuation of shear modulus with shear strain is usually reflected by the normalization method. The *G/G0-γ* normalization curves of GRS in laboratory and in situ tests are showed in Fig.6, which indicates that the attenuation rate of stiffness parameters in RCT curve is higher than that of in-situ curves.

The reason of the discrepancy between *G -γ* and *G/G0-γ* curves of the in-situ tests and the laboratory test is caused by the irrecoverable structural damage occurs during the process of sampling, transportation and preparation, which results in the decrease of shear modulus in the process of soil deformation. This phenomenon is more obvious in structural soils which are susceptible to disturbance, such as granite residual soil, structural soft soil and expansive soft rock. In consequence, excessive reliance on laboratory tests inevitably would result in economic wastes for determining engineering parameters of structural soils. In order to obtain real and precise engineering parameters of soil, more attention should be paid on the application of in-situ tests.

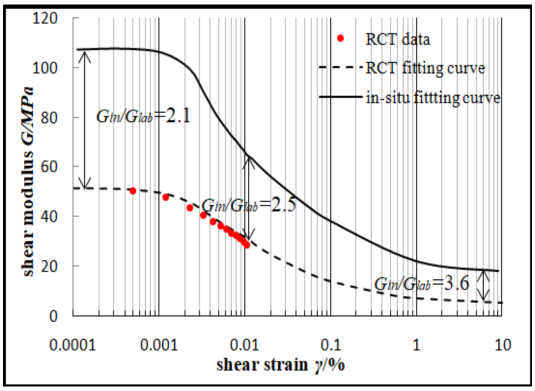

Fig. 5 The results of RCT and in-situ test

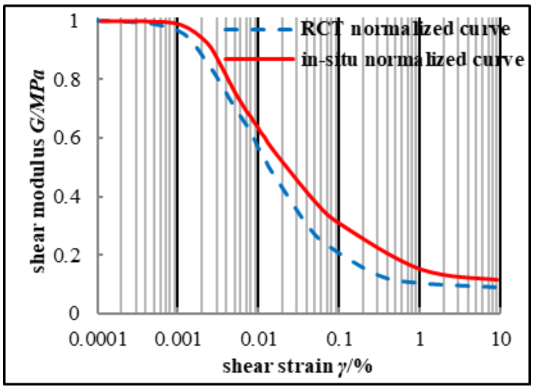

Fig. 6 The normalized in-situ and RCT fitting curves

4 Conclusion

(1) Geotechnical in-situ tests are important technical means to obtain the mechanical properties of soil, especially for structural soils. In this paper, in-situ stiffness tests of three kind of typical structural soil are carried out with self-boring pressuremeter and seismic diameter to propose a suggested method for obtaining in-situ G-γ decay curves of soil.

(2) The mathematical model obtained by Ken Stokoe can suitably describe the variation trends of in-situ shear modulus G of the three kind of soil with shear strain γ. By comparing the experimental data, it is proved that the applicability demand for predicting the in-situ stiffness attenuation law can be satisfied.

(3) The results show that the proposed method evades the shortcomings of the laboratory tests and possess of better suitability in the study on the stiffness attenuation law of structural soils. The in-situ G-γ decay curves from the proposed method can provide a reasonable reference for the selection of stiffness parameters of soil.

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References

1. J. H. Atkinson. Non-linear soil stiffness in routine design. Geotechnique, **50**, 5, 487-508 (2000).
2. P. W. Mayne., J. A. Schneider., G. K. Martin. Small- and large-strain soil properties from seismic flat dilatometer tests. Proceedings of the International Symposia on Pre-Failure Deformation Characteristics of Geomaterials.419–426 (1999).
3. Z. Khan., M.H. El Naggar., G. Cascante. Frequency dependent dynamic properties from resonant column and cyclic triaxial tests. Journal of the Franklin Institute (2010).
4. J. H. Jardine., D. M. Potts., A. B. Fourie., et al. Studies of the influence of non-linear stress-strain characteristics in soil-structure interaction. Geotechnique, **36**, 3, 377—396 (1986).
5. Ramberg, Walter and Osgood, William R., Description of Stress-Strain Curves by Three Parameters. Technical Notes National Advisory Committee for Aeronautics 902 (1943)
6. Stokoe, K. H., Darendeli, M. B., Andrus, R. D. & Brown, L. T. Dynamic soil properties: laboratory, field and correction studies. *Proc. 2nd Int. Conf. on Earthquake Geotech. Engng*, Lisbon 3, 811–845 (1999).
7. R. An., L.W. Kong., C. S. LI., et al. A proposed method to determine in-situ shear modulus and shear strain decay curves of granite residual soil and its suitability analysis Rock and Soil Mechanics:1-9 (2018)
8. P. Monaco., Totani G., M. Calabrese. DMT-predicted vs observed settlements: a review of the available experience. Proc. 2nd Int. Conf. on the Flat Dilatometer, Washington D.C., 244-252 (2006).
9. M. Fahey., B. Lehane., D. Stewart. Soil stiffness for shallow foundation design in the Perth CBD. Australian Geomechanics, **38**, 3, 61–89 (2003).
10. S. Amoroso. *G –γ* decay curves by seismic dilatometer (SDMT). *PhD Thesis*, University of L'Aquila (2011).
11. M. Manassero. Stress-strain relationships from drained self-boring pressuremeter tests in sands. Géotechnique, **39**, 2, 293—307 (1989).
12. S. Marchetti., P. Monaco., G. Totani., Marchetti D. In Situ Tests by Seismic Dilatometer (SDMT). ASCE Geot. Special Publication GSP 170 honoring Dr. J. H. Schmertmann, 292-311 (2008).
13. M. D. Bolton., R. W. Whittle., A non-linear elastic/perfectly plastic analysis for plane strain undrained expansion tests. Géotechnique, **49**, 1, 133–141 (1999).

14. W. D. Muir. Strain-dependent moduli and pressuremeter tests. Géotechnique, **40**, 3, 509－512 (1990)