Pure Appl. Geophys. 176 (2019), 669–684

https://doi.org/10.1007/s00024-018-2011-x

Pure and Applied Geophysics

Correlations between Shear Wave Velocity and Geotechnical Parameters for Jiangsu Clays of China

WEI DUAN,[1] GUOJUN CAI,[1] SONGYU LIU,[1] and ANAND J. PUPPALA[2]

Abstract—The shear wave velocity (V_s) is an important factor reflecting the dynamic characteristics of soil. Measured V_s values are always used in combination with laboratory parameters (e.g., effective confining pressure, σ'_m, and void ratio, e) and in situ penetration parameters from the standard penetration test (SPT) and piezocone penetration testing (CPTU). This study aims not only to estimate V_s based on correlations with other parameters in the absence of site-specific data, but also to outline relationships for estimation of soil properties. A database of seismic CPTU (SCPTU) and soil properties information for Jiangsu clays in East China was used to develop correlations between V_s and geotechnical parameters (vertical effective stress, unit weight, preconsolidation stress, site-specific parameters, undrained shear strength, and CPTU net cone resistance). Laboratory tests were carried out on thin-walled tube samples and high-quality block samples to measure soil properties. The results showed that the predicted values of V_s were in good accordance with measured values from field tests, especially the V_s values predicted from the CPTU net cone resistance. The relationship between V_s and the undrained shear strength showed better performance than the others. The good relationships between V_s and geotechnical parameters could be used to interpret engineering properties of Jiangsu clays for site investigation.

Key words: Shear wave velocity, CPTU, clay, engineering characteristics.

1. Introduction

In geotechnical engineering, description of the stress–strain behavior of soils is a key issue. It is known that the strain level affects the shear modulus (G) of geomaterials. At low strain levels (i.e., about 10^{-6} or less), G is approximately equal to the small-strain shear modulus (G_0). Once G_0 is obtained, it can be applied to estimate the shear response at different strain levels. The shear wave velocity (V_s) is always related to G_0 based on elastic theory, which can be expressed as $G_0 = \rho V_s^2$, where ρ is the soil density. Thus, it is essential to estimate the V_s value of soils to determine G_0. Moreover, V_s can also be used for liquefaction analysis, soil stratigraphy, and in situ strength estimation (Schneider et al. 2001; Andrus et al. 2004; Long and Donohue 2007; Cunning et al. 1995; Cha and Cho 2007; Tang et al. 2016; Oh et al. 2017).

V_s can be measured by laboratory or field tests. Laboratory methods include bender element, resonant column, the piezoelectric ring-actuator technique, etc. (Kim et al. 2013; Yang and Gu 2013; Karray et al. 2015), but the accuracy of such V_s measurements is strongly related to sample disturbance. Freezing samples is expensive, hindering application of this method. Meanwhile, in situ V_s measurements are also widely performed by geophysical field tests. In situ V_s measurements are widely performed by invasive testing (e.g., down-hole, cross-hole, and up-hole tests) as well as noninvasive geophysics methods (e.g., spectral analysis of surface waves, multichannel analysis of surface waves tests, etc.). The seismic piezocone penetration test (SCPTU) is a new kind of down-hole method, and the measured V_s is independent of the operator (Campanella et al. 1986; Cai et al. 2010; Mayne 2007). In the absence of direct testing or when in situ testing is not economically feasible for some low-risk projects, values of V_s can be estimated based on empirical correlations.

In previous studies, relationships between V_s and geotechnical parameters were developed using direct V_s measurements (Kulkarni et al. 2010; L'Heureux and Long 2017). However, it seems that the established empirical correlations suggested by prior

[1] Institute of Geotechnical Engineering, Southeast University, Nanjing 211189, Jiangsu, China. E-mail: zbdxdw@163.com; focuscai@163.com; liusy@seu.edu.cn
[2] Department of Civil Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA. E-mail: anand@uta.edu

studies were merely based on rather selective and limited laboratory and/or in situ data. Chang and Cho (2010) proposed a method to estimate the geotechnical engineering parameters of clays using V_s from laboratory tests, but the method is only applicable to reclaimed clays. Due to differences in soil type and soil variability, the established empirical correlations are not constant and will vary from place to place. Therefore, their application might be limited to site-specific conditions but not be suitable for other areas. On the other hand, although direct in situ measurements of V_s are preferable to indirect estimation, there are some disadvantages (e.g., the requirement for specialized equipment and experience). Thus, relationships between V_s and other parameters can be used for site investigation when in situ V_s measurements are not available.

The primary purpose of this study is to develop reliable relationships between geotechnical properties of Jiangsu clays and V_s values from SCPTU soundings. In this study, a database from 19 Jiangsu clay sites (in eight cities) was studied and an effort made to interlink the V_s values with engineering indices to obtain further understanding of their mutual correlations. Based on this database, some well-defined correlations were established. Relationships among V_s and the vertical effective stress (σ'_{v0}), unit weight (γ), preconsolidation stress (σ'_p), site-specific parameters (α, β), undrained shear strength (s_u), and piezocone penetration parameters are presented and compared with existing correlations. s_u and σ'_p were both obtained from laboratory tests conducted on thin-wall tube samples and high-quality block samples. The relationships established herein could be used to evaluate basic soil properties using known V_s values, and vice versa. It is believed that such relationships represent an important development for reliable estimation of Jiangsu clay site characterization.

2. Testing Method and Database

2.1. Site Description

Geotechnical investigations were conducted in Jiangsu Province, China. Eight cities (Nanjing, Lianyungang, Yancheng, Huai'an, Taizhou, Zhenjiang, Nantong, and Suzhou) that contain sensitive clay deposits were selected to perform SCPTU. Figure 1 shows a map of Jiangsu Province with the approximate study site locations. Average values of soil engineering properties are presented in Table 1.

2.2. Testing Equipment and Data Processing

SCPTU field tests were conducted using a lightweight truck with a 20-ton-capacity hydraulic system, which is in accordance with international standards (ASTM D5778, 2012). The penetration rate was set as 20 mm/s, and nearly continuous data were produced at intervals of about 50 mm. V_s could also be measured by pushing the cone at 1.0-m intervals. Hammer impact was used for wave triggering, while two down-hole geophones measured the shear wave. The time delay between two shear wave arrivals at consecutive depths was determined by cross-correlation methods, then V_s values were determined for the midpoint of the two consecutive depths.

2.3. Sampling and Laboratory Testing

High-quality samples were taken at various depths corresponding to the depths where V_s data were obtained at each investigated site. The soil samples were collected using a stationary piston sampler with diameter of 76 mm at intervals of 1.0 m from ground level to the depth of penetration. When the fixed-piston sampler was removed from the borehole, the soil sample was sealed using wax for laboratory testing. Many measures were taken to ensure that little or no disturbance occurred during transportation.

The laboratory testing program with respect to the basic geotechnical properties of soils included the water content (w), unit weight (γ), Atterberg limits, void ratio (e), s_u, σ'_{v0}, and σ'_p. Note that s_u was measured by direct simple shear (DSS), anisotropically consolidated undrained triaxial compression (CAUC), and field vane tests. For the CAUC tests, each specimen was isotropically consolidated to an all-round stress (about 1/6–1/4 of σ'_{v0}) equal to the suction pressure applied on the specimens. Then, it was isotropically consolidated to the stress

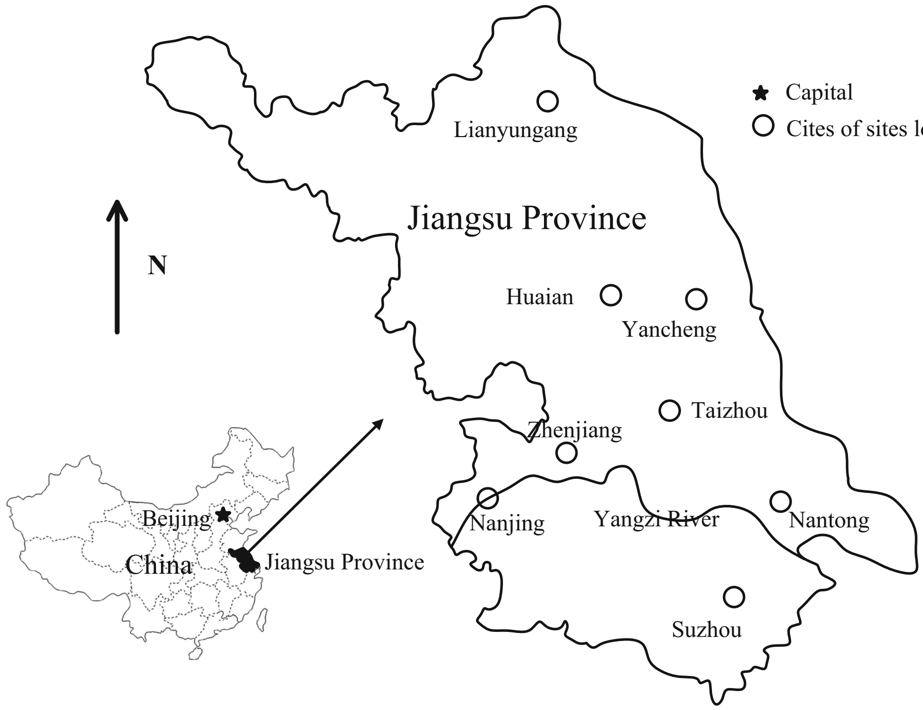

Figure 1
Distribution map of study sites

Table 1

Summary of soil engineering properties in this study

Site	γ (kN/m^3)	w (%)	w_L (%)	I_p	s_u (kPa)	σ'_{v0} (kPa)	σ'_p (kPa)	q_{net} (MPa)
Nanjing	17.0–19.1	10–43	32–42	10–14	10–51	17.5–150.0	76–125	0.10–0.83
Lianyungang	15.4–20.4	24–70	27–87	11–27	11–92	17.6–208.9	42–83	0.17–2.94
Yancheng	16.7–19.7	27–54	38–65	12–26	19–94	18.2–225	43–120	0.10–1.02
Huai'an	16.2–20.4	24–45	35–47	14–25	25–32	17.5–137.2	40–92	0.27–1.60
Taizhou	16.5–19.5	30–65	31–50	12–20	12–34	17.9–138.4	41–98	0.27–1.64
Zhenjiang	17.2–18.5	31–48	30–52	11–20	8–19	17.6–84.2	42–86	0.25–0.81
Nantong	16.7–19.2	26–55	28–49	10–21	20–58	17.5–65.2	45–122	0.40–1.62
Suzhou	15.4–19.6	25–57	30–51	12–36	28–79	17.8–183.5	40–105	0.50–1.26

w water content, w_L liquid limit, I_p plasticity index, q_{net} net cone resistance

[a]See text for explanation of γ, s_u, σ'_{v0}, and σ'_p

corresponding to the in situ stress. The strain rate was 0.096 %/min. σ'_p was determined using the Casagrande method by conventional oedometer tests. Once specimens were placed in the oedometer cell, vertical stress was applied. The settlements were measured by a gauge with precision of 0.001 mm. Each load was doubled relative to the previous load, and the duration of each loading step was about 24 h at least. When settlement did not proceed, the settlement was recorded. Finally, σ'_p was obtained from e and σ'_{v0} on logarithmic scale. Using the above-mentioned methods, soil parameters were obtained for the 19 study sites over the depth range for which shear wave velocity and high-quality sample data were available.

The values of w of Jiangsu clay ranged between 20 and 80% (Fig. 2a), with a large proportion being in the range of 30–40%. The majority of the plasticity

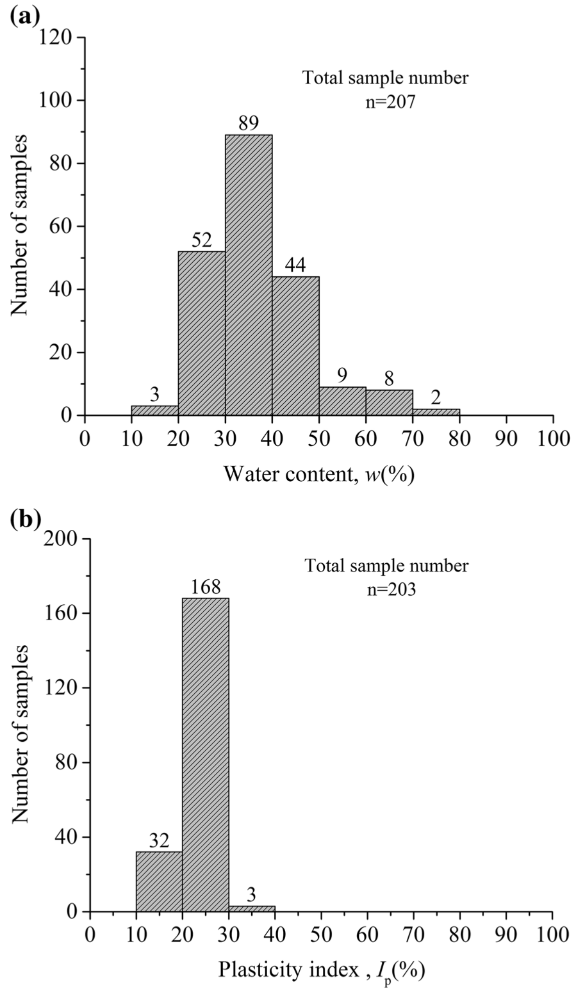

Figure 2
Summary of soil properties from the database of Jiangsu clays: **a** water content, **b** plasticity index

index values varied between 10 and 40%, as shown in Fig. 2b, with the range of 20–30% accounting for a large proportion.

The sample depth of the different Jiangsu clay samples analyzed in this study is shown in Fig. 3a. The in situ σ'_{v0} values for these depths can be determined from the total stress and hydrostatic pressure when the water table and unit weight are known. Figure 3b presents a histogram of the in situ σ'_{v0} values for the samples, showing values ranging from 17 to 225 kPa. Note from this figure that the greatest proportion of values lie around 100 kPa. The σ'_{p} value can be used to assess the overconsolidation

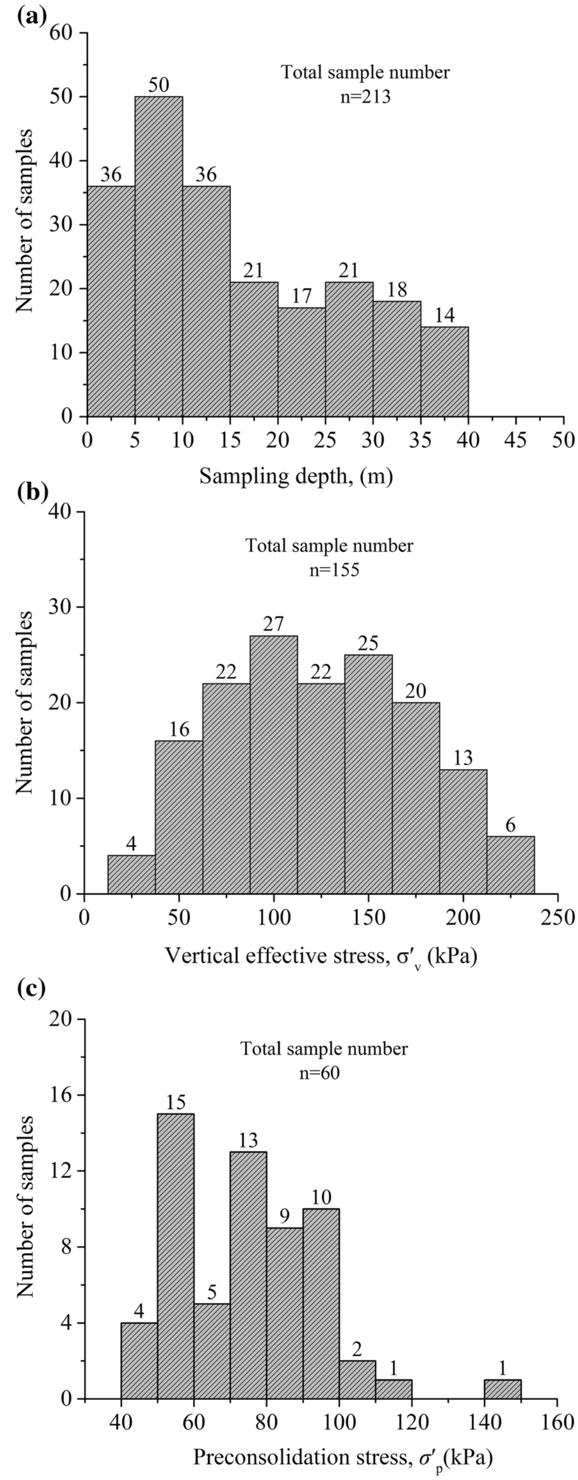

Figure 3
a Sampling depth, **b** in situ vertical effective stress, and **c** preconsolidation stress for samples in the database of Jiangsu clays

ratio (OCR) when combined with the current σ'_{v0}, as shown in Fig. 3c.

2.4. In Situ Shear Wave Velocity

Figure 4 summarizes all the available V_s data in this study. It can be observed from Fig. 4 that the variation of V_s with increasing depth shows a very similar linear trend overall, differing only at depths close to the ground surface. The reason for these results is the effect of the increase in effective stress, which indicates that V_s depends on the effective stress, as mentioned above. It can also be noted that the magnitude of V_s is higher or lower at some sites compared with others. The very soft clay areas have lower V_s values. These may be affected by overconsolidated soil or high water content and organic clay, respectively.

The relationship between V_s and depth can be expressed using an equation of the following form proposed by Teachavorasinskun and Lukkunaprasit (2004):

$$(V_s)_z = (V_s)_g + mz, \tag{1}$$

where $(V_s)_z$ (m/s) is the value at depth z (m), $(V_s)_g$ (m/s) is the value close to the ground surface, and m (s^{-1}) is the slope of the trend line of V_s against depth. The value $m = 9$ was adopted in this study, based on regression analysis of the collected Jiangsu clay database.

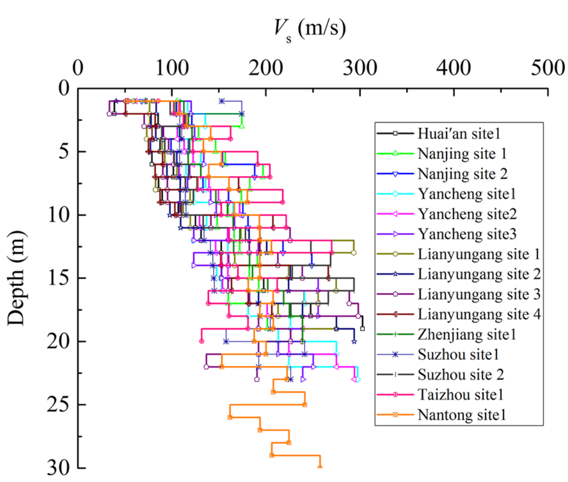

Figure 4
Summary of all V_s data for the Jiangsu clay database

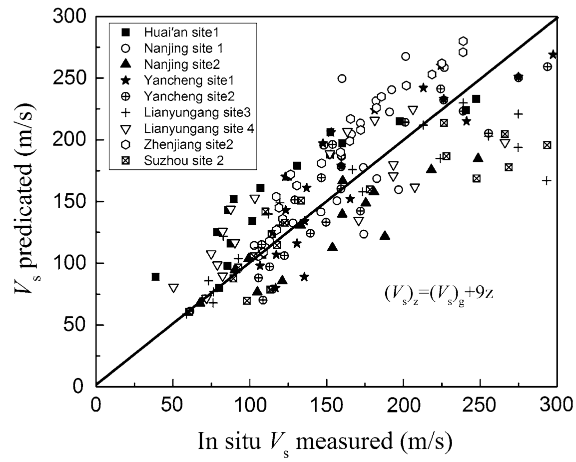

Figure 5
Comparison of measured V_s with predictions based on Eq. (1)

Figure 5 depicts a comparison of the measured V_s values versus those predicted using Eq. (1) with $m = 9$. Note that V_s is a function of the depth of the soil and can be estimated at any depth based on the known V_s value at the ground surface.

3. Correlations between Shear Wave Velocity and Geotechnical Parameters

3.1. State Characteristics

3.1.1 Vertical Effective Stress

It is known that V_s is affected by σ'_{v0}, ρ, e, the soil structure and fabric, etc. (Hardin and Black 1968; Fumal 1978; Fumal and Tinsley 1985; Sully and Campanella 1995; Santamarina et al. 2001; Moon and Ku 2016). Figure 6 depicts all the collected data and the relationship between the in situ V_s and σ'_{v0} obtained at each investigated site in the collected database of Jiangsu clays. Note that V_s increases with increasing σ'_{v0}. A good linear relationship between V_s and σ'_{v0} can be seen in the fitting of the data. The best fit equation for the data ($R^2 = 0.68$) is

$$V_s = 0.99\sigma'_{v0} + 49.68. \tag{2}$$

Most of the data fall within 40 % of Eq. (2). The main reason why the other data fall outside this range is that there are some uncertainties in the evaluation of σ'_{v0} in the field. The relationship between V_s and

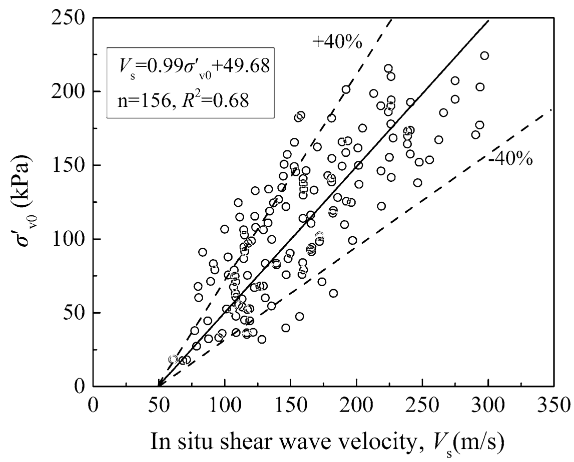

Figure 6
Relationship of V_s versus σ'_{v0}

σ'_{v0} indicates that the magnitude of V_s in geomaterials is closely linked to the vertical effective stress.

In addition, this relation between V_s and σ'_{v0} is closely related to the fact that in situ V_s values are often normalized by σ'_{v0} at 1 atmospheric pressure for evaluation of soil liquefaction (Kayen et al. 2013). Thus, the in situ σ'_{v0} can be estimated from the measured V_s using Eq. (2), and vice versa.

3.1.2 Unit Weight

Some empirical correlations between γ and V_s are listed in Table 2. Because the estimation of γ proposed by Lunne et al. (1997) had some limits in terms of applicable soil types, various empirical relationships for CPT-based γ estimation were developed thereafter (Mayne et al. 2009; Robertson and Cabal 2010; Moon and Ku 2016).

Table 2

Summary of unit weight and shear wave velocity relationships

Empirical relationship	Parameter	References
$\gamma_t = 6.87(V_s)^{0.227}/(\sigma'_{v0})^{0.057}$	V_s	Burns and Mayne (1996)
$\gamma_{sat} = 8.32\log(V_s) - 1.61\log(z)$	V_s	Mayne (2001)
γ_t=4.17 ln(V_{s1}) − 4.03	V_s	Mayne (2007)
γ_t=0.0629 (V_{s1}) + 8.75	V_s	Kim et al. (2001)
γ_t=3.2$V_p^{0.25}$	V_p	Tezcan et al. (2009)
γ_t=γ_0 + 0.002V_p	V_p	Tezcan et al. (2009)
γ_t=4.75 ln(V_{s1}) − 6.73	V_s	Moon and Ku (2016)

Although most of the empirical correlations suggested in previous studies seem reasonable, there is still a need for specific research to overcome the limited test sites and suggest new correlations for Jiangsu clays. Nineteen sites were tested and readings of V_s were measured at intervals of 1 m. The values of V_s obtained from the SCPTU readings and the values of γ obtained from laboratory tests are plotted on semilog scale in Fig. 7. It can be observed that γ increases with increase in V_s. Regression analysis revealed that the relationship between V_s and γ could be appropriately fit ($R^2 = 0.83$) using the following expression:

$$\gamma = 4.96 + 5.97 \cdot \lg V_s. \quad (3)$$

The correlation coefficient is 0.83, indicating relatively high fitting accuracy. In addition, this correlation between V_s and γ is feasible. As mentioned above, V_s can be treated as an effective stress parameter and the total overburden stress (σ_{v0}) can determine σ'_{v0}. The value of σ_{v0} can be calculated from the accumulation of γ with depth ($\sigma_{v0} = \int \gamma\, dz$), which indicates that the σ'_{v0} value at any depth is a function of the γ of the soil. Thus, V_s is very closely related to γ and the developed relationship can be used to estimate V_s from γ, and vice versa.

3.1.3 Preconsolidation Stress

Soil behavior in terms of strength, compressibility, and permeability is distinguished by preconsolidation

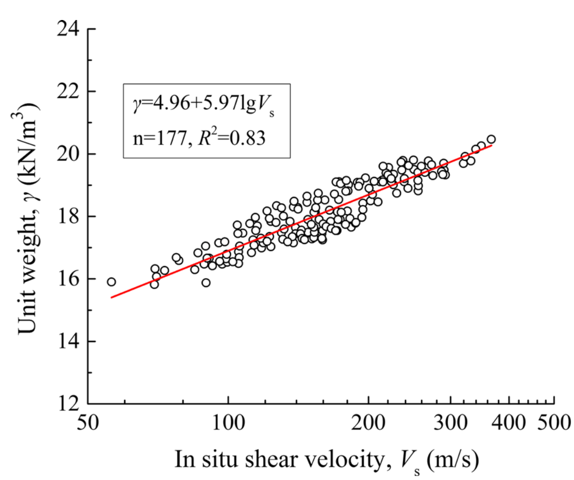

Figure 7
Relationship between shear wave velocity and unit weight

stress. The first step to determine the behavior of a soil formation is to obtain a nearly continuous yield stress profile. Thus, σ'_p is an important focus for soil behavior and has been considered to be an important geotechnical parameter. Based on compression measurements, many methods for evaluating σ'_p have been proposed and the results obtained by plotting methods and curve-fitting procedures. The first and most common method for determining σ'_p was the graphical method proposed by Casagrande (1936). Thereafter, other researchers attempted to improve this by developing new and more definitive methods, e.g., Schmertmann's (1953) reconstruction method, Janbu's (1969) constrained modulus method, Butterfield's (1979) logarithmic methods, the Becker et al. (1987) work-energy method, and Wang and Frost's (2004) dissipated strain energy method.

However, the small-strain behavior was not considered in the commonly used methods mentioned above, and those methods that use the effective stress–void ratio relationship only reflect the global settlement. It is well known that the V_s profile can be applied in both static and dynamic geotechnical analyses, as it provides the small-strain shear modulus. Yoon et al. (2011) developed a reliable method for evaluating σ'_p based on V_s while considering the small-strain behavior, but the V_s values were measured using bender elements in laboratory tests. Evaluation of σ'_p based on in situ V_s measurements was studied by L'Heureux and Long (2017), but the proposed correlations are limited to the test sites. Therefore, it is very important and necessary to develop a new relationship between V_s and σ'_p including the small-strain behavior of V_s.

σ'_p can be estimated using empirical relationships or analytical solutions with in situ V_s measurements. Figure 8 presents the relationship between σ'_p and V_s (σ'_p determined by the traditional Janbu method). Note that σ'_p increases with an increase in V_s. As expected, the correlation between these parameters is strong, since V_s is strongly related to the maximum past vertical effective stress experienced by clays. There is generally a satisfactory power function agreement between σ'_p and V_s. Some of the scatter and variation in Fig. 8 may be caused by highly overconsolidated clay, indicating that the fit may not

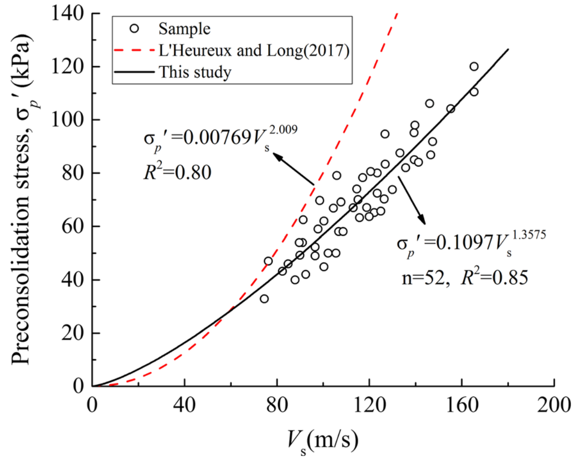

Figure 8
Relationship between shear wave velocity and preconsolidation stress

be good for OCR, consistent with the study by L'Heureux and Long (2017).

$$\sigma'_p = 0.1097 \cdot (V_s)^{1.3575} \quad R^2 = 0.85. \tag{4}$$

Note that the correlation between σ'_p and V_s is satisfactory overall and the fit trendline has a reasonable R^2 value of 0.85. This is helpful given the sensitivity of settlement calculations to the σ'_p value. However, the magnitude of OCR will affect the fit trendline, and highly overconsolidated clays behave differently and were excluded from this trendline. This is because V_s would be expected to represent the current state of stress, not at any higher stress stiffness. Therefore, the OCR effect will affect the fit trendline and cause data scatter. This finding is also reflected in Fig. 9.

The measured σ'_p values and those predicted using Eq. (4) are shown in Fig. 9. Here, the σ'_p values were calculated from Eq. (4) based on in situ V_s measurements. Notably, the measured and predicted σ'_p values are in good agreement (Fig. 9). Therefore, the developed relationship could be used as a first-order estimate of stress history when only shear wave velocity data are available rather than any other geotechnical investigations.

3.1.4 Site-Specific Parameters

Previous works have illustrated that the magnitude of V_s is affected by the effective confining stress (σ'_m), e,

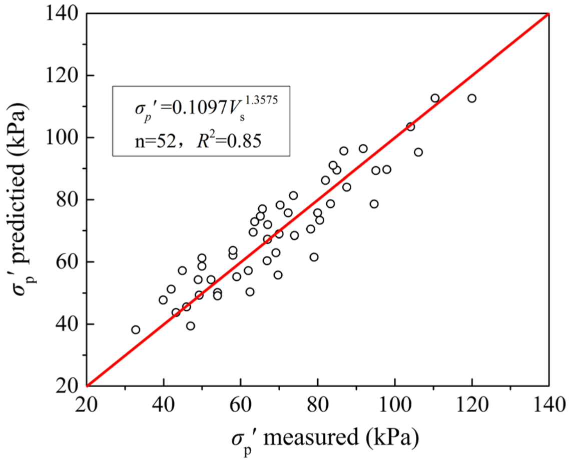

Figure 9
Values of σ_{p}' measured and predicted from the new expression (Eq. 14)

fabric, etc. V_{s} can be treated as an important parameter to quantify the compression and stiffness properties of geomaterials. As the simplest correlation among the various relationships between V_{s} and the influential factors, the expression relating the stress and void to V_{s} can be expressed as (Santamarina et al. 2001)

$$V_{\mathrm{s}} = \alpha(\sigma_{\mathrm{m}}'/1\,\mathrm{kPa})^{\beta}, \tag{5}$$

where the parameter α (m/s) and the exponent β are material constants. The values of α and β can be obtained based on experimental data using Eq. (5).

In fact, as shear waves describe the interparticle contact behavior, the parameter α and exponent β are correlated with the contact behavior between the particles and their packing type, even at small strain (Lee et al. 2015). Thus, it has been suggested that relationships between the coefficient α and exponent β can be used to characterize soil behavior at small strain. Table 3 summarizes the α and β relationships reported in previous research. Note that σ_{m}', as a factor affecting V_{s}, can be categorized as (1) the mean normal stress, $\sigma_{\mathrm{m}}' = (\sigma_1' + \sigma_2' + \sigma_3')/3$, where σ_1', σ_2', and σ_3' are the effective stresses in x, y, and z direction; (2) the individual stress, $\sigma_{\mathrm{m}}' = \sigma_x' \cdot \sigma_y'$, where σ_x' and σ_y' are the principal effective stresses in the direction of propagation and polarization; (3) the individual stress, $\sigma_{\mathrm{m}}' = (\sigma_x' + \sigma_y')/2$; and (4) the effective vertical stress, $\sigma_{\mathrm{m}}' = \sigma_{v0}'$. In previous studies, inverse relationships between α and β were primarily obtained based on selective laboratory testing and some limited in situ testing (Bate et al. 2013; Cha et al. 2014; Lee et al. 2015; Ku et al. 2016). In this study, the compiled Jiangsu clay database was applied to investigate the relationships between α and β observed in situ. In this work, it is proposed that the relationship between α and β is based on the vertical effective stress (e.g., the in situ V_{s}–σ_{v0}' model) because measurement of in situ horizontal effective stresses is a very difficult task.

The in situ parameters α and β can be determined by plotting V_{s} versus the model vertical effective

Table 3

Summary of relationships between α and β

Model	Test type	Relationship	R^2	References
Average stress	In situ	$\beta = 1.01 - 0.18\ln(\alpha)$	0.9	Ku et al. (2016)
Average stress	Laboratory	$\beta = 0.7 - 0.11\ln(\alpha)$	0.83	Ku et al. (2016)
Mean normal stress	Laboratory	$\beta = 0.36 - (\alpha/700)$	–	Santamarina et al. (2001)
Mean normal stress	Laboratory	$\beta = 1217.93/(\alpha + 117.21)^{1.64}$	0.87	Kang et al. (2014)
Mean normal stress	Laboratory	$\beta = -0.011\alpha + 0.3099$	0.76	Kang et al. (2014)
Mean normal stress	Laboratory	$\beta = 0.73 - 0.27\log\alpha$ $1 \le \alpha \le 500$ m/s	0.94	Cha et al. (2014)
Mean normal stress	In situ	$\beta = 1.02 - 0.18\ln(\alpha)$	0.9	Ku et al. (2016)
Individual stress	In situ	$\beta = 0.51 - 0.09\ln(\alpha)$	0.9	Ku et al. (2016)
Effective vertical stress	Laboratory	$\beta = 0.5023 - (\alpha/217.39)$	0.83	Bate et al. (2013)
Effective vertical stress	Laboratory	$\beta = 2/\sqrt{\alpha}$ $5 \le \alpha \le 200$ m/s	–	Lee et al. (2015)
Effective vertical stress	In situ	$\beta = 1.00 - 0.18\ln(\alpha)$	0.86	Ku et al. (2016)
Effective vertical stress	In situ	$\beta = 0.953 - 0.168\ln(\alpha)$	0.92	Moon and Ku (2016)

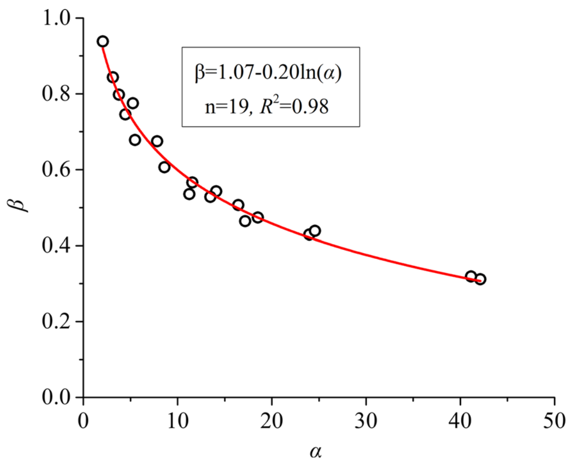

Figure 10
Compilation of in situ α–β computed for each site based on the effective vertical stress

stress when geostatic stress conditions are evaluated, as discussed above. After careful examination of the correlations for all sites in the present study, the α and β values are plotted with trend lines in Fig. 10. Each data point expressed as a value of the coefficient α and corresponding exponent β in Fig. 10 represents critical reference information on the stress dependence for each test site. The relationship between α and β can be appropriately fit ($R^2 = 0.98$) using the following expression:

$$\beta = 1.07 - 0.20\ln(\alpha). \tag{6}$$

It can be seen from Fig. 10 that the log-linear relationship shows good performance. The overall range of exponent β values obtained from in situ testing is between 0.3 and 0.85. This relationship between α and β is in agreement with the study by Ku et al. (2016). Note that four clay sites (e.g., Lianyungang site1, Lianyungang site 2, Lianyungang site 3, and Suzhou site 2) resulted in high values of the exponent β in the range of 0.68–0.94. It can also be seen that the in situ measurement data show a rather wide range of β values (e.g., high β) compared with the correlation suggested by Cha et al. (2014) and Kang et al. (2014). This is not surprising, as both of those works were based on laboratory tests, in which a predetermined stress path will be exerted on an undisturbed sample. The undisturbed sample will undergo void ratio changes along the selected stress path. Overall, the type of test used, the test conditions, the actual aging effect, the inherent variability of soil, etc. will affect the resulting values of α and β. It is therefore difficult to simulate the actual situation in laboratory tests. This is one possible reason for the higher values observed in in situ conditions. Moreover, the relationship between α and β obtained from the shear wave velocity–stress models listed in Table 3 will also affect the values of α and β even for the same type of test. Therefore, it is suggested that separate equations should be used for laboratory-based and in situ measurements for better estimation of β values.

3.2. *Strength Characteristic*

As mentioned above, the V_s of soils mainly depends on σ'_{v0} and e. The properties of V_s and s_u depend on common parameters, and V_s can also be directly used to estimate s_u. Many studies have been done by researchers to develop relationships between V_s and s_u (Blake and Gilbert 1997; Yun et al. 2006; Chang and Cho 2010; Kulkarni et al. 2010; Taboada et al. 2013; Agaiby and Mayne 2015; Oh et al. 2017; L'Heureux and Long 2017; etc.). An overview of some correlations between V_s and s_u for clays all over the world is presented in Table 4. Note that most of the expressions have the same format, but different correlation coefficients. The primary reason for this phenomenon is that the value of s_u depends on the testing method used. Therefore, it is of great significance to know the origin of the data used to reach such conclusions. The same format can be expressed as

$$s_u = aV_s^b, \tag{7}$$

where a and b are correlation parameters that are often significantly related to site-specific conditions. Although the results of previous studies produced relationships between s_u and V_s with good performance, further studies of different regions are required. Figure 11 presents the relationship between s_u and V_s for Jiangsu clay, where the s_u values were obtained from the CAUC test. Note that s_u increases with increase in V_s, and the power function fit shows better performance. The best fit relationship is given by the following equation:

Table 4

Examples of available s_u–V_s correlations for clays

Correlation between s_u and V_s	Clay location	s_u measured by	References
$V_s = 23 \cdot s_u^{0.475}$	San Francisco Bay clay	Fall cone tests	Dickenson (1994)
$s_u = 1.87 \cdot V_s^{1.12}$	Offshore NW USA (55 tests)	Triaxial	Blake and Gilbert (1997)
$V_s = 23 \cdot s_u^{0.475}$	Bangkok clays (13 sites)	Unspecified	Ashford et al. (2000)
$V_s = 187(s_u/p_a)^{0.372}$ $V_s = 228(s_u/p_a)^{0.510}$	Bangkok clays (three sites) based on DHT and MASW, respectively	Unspecified	Likitlersuang and Kyaw (2010)
$V_s = 19.4 s_u^{0.36}$	Gulf of Mexico (38 tests)	Unspecified	Yun et al. (2006)
$s_u = 5 \times 10^{-4}\ V_s^{2.5}$	Indian coastal soils (130 tests, $R^2 = 0.82$)	Unconsolidated undrained triaxial	Kulkarni et al. (2010)
$V_s = 31 s_u^{0.414}$	Bay of Campeche clay	Unconsolidated undrained triaxial and in situ vane tests	Taboada et al. (2013)
$s_u = 0.152 V_s^{1.142}$	Worldwide soils (360 tests, $R^2 = 0.76$)	Triaxial compression	Agaiby and Mayne (2015)
$s_{u1} = 61.5 \log(V_s/32.3) - 5.2$ 8.1–11 m $s_{u2} = 88.1 \log(V_s/28.8) - 15.2$ 11–14 m $s_{u3} = 86.4 \log(V_s/30.2) - 11.9$ 14–17.8 m	Busan, Korea	In situ vane tests	Oh and Bang (2016)
$s_u = 0.038 V_s^{1.063} I_p^{0.14} OCR^{0.31} e_0^{0.07} \sigma_{v0}'^{0.23}$	Worldwide soils (362 tests, $R^2 = 0.87$)	Triaxial compression	Agaiby and Mayne (2015)

DHT down-hole test, *MASW* multichannel analysis of surface waves

$$s_u = 0.162 V_s^{1.50} \qquad R^2 = 0.89. \qquad (8)$$

As expected, the correlation between these two parameters is strong with correlation coefficient R^2 of 0.89. Comparing the results presented in Table 4 and Fig. 11, the *a* and *b* values are found to match well with values reported in literature, especially those of Agaiby and Mayne (2015) for a correlation based on soils worldwide. This illustrates that Eq. (8) can be employed for evaluation of s_u of such clays if values of V_s are known.

The trend lines corresponding to the correlations of Kulkarni et al. (2010) and L'Heureux and Long (2017) are also displayed in Fig. 11. The value of the correlation coefficient (0.89) in this study is higher than those of Kulkarni et al. (2010) or L'Heureux and Long (2017). The trend line in this study is located below the lines obtained in other studies (as shown in Fig. 11). These differences may be caused by: (1) the fact that the correlations developed by both Kulkarni et al. (2010) and L'Heureux and Long (2017) are from laboratory measurements of V_s, while in this study the V_s measurements were obtained by in situ testing, and (2) the fact that regional differences

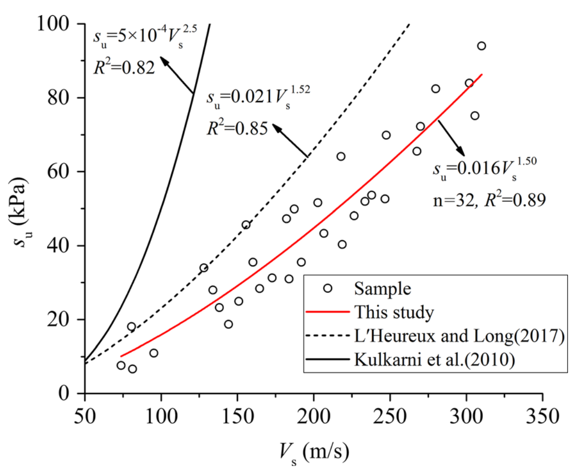

Figure 11
Relationship between shear wave velocity and undrained shear strength

cause some soils to show different engineering properties.

The relationship between s_u and V_s also belongs to one kind of stiffness–strength correlation. Although large- and small-strain phenomena are not causally related and correspond to different particle-

Table 5

Examples of available q_t–V_s correlations for clays

Correlation between cone resistance and V_s	Clay location	Number of data	R^2	Ref.
$V_s = 0.1q_c$	Mexico City	23	–	Jaime and Romo (1988)
$V_{s1} = 102q_{c1}^{0.23}$	Canada	–	–	Robertson et al. (1992)
$V_{s1} = 135q_{c1}^{0.23}$	Alaska	–	–	Fear and Robertson (1995)
$V_{s1} = 149q_{c1}^{0.205}$	Canada	–	–	Karray et al. (2011)
$V_s = 1.75q_{c1}^{0.627}$	Worldwide	481	0.740	Mayne and Rix (1995)
$V_s = 9.44q_{c1}^{0.435}e_0^{-0.532}$	Worldwide	339	0.830	Mayne and Rix (1995)
$V_s = 14.13q_c^{0.359}e_0^{-0.473}$	Worldwide	406	0.890	Hegazy and Mayne (1995)
$V_s = 3.18 \cdot q_c^{0.549} \cdot f_s^{0.025}$	Worldwide	229	0.780	Hegazy and Mayne (1995)
$V_s = 11.9 \cdot q_c^{0.269} \cdot f_s^{0.108} \cdot D^{0.127}$	USA	20	0.910	Piratheepan (2002)
$V_s = 2.994q_{c1}^{0.613}$	Norway	35	0.613	Long and Donohue (2010)
$V_s = 65q_{c1}^{0.150}e_0^{-0.714}$	Norway	35	0.758	Long and Donohue (2010)
$V_s = 1.961q_t^{0.579}(1 + B_q)^{1.202}$	Norway	–	0.777	Long and Donohue (2010)
$V_s = 14.4q_{net}^{0.265}\sigma'^{0.137}_{v0}$	Bay of Campeche	274	0.94	Taboada et al. (2013)
$V_s = 16.3q_{net}^{0.209}(\sigma'_{v0}/w)^{0.165}$	Bay of Campeche	274	0.948	Taboada et al. (2013)
$V_s = 7.95q_{c1}^{0.403}$	Jiangsu, China	35	0.631	Cai et al. (2014)
$V_s = 90q_{c1}^{0.101}e_0^{-0.663}$			0.794	
$V_s = 4.541q_t^{0.487}(1 + B_q)^{0.337}$			0.825	
$V_s = 8.35q_{net}^{0.22}\sigma'^{0.357}_{v0}$	Norwegian clays	115	0.73	L'Heureux and Long (2017)
$V_s = 71.7q_{net}^{0.09}(\sigma'_{v0}/w)^{0.33}$			0.89	

level processes, it is important and interesting that these two parameters can be related through the effective stress variable. These results show that s_u can be approximately estimated from V_s, and vice versa.

3.3. CPTU Characteristic Parameter

The CPTU is a robust, simple, and economical test that gives rapid, continuous soil profiling for site investigation and design (Lunne et al. 1997; Cai et al. 2010). Meanwhile, V_s is an important geotechnical characteristic for soil properties. Therefore, it is important to develop relationships between V_s and various CPTU parameters, as these two techniques can be used complementarily. A number of empirical correlations between V_s and CPTU parameters have been developed by various researchers. The relevant CPTU parameters are the tip resistance (q_c), corrected tip resistance (q_t), q_{net}, sleeve friction (f_s), pore pressure (u_2), pore pressure parameter (B_q), etc.

Table 5 summarizes empirical correlations between V_s and CPTU parameters from literature. Note that the correlations have a similar form worldwide. Although the correlation equations have the same form, there is also a special need to include different factors into the equation to obtain a good fit for specific sites. Moreover, use of q_t, which is slightly better than q_c, to improve the fit of the data and using B_q instead of the soil index property (e_0 or w) can also improve the performance of the correlation equations. Among the basic measurements obtained from CPTU, the variations in decreasing order are u_2, q_t, and f_s (Powell and Lunne 2005; Long et al. 2008; Long and Donohue 2010) and the relationships developed based on q_t or B_q are more reliable than those based on f_s.

Even though these relationships are limited to the test sites only, the proposed relationships seem reasonable because (1) V_s can be related to the penetration resistance in CPTU and the penetration resistance is also affected by e, the density (ρ), and σ'_{v0}, and (2) V_s strongly depends upon σ'_m and e.

It is known that the parameter q_t is considered as the primary CPTU parameter for statistical regression analyses. The correlations related to q_t or B_q and V_s for Jiangsu clays were studied by Cai et al. (2014), but correlations related to the parameter q_{net} have not yet been studied. The parameter q_{net} is equal to $q_t - \sigma_{v0}$, which is related to the vertical total stress (σ_{v0}). Multiple statistical regression analyses were carried out in the current study to develop various forms of power function to relate V_s and q_{net}. The V_s values of the clays showed reasonable agreement when using a power function of q_{net} expressed as

$$V_s = 11.58 q_{net}^{0.382}. \tag{9}$$

The R^2 value was 0.60, and the number of datasets was 205 (Fig. 12). The prediction given by Eq. (9) can be improved by introducing the vertical effective stress (σ'_{v0}), as shown in Fig. 13a, resulting in the expression ($R^2 = 0.68$)

$$V_s = 9.337 (q_{net})^{0.2306} (\sigma'_{v0})^{0.2721}. \tag{10}$$

The correlation coefficients in decreasing order are 0.60 and 0.68, respectively, revealing that a better correlation between the V_s and CPTU parameters for Jiangsu clay in this study can be obtained using the combination of q_{net} with σ'_{v0}. Note that the predicted value of V_s is highly consistent with the measured V_s. Moreover, Jiangsu clays are highly structured and sensitive, so estimation of V_s directly using f_s or combined with other CPTU parameters may be unreasonable.

The measured V_s values and those predicted using the original expressions of L'Heureux and Long (2017) and Taboada et al. (2013) are presented in Fig. 13b and c, respectively. The values of V_s predicted using their expressions deviate from the V_s values measured for Jiangsu clays. Due to their dependence on soil type and some uncertainties (soil heterogeneity and geologic origin, inherently) of the

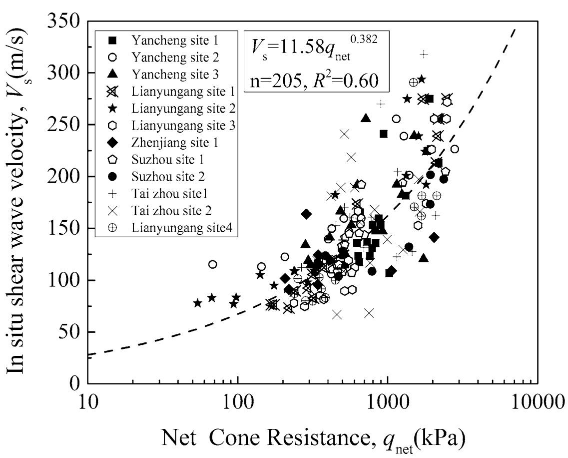

Figure 12
Comparison of measured V_s with that predicted from the net cone resistance (q_{net}) in this study

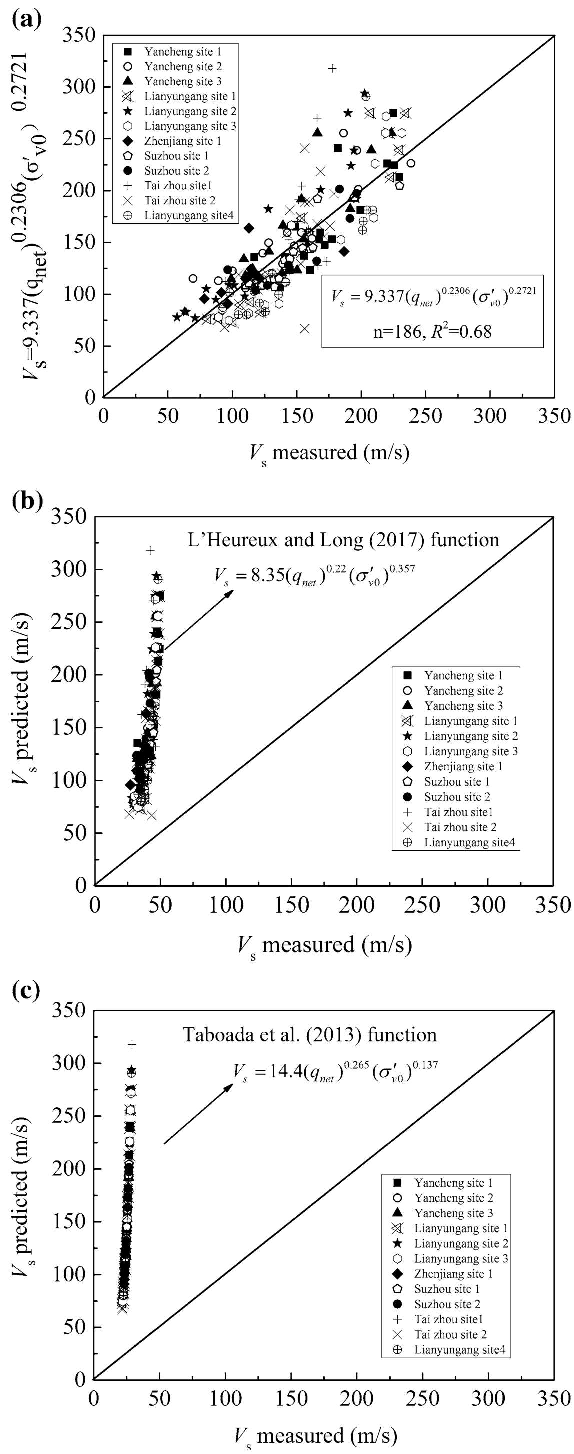

Figure 13
Comparison of measured V_s with that predicted using the expressions **a** for the net cone resistance (q_{net}) and effective stress (σ'_{v0}) in this study, **b** of L'Heureux and Long (2017), **c** of Taboada et al. (2013)

established empirical correlations, they cannot always be applied at different locations. Thus, new relationships developed for specific sites are significant.

It can be observed from Fig. 13a that methods based on CPTU parameters (q_{net}) and σ'_{v0} match the measured data well. The most important point is that measurements of V_{s} are independent from the CPTU data. It appears that good predictions of V_{s} can be obtained based on CPTU parameters for Jiangsu clays and the developed relationships can be used for cross-checking with each other. Thus, the V_{s} value of clays can be estimated using measured CPTU parameters.

4. Discussion

It is well known that a shear wave can only cause shear deformation and that its velocity (V_{s}) can be treated as an effective stress parameter (Hussien and Karray 2015). Calculation of geotechnical parameters is mostly based on the principle of effective stress, thus fundamental relationships exist between V_{s} and geotechnical parameters of soils.

Figure 14 presents a flowchart for estimating geotechnical parameters based on V_{s}. Note that the in situ V_{s} value is generally superior to the V_{s} value measured by laboratory tests (with very little or no soil disturbance at lower cost) (Cai et al. 2010). The specific process is as follows:

1. Equation (1) with $m = 9$ can be used to roughly estimate V_{s} at any depth based on a known V_{s} value at the ground surface. However, the value of V_{s} on the ground surface is influenced by many factors and the measured value is not always very accurate;
2. The relationships between V_{s} and σ'_{v0}, and site-specific parameters (α, β) are given by Eqs. (2) and (6), respectively;

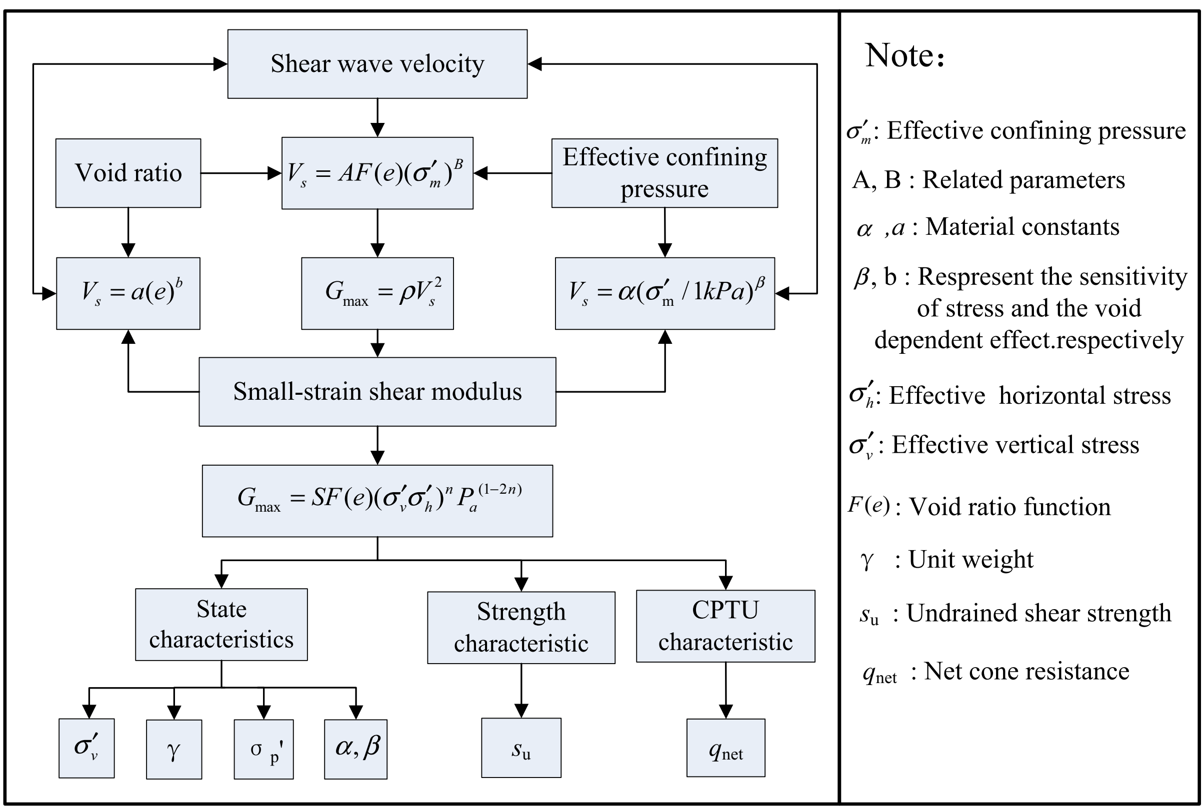

Figure 14
Flowchart for V_{s}-based assessment of geotechnical parameters

3. The relationships between G_0 or V_s and γ are given by Eq. (3);
4. The relationships between V_s and σ'_p or s_u are given by Eqs. (4) and (8), respectively;
5. The relationships between V_s and CPTU parameters (q_{net} or q_{net} combined with σ'_{v0}) are given by Eqs. (9) and (10), respectively.

Although geotechnical parameters vary with depth or location, these reliable correlations have been established based on a large number of data for preliminary estimation or design. Some of the developed relationships may not be satisfied at sites where clays are heavily overconsolidated or with soil and geologic origin heterogeneity. Overall, for investigation of a region of interest at a site, if in situ tests are conducted to obtain the V_s profile, the described correlations could be used to give first-order estimates of soil properties at any depth for engineers. It would be worthwhile to carry out further experimentation to revise these correlations using a larger number of test data.

5. Conclusions

The aims of this study are to provide engineers with guidelines for estimating V_s of Jiangsu clays when site-specific data are absent or for first-order estimates of soil properties when V_s data are known and available prior to other geotechnical investigations. To achieve these aims, a database of Jiangsu clays was compiled and statistically analyzed to produce relevant correlations. Some of the reliable and important results are as follows:

1. It was found that the soil unit weight of Jiangsu clays could be approximately estimated from the measured V_s. The new expression developed may be affected by the stress level, which is a stress-independent expression for the soil γ; It was also observed that the values of α and β for the stress-dependent model could be determined site-specifically in Jiangsu clays. The relationship between α and β can be expressed specifically as $\beta = 1.07 - 0.20\ln(\alpha)$ for Jiangsu clays of this study
2. It was noted that the in situ V_s correlates satisfactorily with the σ'_p or s_u values, and that these correlations can be used to evaluate soil parameters such as σ'_p or s_u from the measured V_s, and vice versa. The relationship between V_s and s_u shows better performance than the others, and the developed relationship between V_s and s_u also belongs to one kind of stiffness–strength correlation.
3. The suggested correlations based on CPTU parameters could be used for preliminary estimation of V_s for Jiangsu clays. The new relationships for Jiangsu clays expressed by $V_s = 9.337(q_{net})^{0.2306}(\sigma'_{v0})^{0.2721}$ containing the σ'_{v0} parameter can be used for preliminary estimation of V_s in geotechnical engineering investigations.

Acknowledgements

The majority of the work presented in this paper was funded by the National Key R&D Program of China (grant no. 2016YFC0800200), National Natural Science Foundation of China (grant nos. 41672294 and 41877231), and Fundamental Research Funds for the Central Universities and Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX17_0139). This financial support is gratefully acknowledged. The authors would like to express appreciation to the editor and anonymous reviewers for their valuable comments and suggestions.

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(Received November 4, 2017, revised September 29, 2018, accepted October 3, 2018, Published online October 12, 2018)