

Indirect evaluation of the shear wave velocity of clays via piezocone penetration tests

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Abstract. This paper presents the re-evaluation of existing piezocone penetration test (CPTu)-based shear wave velocity (V_s) equations through their application into well-documented data obtained at nine sites in six countries. The re-evaluation indicates that the existing equations are appropriate to use for any specific soil, but not for various types of clays. Existing equations were adjusted to suit all nine clays and show that the correlations between the measured and predicted V_s values tend to improve with an increasing number of parameters in the equations. An adjusted equation, which comprises a CPTu parameter and two soil properties (i.e., effective overburden stress and void ratio) with the best correlation, can be converted into a CPTu-based equation that has two CPTu parameters and depth by considering the effect of soil cementation. Then, the developed equation was verified by application to each of the nine soils and nine other worldwide clays, in which the predicted V_s values are comparable with the measured and the stochastically simulated values. Accordingly, the newly developed CPTu-based equation, which is a time-saving and economical method and can estimate V_s indirectly for any type of naturally deposited clay, is recommended for practical applications.

Keywords: clay; correlations; CPTu; empirical methods; shear wave velocity

1. Introduction

The shear wave velocity (V_s) and maximum shear modulus (G_0) are fundamental geotechnical properties for ground and foundation vibration problems (Dobry and Gazetas 1986, Stokoe *et al.* 1978). These parameters can be applied in characterizing various soil properties (Cho *et al.* 2018, Kulkarni *et al.* 2010, Long and Donohue 2010, Safdar *et al.* 2021, Yoon *et al.* 2011), classifying soil deposits for earthquake-resistant design (KDS 2019, Foundation Engineering Manual 1985), settlement prediction (Cho *et al.* 2017, 2020), and assessing sample quality (Chung and Kweon 2013, Chung *et al.* 2014, Donohue and Long 2010, Nishida *et al.* 2006). In situ V_s is measured using various wave propagation tests, including the cross-hole (CH) and down-hole (DH) tests, spectral analysis of surface waves (SASW), multichannel analysis of surface waves, and seismic refraction and reflection tests. Hybrid in situ tests, such as seismic piezocone penetration (SCPTu) and seismic flat dilatometer (SDMT) tests, are used as cost-effective DH tests (Campanella *et al.* 1986, Lunne *et al.* 1997, Martin and Mayne 1997). Traditional methods that require two or more

boreholes (e.g., CH) are costly. By contrast, recently developed hybrid techniques are sophisticated but economic. Thus, these techniques have been increasingly used for site investigation. In-situ methods are reliable and repeatable. Laboratory methods, including bender element (BE), resonant column (RC), and cyclic triaxial tests, are also available for measuring V_s on soil samples (Lo Presti *et al.* 1993, Singh and Chung 2013, Tatsuoka and Shibuya 1992). Thereafter, G_0 is calculated using density (ρ): $G_0 = \rho V_s^2$. Moreover, V_s and G_0 are empirically and indirectly estimated using either geotechnical properties measured in the laboratory or soil parameters from other extensively used in situ tests, such as the piezocone penetration test (CPTu).

In developing empirical methods, V_s and G_0 are traditionally considered as a function of effective overburden stress (σ'_{v0}) and in situ void ratio (e_0) (Jamiolkowski *et al.* 1994, Shibuya and Tanaka 1996). Several other factors, including cementation, structure, overconsolidation ratio (OCR), saturation, temperature, grain characteristics, strain amplitude, vibration frequency, and cementing material characteristics, are considered for naturally cemented soils (Chang 1986, Schnaid 2009). The CPTu, which is most extensively used in the field, has been increasingly adopted for the indirect estimation of V_s . Mayne and Rix (1993, 1995) reported that V_s (and G_0) and cone resistance (q_c or corrected $q_c [q_{t,i}]$) are influenced by effective confining stress level, anisotropic K_0 -stress, mineralogy, aging, bonding, and other factors. Additional attempts (Kawaguchi and Tanaka 2008, Lunne *et al.* 1997, Mayne and Rix 1993, 1995) have been made to correlate V_s

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Table 1 CPTu-based empirical equations for V_s

Empirical formulas*	Test methods	References
$V_s = 16.5 q_{tIN}^{0.411} I_c^{0.970} ASF(p_a/\sigma'_{v0})^{-0.25}$	SCPT, CHT, BE, RC	Andrus <i>et al.</i> (2007)-(a)
$V_s = 2.27 q_t^{0.412} I_c^{0.989} z^{0.033} ASF$		-(b)
$V_s = [(10.1 \log q_t) - 11.4]^{1.67} (f_s/q_t \cdot 100)^{0.3}$	Various in situ tests	Hegazy and Mayne (1995)
$V_s = 3.18 q_c^{0.549} f_s^{0.025}$	SCPT, DHT, CHT & SASW	Hegazy and Mayne (2006)-(a)
$V_s = 0.0831 q_{c1N} (\sigma'_{v0}/p_a)^{0.25} e^{1.786I_c}$	SCPT, DHT, CHT & SASW	-(b)
$V_s = 71.7 q_{net}^{0.09} (\sigma'_{v0}/w_n)^{0.33}$	Various in situ tests	L'Heureux and Long (2017)
$V_s = 1.96 q_t^{0.579} (1 + B_q)^{1.202}$	Various in situ tests	Long and Donohue (2010)
$V_s = 117 + 1.33 f_s$	Various in situ tests	Mayne and Burns (1995)
$V_s = 1.85 q_c^{0.618}$		Mayne and Rix (1995)-(a)
$V_s = 8.60 (q_c - \sigma_{v0})^{0.410}$		-(b)
$V_s = 9.44 q_c^{0.435} e_0^{-0.532}$	CHT, DHT, SASW	-(c)
$V_s = 40.3 (q_c - \sigma_{v0})^{0.219} e_0^{-0.508}$		-(d)
$V_s = [10^{0.55I_c + 1.68} (q_t - \sigma_v)/p_a]^{0.5}$	SCPT	Robertson (2009)
$G_0 = 21.5 q_c^{0.79} (1 + B_{qc})^{4.59}$	SCPT, CHT, BE, RC	Simonini and Cola (2000)
$V_s = 34.8 q_t^{0.269} f_s^{0.097} I_c^{-0.5}$	SCPT	Wang <i>et al.</i> (2021)-(a)
$V_{s1} = 878.7 f_s^{0.1499} I_c^{-1.887}$		-(b)

* $B_q = \Delta u/q_{net} = (u_2 - u_0)/(q_t - \sigma_{v0})$, B_{qc} = the pore pressure parameter (Simonini and Cola 2000) = $\Delta u/q_c$, $I_c = [(3.47 - \log Q)^2 + (\log F + 1.22)^2]^{0.5}$ where $Q = (q_t - \sigma_{v0})/\sigma'_{v0}$ and $F = f_s/(q_t - \sigma_{v0}) \times 100\%$, $q_{tIN} = (q_t/p_a)(p_a/\sigma'_{v0})^n$ where $n = 1$ for clay, $q_{c1N} = (q_c/p_a)(p_a/\sigma'_{v0})^n$ where $n = 0.75$ for clay, z = depth, ASF = age scaling factor (= 1 for Holocene); $V_{s1} = V_s(p_a/\sigma'_{v0})^{0.25}$; p_a = reference stress, and w_n = water content

and q_t by incorporating e_0 or other indices. Here, the directly measured values (i.e., q_c or q_t , f_s [sleeve friction], and u_2 [pore pressure]) are denoted as primary CPTu parameters. Moreover, secondary CPTu parameters, such as soil behavior type index (I_c), pore pressure ratio (B_q), and normalized cone tip resistance (q_{tIN}), have been utilized (Andrus *et al.* 2007, Long and Donohue 2010, Robertson 2009, Tonni and Simonini 2013).

CPTu-based methods that incorporate e_0 (or other geotechnical properties) and the primary or secondary CPTu parameters for the improved evaluation of V_s require continuous sampling to obtain the profiles of index properties (e.g., e_0 and bulk unit weight, γ_t , that is used to calculate σ'_{v0} and σ_{v0}). Such soil sampling and testing are costly and time-consuming. Despite such efforts, CPTu-based methods yield underestimated or overestimated V_s (and G_0). This finding indicates that most of the existing empirical formulas may be appropriate to apply satisfactorily for any local soil, but not for all types of clays in the world. Thus, a sole CPTu-based method (i.e., a cost-effective and time-saving method without the adoption of sampling), which is applicable to any type of clay, needs to be developed especially for preliminary investigations. Therefore, this study aims to develop CPTu-based methods that can determine V_s indirectly by using only the primary CPTu parameters and can be applied to most types of clays. Thus, existing CPTu-based methods that comprise different types of primary or secondary parameters and geotechnical properties are reviewed and applied to well-documented geotechnical profiles that include soil descriptions and the profiles of $V_{s,F}$, CPTu parameters, and geotechnical properties. Then, a new empirical method for V_s is proposed by the direct consideration of CPTu parameters and the

indirect consideration of the structural level of clay (i.e., cemented or sensitive clay). The sensitivities of three parameters adopted in the empirical equation are investigated. Then, stochastic simulation is performed to consider a significant amount of uncertainties that occur during soil investigation and prediction. Finally, estimated V_s values obtained using the proposed formulas are validated through comparison with the measured and the stochastically simulated V_s values on various clays in the world.

2. Existing empirical correlations for V_s and their applicability

2.1 Existing empirical formulas

Hardin and Black (1968, 1969) first suggested the following empirical equation by using geotechnical properties to evaluate G_0 at low-amplitude shear strains

$$G_0 = \chi \cdot f(e) \cdot OCR^\kappa (\sigma'_m)^n \quad (1)$$

where χ is a fitting parameter; $f(e)$ is a function of e_0 ; and κ and n are the fitting parameters related to soil plasticity and the mean effective stress σ'_m , respectively. Thereafter, several empirical formulas in terms of e_0 and σ'_m (or vertical effective stress σ'_v) with or without OCR and CPTu parameters were proposed (Jamiolkowski *et al.* 1994, Mayne and Rix 1993, 1995, Shibuya and Tanaka 1996).

Table 1 shows several empirical correlations between V_s and CPTu parameters for clay: q_c (or q_t), sleeve friction (f_s), B_q , I_c , and σ_{v0} or σ'_{v0} . Moreover, other CPTu-based

Table 2 Description of various worldwide clays

	Sites	Deposits	Soil types
Busan, Korea	D2 & DIS-5	Deltaic deposit	Soft massive clay with few shelly layers in the inner self (IS) depositional unit (up to 20–30 m) and soft to firm clay with few sandy or silty clay layers in the lower tidal flat [TF(L)] unit (below the depth)
Saga, Japan	JP	Marine deposit	Thick soft and sensitive silt and silty clay with thin sand lenses
Bothkennar, UK	UK	Deltaic deposit	Thick micaceous silty clays with an organic content of 3–8% and variety in structure and fabric induced by different depositional conditions.
Bangkok, Thailand	AIT, NHH, & SUT	Deltaic deposit	Generally, the top weathered crust is about 2 to 4 m thick which is followed by soft and dark gray clay with some shells/organic matters (up to ~ 11 m), soft and grayish clay with thin sand and/or silt lenses (up to ~ 15m), ~7 m thick light brown stiff clay (i.e., up to ~ 22 m), and finally followed by dense sand layer commonly known as Bangkok aquifer.
Sarapui, Brazil	SR	River deposit at a flat swampy area	Very soft organic plastic slightly overconsolidated clay. The organic content is in the range of 5–18%, with higher values to the depth of 3 m.
Fucino Basin, Italy	FU	Lacustrine deposit	Clayey and silty soils with thin sandy layers at few depths; no significant variation in grading but the calcium carbonate content varies considerably with depth.

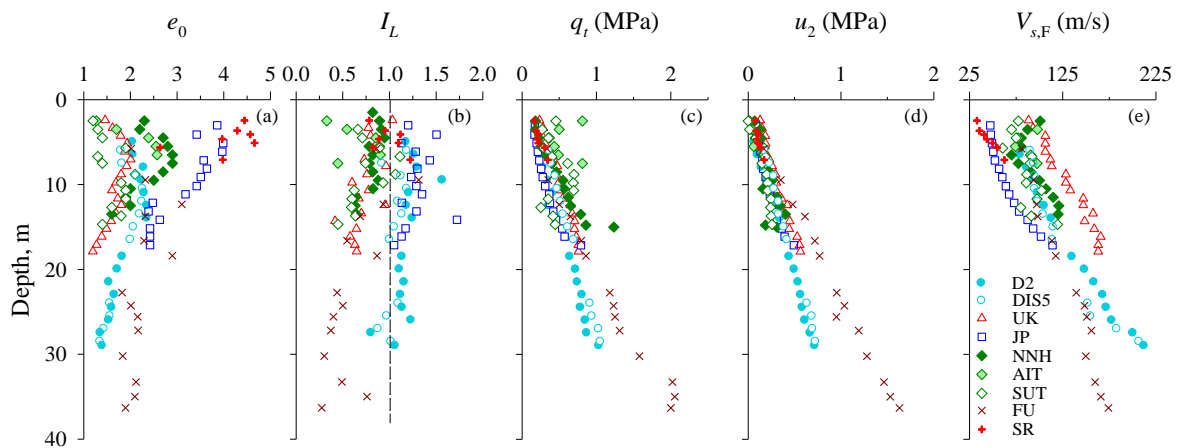


Fig. 1 Geotechnical property profiles of nine clays

equations included an additional geotechnical parameter (i.e., e_0 , and w_n) to enhance correlations. Most of the empirical methods are developed to suit local soils and require soil sampling.

2.2 Data sources and site descriptions

Well-documented test data that included soil description and the profiles of $V_{s,F}$, primary and secondary CPTu parameters, and geotechnical properties were collected from nine sites in six countries: Busan (D2 and DIS-5 sites) in Korea (Chung *et al.* 2017, Singh and Chung 2015), Bangkok (NNH, AIT, and SUT sites) in Thailand (Shibuya and Tamrakar 2003), Ariake (JP site) in Japan (Chai *et al.* 2017, Kawaguchi and Tanaka 2008, Tanaka *et al.* 2001, 2012), Bothkennar (UK site) in the United Kingdom (Hawkins *et al.* 1989, Hight *et al.* 2003), Sarapuí (SR site) in Brazil (Jannuzzi *et al.* 2015), and Fucino basin (FU site) in Italy (Soccodato 2003). Table 2 presents the brief description of the six types of clays at nine sites. Soil types

varied from very soft organic soil to clayey silt deposited under various environments (i.e., alluvial, deltaic, marine, and lacustrine environments). The geotechnical properties of the clays are presented in Table 3. Herein, G_0 was converted from V_s by using bulk density. Different sampling techniques, i.e., oil-operated (Chung and Kweon 2013), mechanical (JGS 1998), Shelby-tube samplers, and others, were adopted at each site. The CPTu/SCPTu with different sizes of cones (10 or 15 cm², 60° apex angle, and u_2 -measurement) and the standard procedure were adopted for the sites. The direct measurement of V_s was also conducted using different types of equipment at each site: SDMT (Busan and Sarapui sites), SCPTu (Bangkok, UK, and Japan sites), and CH tests (Fucino site). Single V_s sounding was used at most sites, especially with two CH (seismic cone and CH) tests at the FU site.

Fig. 1 shows the variations in geotechnical properties and CPTu parameters with depth at the sites. The e_0 of the clays varied between 1 and 5. The lowest and highest values were observed in the SUT and SR sites, respectively. Most

Table 3 Basic geotechnical properties of various worldwide clays

Site	Depth (m)	γ_r (t/m ³)	e_0	w_n (%)	w_L (%)	G_s	q_t (kPa)	u_2 (kPa)	S_r	G_0 (MPa)	Reference
D2 *	5–29	1.5–1.7	1.35–2.50	50–93	50–79	2.69–2.72	230–1033	65–717	4–27	10–78	Chung <i>et al.</i> (2017), Singh and Chung (2015)
DIS-5	6–29	1.5–1.7	1.35–2.26	50–84	49–79	2.69–2.71	359–1054	176–726	6–9	13–74	
NNH	2.5–12	1.4–1.6	1.90–2.90	65–105	84–120	2.47–2.97	181–622	70–313	3–5	7–21	Shibuya and Tamrakar (2003)
AIT	4.5–6.5	1.5–1.5	2.39–2.57	90–96	100–104	2.66–2.70	367–490	60–171	2–9	8–12	
SUT	5.7–13.7	1.6–1.9	1.3–2.10	49–77	46–97	2.66–2.82	253–699	149–248	3–5	6–17	
JP	3–17.2	1.3–1.4	2.39–3.99	92–152	67–129	2.04–3.20	168–792	86–492	3–11	3–18	Chai <i>et al.</i> (2017), Tanaka <i>et al.</i> (2001, 2012), Kawaguchi and Tanaka (2008)
UK	2.4–18	1.5–1.8	1.20–2.01	45–75	54–90	2.64–2.70	236–759	129–564	2–3	14–49	Hight <i>et al.</i> (2003), Hawkins <i>et al.</i> (1989)
SR	2.5–7.1	1.3–1.4	2.64–4.66	101–181	117–211	2.52–2.69	168–347	75–171	–	1–5	Jannuzzi <i>et al.</i> (2015)
FU	5.8–36.3	1.4–1.6	1.82–3.10	63–109	74–119	2.63–3.04	335–2054	169–1632	–	10–47	Soccodato (2003)

*The abbreviations of each site are as follows: D2 and DIS-5 = Busan, Korea; NNH, AIT and SUT = Bangkok sites, Thailand; JP = Ariake sites, Japan; UK = Bothkennar, the United Kingdom; SR = Sarapui II site, Brazil, and FU = Fucino basin, Italy

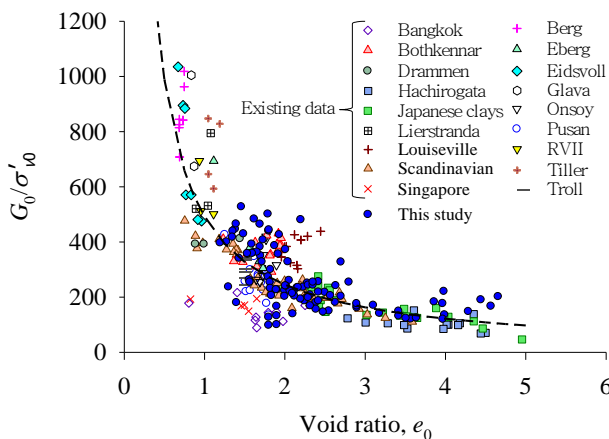


Fig. 2 Relationships between G_0/σ'_{v0} and e_0 [Existing test data from Long and Donohue (2010) and Tanaka (2007)]

clays exhibited the highest e_0 value at depths of 5–8 m, and its decrease toward the ground surface might have resulted from desiccation or groundwater level fluctuations. The liquidity index (I_L) of the JP (Japan) and Busan clays were lower than 1.0, whereas those of other clays were higher than 1.0. Moreover, measured V_s , q_t , and pore pressure (u_2) tended to increase with increasing depth. By contrast, an opposite variation between e_0 and $V_{s,F}$ was observed at the top of Bangkok (NNH, AIT, and SUT) sites. Furthermore, comparing $(G_0/\sigma'_{v0})-e_0$ relationships obtained from the above 9 sites and other 18 sites (Long and Donohue 2010, Tanaka 2007) was attempted to validate the appropriateness of the adopted data. As shown in Fig. 2, the $(G_0/\sigma'_{v0})-e_0$ relationships of the nine clays exhibited a tendency similar to those of existing data. Such trend was also obtained from many other clays (Jamiolkowski *et al.* 1994, Tanaka 2007). Thus, the selected nine data might be reliably used for this study.

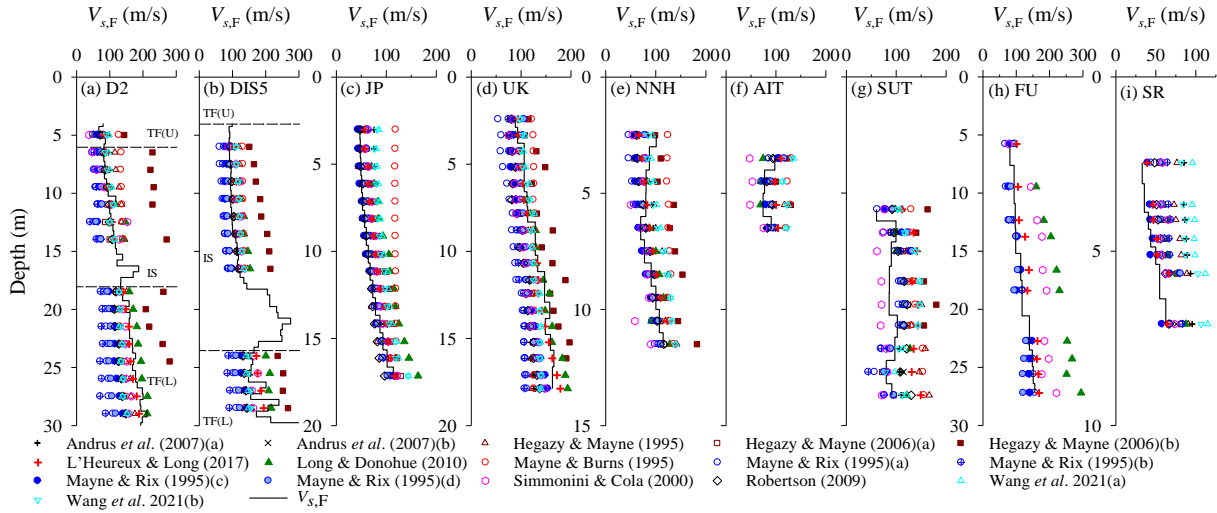
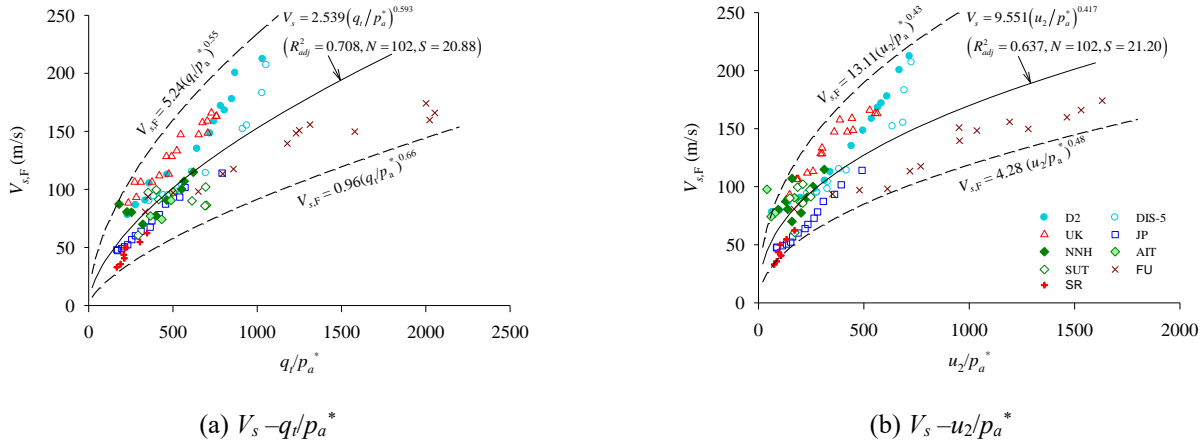
2.3 Applicability of existing empirical formulas

Fig. 3 compares the measured V_s values and estimated V_s profiles obtained using existing empirical equations (Table 1) on Busan, JP, UK, Bangkok, SR, and FU clays. Results indicated that most empirical formulas were inappropriate for reliably estimating the V_s for all clays. Evidently, the applicability of the equations was different from one site to another. Amongst all methods, the best correlation (adjusted coefficient of determination [R_{adj}^2] for clays = 0.744) was estimated using the formula suggested by L'Heureux and Long (2017) based on three parameters (i.e., q_{net} , σ'_{v0} , and w_n). The second-best correlation ($R_{adj}^2 = 0.684$) was estimated from that by Mayne and Rix (1995) on the basis of two parameters (i.e., q_c and e_0). By contrast, the empirical formula suggested by Long and Donohue (2010) tends to predict the upper bound of V_s , whereas the q_c - or $(q_c - \sigma_{v0})$ -based formula by Mayne and Rix (1995) exhibited the lower bound at most sites. However, f_s - and $(q_t, \sigma'_{v0}, e_0, \text{ or } n)$ -based formulas suggested by Mayne and Burns (1995) and Hegazy and Mayne (2006) produce different profiles with poor correlations. The predicted values from other formulas (with the highest $R_{adj}^2 = 0.562$ in average) lay between both bounds and partly agree with the measured values.

3. Development of CPTu-based V_s correlations

3.1 Use of CPTu parameters and geotechnical properties

Most of the empirical formulas listed in Table 1 comprise either the primary CPTu parameters (i.e., q_c or q_t ,


 Fig. 3 Comparison between the measured and estimated V_s by using existing CPTu-based methods

 Fig. 4 Primary CPTu parameters (q_t and u_2) versus V_s

and f_s) or the same parameters with basic soil properties (i.e., e_0 , w_n , σ_{v0} , and σ'_{v0}). Moreover, the complicated secondary parameters I_c (i.e., the function of q_t , f_s , σ_{v0} and σ'_{v0}) and B_q ($= (u_2 - u_0)/(q_t - \sigma_{v0})$) are adopted for formulas. I_c may effectively reflect soil type variations and structure (Andrus *et al.* 2007, Long and Donohue 2010, Robertson 2009, Simonini and Cola 2000, Wang *et al.* 2021). Here, the use of σ_{v0} and σ'_{v0} requires undisturbed sampling for the estimation. By contrast, using only the primary CPTu parameters in the empirical formulas may be practically beneficial and economical. Of the three parameters, u_2 is reliably measured if the pore pressure measurement system is sufficiently saturated. However, f_s is erratic and varies from one type of equipment to another, i.e., the parameter may be less reliable than the two other parameters in soft clays (Long and Donohue 2010). Thus, q_t and u_2 can be considered as the main parameters in the present study.

The CPTu parameters q_t and u_2 normalized by a reference pressure $p_a^* = 1$ kPa (i.e., q_t/p_a^* and u_2/p_a^*) can be correlated with V_s (m/s) by using the data of nine sites, in which the best fit curves were obtained as follows (Fig. 4).

$$V_s = 2.539 \left(q_t / p_a^* \right)^{0.593} \quad (2)$$

$$V_s = 9.551 \left(u_2 / p_a^* \right)^{0.417} \quad (3)$$

where $R_{adj}^2 = 0.71$ and 0.64 , and the standard error of regression (S) = 20.9 and 21.2 m/s for the respective equations. As shown in Fig. 4, the variation in $V_s - u_2/p_a^*$ relationships tends to be similar to that of $V_s - q_t/p_a^*$ relationships. The average correlations obtained from the two relationships are remarkably influenced by clay types. In contrast to the deltaic and marine clays, the lacustrine clay (i.e., FU site) lies close to the lower bound.

Another approach based on only the CPTu parameters, i.e., $V_s - f(q_t, B_q$ or $B_{qc})$ relationships proposed by Long and Donohue (2010) and Simonini and Cola (2000), may be considered here: $B_q = \Delta u / q_{net} = (u_2 - u_0)/(q_t - \sigma_{v0})$ and $B_{qc} = \Delta u / q_c =$ the pore pressure parameter (Table 1). The applied results to the nine data are shown in Fig. 5.

$$V_s = 1.791 \left(q_t / p_a^* \right)^{0.598} \left(1 + B_{qc} \right)^{0.806} \quad (4)$$

$$V_s = 2.786 \left(q_t / p_a^* \right)^{0.560} \left(1 + B_q \right)^{0.337} \quad (5)$$

where $R_{adj}^2 = 0.623$ and $S = 27.14$ m/s for Eq. (4) and $R_{adj}^2 =$

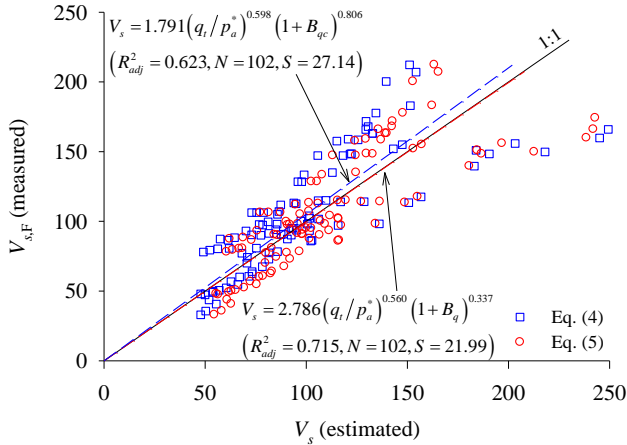


Fig. 5 Comparison between modified B_q - and B_{qc} -based equations

0.715 and $S = 21.99$ m/s for Eq. (5). The use of B_q produced better correlation than that of B_{qc} .

Combining the primary CPTu parameter (q_t or u_2) and one or two other soil parameters (σ'_{v0} , σ_{v0} , and e_0) is attempted to improve correlations, which is similar to some existing equations (Cai *et al.* 2014, L'Heureux and Long 2017, Wang *et al.* 2021). Fig. 6 shows the results of using the combined parameters and the estimated relationships are as follows

$$V_s = 10.357(q_t/p_a^*)^{0.038}(\sigma'_{v0}/p_a^*)^{0.491} \quad (6)$$

$$V_s = 6.264(q_t/p_a^*)^{0.355} \left[\frac{(\sigma'_{v0}/p_a^*)}{e_0} \right]^{0.337} \quad (7)$$

where $R_{adj}^2 = 0.767$ and 0.784 , and $S = 17.33$ and 17.34 m/s respectively for the two equations.

In summary, CPTu-based methods with primary and secondary CPTu parameters (q_t and B_q) produce better correlations than those with only the primary parameters (q_t or u_2). The methods with the combined parameters (q_t and σ'_{v0} [and/or e_0]) yield considerably improved correlations compared with those of the previous two cases. In the combined case, supplementary labor, time, and expense are required to estimate additional parameters (i.e., σ'_{v0} , σ_{v0} , and e_0). Thus, converting the additional parameters to any CPTu parameters in the equations is definitely effective for an economical approach.

3.2 Converting geotechnical properties to CPTu parameters

The CPTu-based method with the combined parameters (Eq. (7)), which produces the best correlation, can be considered for the main approach of this study. In this case, two geotechnical properties (σ'_{v0} and e_0) need to be converted into any CPTu parameters for the economical estimation.

First, e_0 is replaced by a normalized parameter e_0/e_L where e_L is the void ratio at the liquid limit state. The e_0/e_L

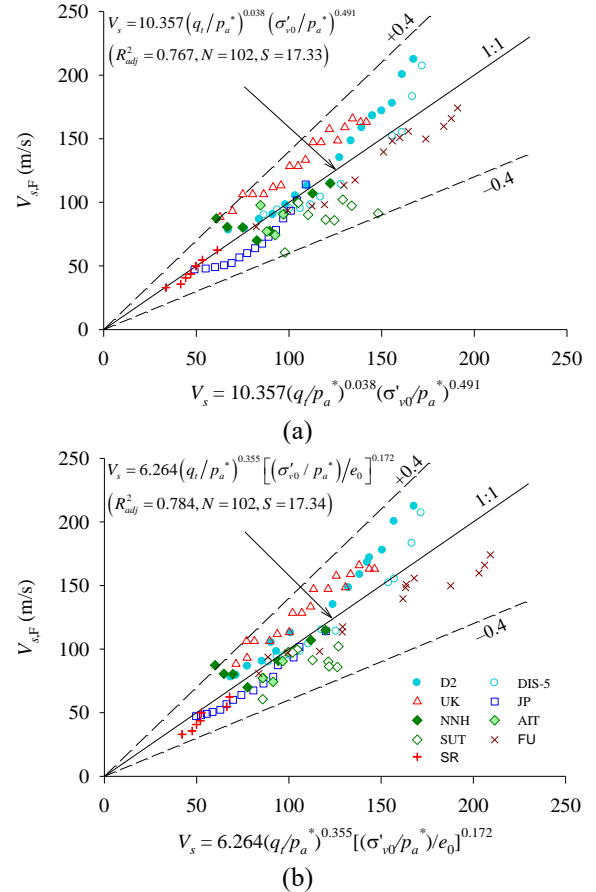


Fig. 6 $V_{s,F}$ versus $f(q_t, \sigma'_{v0})$ and $V_{s,F}$ versus $f(q_t, \sigma'_{v0}/e_0)$ relationships

can be expressed using the level of structure on sensitive (or cemented) clay. The level of structure is used to characterize the geotechnical properties of natural cemented clays. Burland (1990) proposed the intrinsic compression concept, which is defined using void index (I_v). A similar concept is presented in the e_{ISL}/e_L - $\log \sigma'_v$ graph (Nagaraj and Murthy 1986), where the intrinsic state is defined using a specific void ratio (e_{ISL}) along the intrinsic state line (ISL).

$$\frac{e_{ISL}}{e_L} = 1.23 - 0.276 \log \sigma'_v \quad (8)$$

Fig. 7 shows the ISL plotted using Eq. (8) and the in situ states obtained for the nine clays. Most of the clays, whose points lie above the ISL, are classified as normally consolidated (NC) clay. Only two points that lie below the ISL indicate an overconsolidated (OC) clay. Busan and JP clays that lie well above the ISL are considered to be well structured compared with other clays. Based on Eq. (8), e_0/e_L can be expressed as follows:

$$\frac{e_0}{e_L} = \frac{e_0}{e_{ISL}} \times \frac{e_{ISL}}{e_L} = R_{e(\sigma)} (1.23 - 0.276 \log \sigma'_v) \quad (9)$$

where $R_{e(\sigma)} = e_0/e_{ISL}$ is the ratio between the void ratios of the in situ and disturbed soils. Thus, $R_{e(\sigma)} \geq 1.0$ for NC clay, and $R_{e(\sigma)} < 1.0$ for OC clay. e_0/e_L can be expressed as the

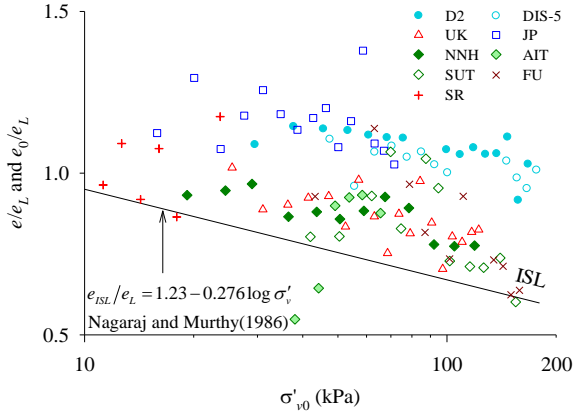


Fig. 7 Level of structure based on the intrinsic compression concept (Nagaraj and Murthy 1986)

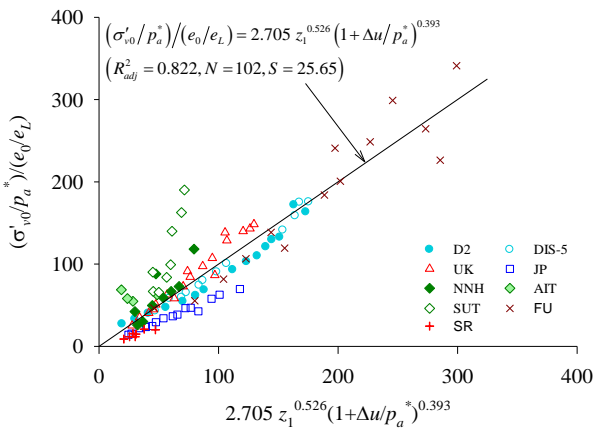


Fig. 8 $(\sigma'_{v0}/p_a^*)/(e_0/e_L)$ versus $f[z_1, (1+\Delta u/p_a^*)]$

structural level at the in situ stress level (i.e., σ'_{v0}). Therefore, the terms of σ'_{v0} and e_0 in Eq. (7) may be identically expressed as the combined function of the structural level and σ'_{v0} .

σ'_{v0} increases linearly with depth in homogeneous soils, that is, the function of depth (z). The effect of inhomogeneity in estimating σ'_{v0} profiles and the structural level (i.e., $R_{e(\sigma)}$) may be considered by one more CPTu parameter in addition to q_t . Simonini and Cola (2000) reported that the variation in u_2 acts as a sensitive indicator of local variation in the soil profile. Thus, the Δu ($= u_2 - u_0$) is effective in interpreting the mechanical behavior of soil. Then, the depth and excess pore pressure are normalized as dimensionless functions: $z_1 = z$ (m)/(1 m) and $(1+\Delta u/p_a^*)$. Fig. 8 shows the relationships of $(\sigma'_{v0}/p_a^*)/(e_0/e_L)$ and $f[z_1, (1+\Delta u/p_a^*)]$ for nine soils with good correlation ($R_{adj}^2 = 0.822$ and $S = 25.65$).

$$\left(\frac{\sigma'_{v0}/p_a^*}{e_0/e_L} \right) = 2.705 z_1^{0.526} (1 + \Delta u/p_a^*)^{0.393} \quad (10)$$

Consequently, a CPTu-based empirical equation is derived by combining Eqs. (7) and (10) as follows

$$V_s = 5.548 (q_t/p_a^*)^{0.341} z_1^{0.131} (1 + \Delta u/p_a^*)^{0.1} \quad (11)$$

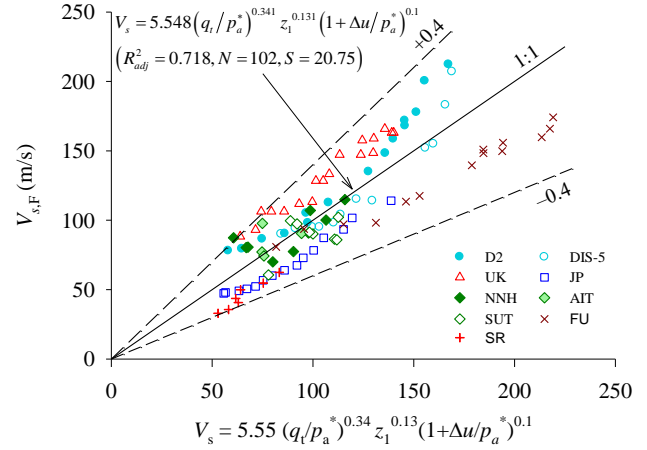


Fig. 9 $V_{s,F}$ versus $f[q_t, z_1, (1+\Delta u/p_a^*)]$

where the optimum values of various constants are determined via the multiple regression analysis. Although V_s is expressed by the primary CPTu parameters (q_t and Δu) and z , the effects of σ'_{v0} and structural level are indirectly reflected. Fig. 9 shows the relationship between the estimated and the measured V_s values for the nine soils with $R_{adj}^2 = 0.718$ and $S = 20.75$ m/s. The R_{adj}^2 value is slightly lower than that from Eq. (7), and the slopes of the upper and lower bounds vary within ± 0.4 . Apparently, the best correlation for each site may also be estimated between the upper and lower bounds.

The relative importance of the three parameters included in Eq. (11) was investigated via one-dimensional sensitivity analysis using the built-in tool “What-if Analysis” in Microsoft Excel. Fig. 11 shows the variations in the estimated V_s values against the measured (q_t/p_a^*) or $(1+\Delta u/p_a^*)$ values, which range from the minimum to the maximum at two depths ($z_1 = 5$ and 15). Sensitivity, defined as the ratio of the percentage change in output to the percentage change in input, was evaluated to be 0.120 for q_t/p_a^* , followed by 0.031 for z_1 and 0.007 for $(1+\Delta u/p_a^*)$.

4. Applicability of the newly developed equation

4.1 Comparison of results obtained using the developed CPTu methods at each site

The existing empirical equations for V_s that comprise different forms and parameters are categorized into three groups: function of q_t or u_2 (Eqs. (2) and (3)), q_t and B_q or B_{qc} (Eqs. (4) and (5)), q_t and σ'_{v0} with e_0 (Eqs. (6) and (7)). Eqs. (5) and (7) exhibited improved correlations ($R_{adj}^2 = 0.715$ and 0.784) for nine soils. Although the newly developed equation (Eq. (11)) exhibits a slightly poorer correlation ($R_{adj}^2 = 0.718$) than Eq. (7), the advantage of the former is economical (using only the directly measured CPTu parameters, such as q_t , z , and Δu). Fig. 10 shows that V_s profiles estimated using the three equations are compared with the measured values for each of the nine clays. The estimated results obtained using the equations seem to be close to each other and considerably agree with the

Table 4 The adjusted coefficient of determination (R_{adj}^2) and standard error of regression (S) obtained using the proposed equations at each site

	R_{adj}^2 and S								
	D2	DIS-5	JP	UK	NNH	AIT	SUT	FU	SR
Eq. (5)	0.888 (13.3)*	0.732 (16.3)	0.938 (6.0)	0.926 (7.0)	0.267 (13.7)	-0.140 (10.3)	-2.217 (13.5)	0.883 (16.3)	0.079 (8.0)
Eq. (7)	0.948 (7.7)	0.798 (13.6)	0.953 (4.6)	0.932 (6.3)	0.531 (14.6)	-3.368 (12.8)	-0.471 (17.4)	0.943 (10.3)	0.676 (5.5)
Eq. (11)	0.911 (10.6)	0.678 (17.1)	0.966 (4.5)	0.930 (6.5)	0.243 (16.8)	-3.446 (20.3)	-1.163 (18.3)	0.935 (11.52)	0.384 (8.2)
Eq. (12)	0.907 (8.8)	0.670 (14.5)	0.970 (3.8)	0.933 (5.3)	0.495 (14.5)	-0.470 (8.9)	-0.217 (21.2)	0.867 (18.2)	0.573 (6.3)

*Values in parenthesis are the standard error of regression (S)

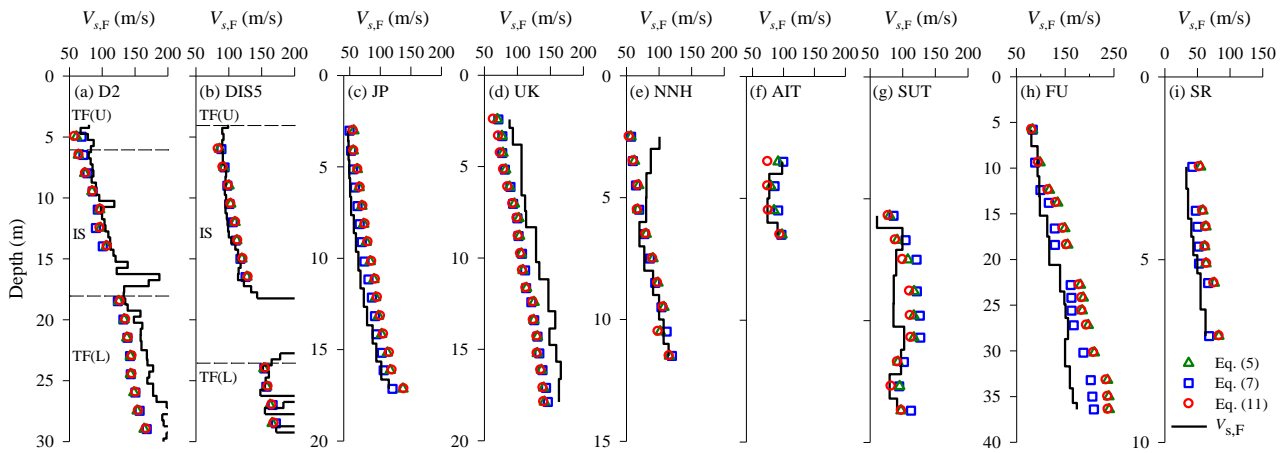


Fig. 10 Measured and predicted V_s profiles at each site

measured V_s profiles at the sites. Table 4(a) shows the R_{adj}^2 and S values obtained by comparing the measured and estimated V_s values at each site. Eq. (7) based on multiple parameters (q_t , σ'_{v0} , and e_0) exhibits the best correlation for most sites and is followed by Eqs. (11) and (5). A different trend is also observed at any site. Notably, because the linear regression lines are set to pass through the origin, negative R_{adj}^2 values are sometimes observed regardless of good agreement between the measured and predicted V_s values. Consequently, the newly developed equation (Eq. (11)) can be applied for the successful estimation of V_s on various types of clays without sampling of undisturbed soils and laboratory tests.

4.2 Stochastic simulation and its application

A significant degree of uncertainty influences any prediction; hence, stochastic simulation is frequently adopted to integrate the prediction technique. For this, seven input parameters (z_1 , e_0 , σ'_{v0} , q_t , u_2 , f_s , and $1+\Delta u$) and the measured shear velocity $V_{s,F}$ ($N = 102$) of the nine sites were normalized to vary from 0 to 1.0 (i.e., from the minimum to maximum values). As part of the simulation

results, the estimated shear velocity $V_{s(SS)}$ was calculated by the iteration of 50,000. The results showed that the correlation between the $V_{s,F}$ and $V_{s(SS)}$ values was strong, with the coefficient of determination $R^2 = 0.724$. Table 5 shows the coefficient of correlation (R) between the $V_{s,F}$ (or $V_{s(SS)}$) values and each of the seven parameters. As can be seen, the $V_{s,F}$ values were more strongly correlated with the non-CPTu parameters (z_1 , e_0 , and σ'_{v0}) than with the CPTu parameters (q_t , u_2 , f_s , and $1+\Delta u$). However, the $V_{s(SS)}$ values were very strongly correlated with all the parameters but e_0 and f_s (i.e., $R \geq 0.94$). Typically, the $V_{s(SS)}-q_t$ relationship is evaluated, as shown in Fig. 12 (or Eq. (12)). Table 4 also shows that the predicted V_s values from Eq. (12) are comparable to those from Eq. (11) and are close to the measured values.

$$V_{s(SS)} = 2.6526(q_t/p_a^*)^{0.5792} \quad (12)$$

where $R_{adj}^2 = 0.843$ and $S = 15.84$ m/s.

Further validation is again attempted by applying the proposed equations to another nine sites in six countries: Myeonji (Singh 2012), Hwajeon (Rao 2004), and Eulsuckdo sites (Kim *et al.* 2005) in South Korea;

Table 5 Coefficient of correlation R between V_s and each of the seven parameters

	q_t	$1+\Delta u$	e_0	σ'_{v0}	z_1	u_2	f_s
$V_{s,F}$	0.7456	0.6651	-0.7519	0.8671	0.8283	0.7239	0.3105
$V_{s(SS)}$	0.9591	0.9452	-0.4237	0.9464	0.9782	0.9782	0.0041

Table 6 Applicability of the proposed formulas to different types of clays

	R_{adj}^2 and S								
	Myeonji (Deltaic, KR)*	Hwajeon (Deltaic, KR)	Eulsuckdo (Deltaic, KR)	Lianyungang (Marine, CH)	Trondheim (Marine, NO)	Amherst (Lacustrine, US)	McDonald (Deltaic, CA)	Treporti (Lagoon, IT)	Malamocco (Lagoon, IT)
Eq. (11)	0.830 (7.0)	0.522 (25.2)	0.719 (19.3)	0.644 (14.2)	0.558 (24.2)	-0.202 (16.9)	0.752 (9.8)	0.315 (30.1)	0.555 (34.4)
Eq. (12)	0.879 (5.4)	0.530 (21.5)	0.677 (18.8)	0.534 (20.9)	0.398 (37.0)	-0.128 (12.0)	0.106 (12.3)	0.260 (79.4)	0.136 (117.6)

* KR: South Korea, CH: China, NO: Norway, US: United States of America, CA: Canada, and IT: Italy

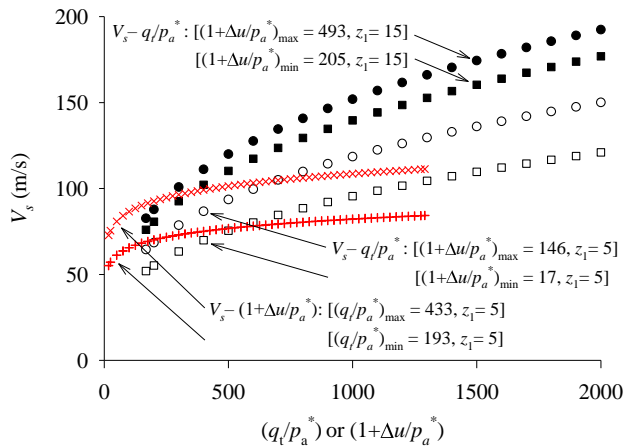


Fig. 11 Estimated V_s values against (q_t/p_a^*) or $(1+\Delta u/p_a^*)$ at $z_1 = 5$ and 15

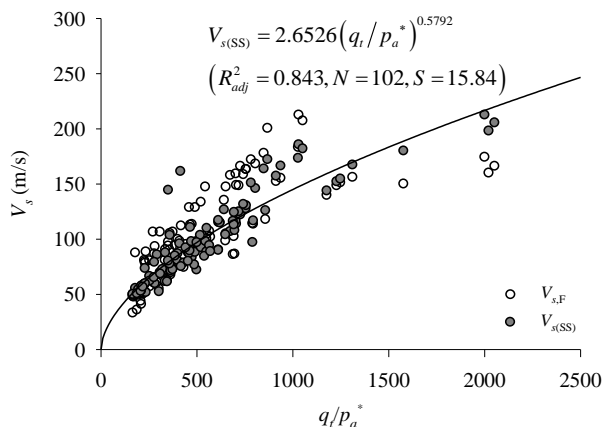


Fig. 12 Measured and estimated V_s values against q_t

Lianyungang site (Duan *et al.* 2019) in China; Trondheim harbor (L’Heureux *et al.* 2013) in Norway; Amherst site (Mayne *et al.* 2009) in USA; McDonald’s Farm site (Campanella *et al.* 1983) in Canada; and Treporti (Tonni and Simonini 2013) and Malamocco sites (Simonini and

Cola 2000) in Italy. The deposits of the sites comprise 4 deltaic, 2 marine, 1 lacustrine, and 2 lagoon clays. Fig. 13 and Table 6 show the applied results of Eqs. (11) and (12) to the clays. The predicted V_s values (with $R_{adj}^2 = -0.202$ to 0.830 and $S = 7.0$ to 34.4 m/s) by using Eq. (11) are close to those (with $R_{adj}^2 = -0.128$ to 0.879 and $S = 5.4$ to 117.6 m/s) by using Eq. (12). As shown in the first (Table 4) and second (Fig. 13 and Table 6) verifications, the proposed equation (Eq. (11)) exhibits correlations comparable to that of the stochastic simulation (Eq. (12)) regardless of clay types. Thus, the proposed formula (Eq. (11)) is likely applied to estimate V_s values indirectly on various types of clays in the world. In addition to a small number of data from limited sites used for this analysis, accumulating data from many other sites are highly anticipated to upgrade the proposed equations and improve their applicability.

5. Conclusions

Existing CPTu-based V_s equations re-evaluated by using nine sets of well-documented data were appropriate to use for any specific soil, but not for various types of clays (i.e., deltaic, marine, alluvial, and lacustrine clays). When equations were categorized into three groups and revised by adjusting their constants or indices to suit the nine soils, correlations between the measured and the predicted V_s values tended to become good (i.e., R_{adj}^2 increases from 0.623 to 0.784 , and S decreases from 27.1 to 17.3 m/s) with increased number of parameters used in the revised equations. Of the revised equations, an equation with a primary CPTu parameter (q_t) and two soil properties (σ'_{v0} and e_0), which produced the best correlation, was selected and converted into that with only the primary CPTu parameters (i.e., q_t and Δu) and depth (z). A sensitivity analysis indicated that the estimated V_s value is more sensitive to the change in q_t than the two other parameters (Δu and z). In the process of conversion, the structural level

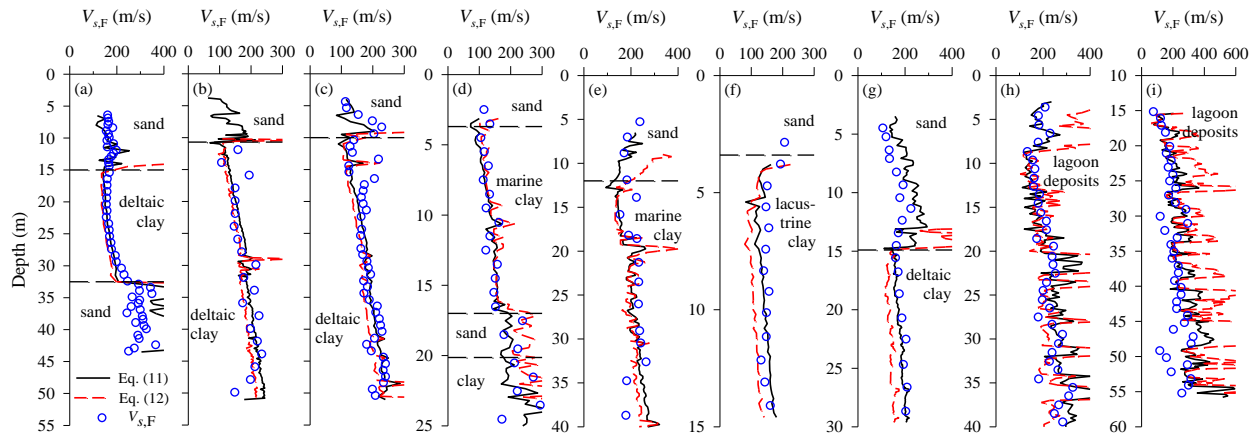


Fig. 13 Case studies for the applicability of newly developed equations: (a) Myeonji (deltaic clay, KR), (b) Hwajeon (deltaic clay, KR), (c) Eulsukdo (deltaic clay, KR), (d) Lianyungang (marine clay, CH), (e) Trondheim harbor (marine-glacial clay, NO), (f) Amherst (lacustrine clay, US), (g) McDonald's farm (deltaic clay, CA), (h) Treporti (lagoon deposit, IT), and (i) Malamocco (lagoon deposit, IT) sites

of soils (i.e., e_0/e_L and e_{ISL}/e_L at σ'_{v0}) was inclusively considered. Then, the newly developed CPTu equation, which is a time-saving and economical method, was validated via application to each geotechnical profile of the nine site. Furthermore, a simple V_s - q_t equation developed based on the stochastic simulation (using seven input parameters) exhibits correlations comparable to the new CPTu equation. Moreover, the different kinds of applicability of the new CPTu equation to nine other clays were verified. Consequently, the newly developed CPTu equation can be recommended to estimate V_s indirectly for any type of naturally deposited clay in the world.

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Notation

A, B, C	empirical constants
ASF	age scaling factor
B_q	pore pressure ratio from CPTu
B_{qc}	pore pressure parameter (Simonini and Cola, 2000)
e	void ratio
e_0	initial void ratio
e_{ISL}	void ratio at the intrinsic state
e_L	void ratio at liquid limit
F	normalized friction ratio
$f(e)$	function of in-situ void ratio
f_s	sleeve friction
G_0	initial shear modulus
$G_{0,F}$	initial shear modulus measured from the field
I_c	soil behavior type index
I_L	liquidity index
ISL	intrinsic state line
I_v	void index
n	fitting parameter related to the mean effective stress
N	number of data
OCR	overconsolidation ratio
p_a^*	reference pressure (1 kPa)
Q	normalized cone resistance
q_c, q_t	uncorrected and corrected cone tip resistance
q_{c1N}	normalized cone tip resistance
$q_{t1\gamma}$	normalized cone tip-corrected resistance
R_{adj}^2	adjusted coefficient of determination
S	standard error of regression
S_t	sensitivity
u_0	in-situ pore pressure
u_2	pore pressure measured behind cone
V_s	shear wave velocity
$V_{s(SS)}$	shear wave velocity estimated from the stochastic simulation
$V_{s,F}$	shear wave velocity measured in the field
w_L	liquid limit
w_n	water content
z	depth
z_1	normalized depth, i.e., $z/1\text{m}$
γ_t	bulk unit weight
Δu	excess pore water pressure
κ	fitting parameter related to soil plasticity
ρ	bulk density
σ'_m	mean effective stress
σ'_{v0}	effective overburden stress
σ_{v0}	total overburden stress
χ	fitting parameter