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New statistical and graphical assessment of CPT-based empirical correlations for the shear wave velocity of soils

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ABSTRACT

The object of this paper is to gather, analyze and assess CPT–Vs correlation equations. Consequently, in this paper the validity of some of these correlations between Vs and CPT parameters for Jiangsu clays was assessed using piezocone data from Yangtze Delta deposits through six existing and two new indexes and the cumulative frequency curve graph. Common existing correlations are briefly reviewed and discussed. New empirical formulae are suggested to correlate CPT-based parameters and Vs, using regression analysis. The comparison is conducted between the existing and proposed equation based on a dataset collected at seven sites in Jiangsu, China. This paper proposes a new statistical assessment method taking the location of the points into account, including the perfect distance and the slope of the specific line that links the point D_{10} and the point D_{90}. The method is more obvious and accurate. The results of these indexes and the cumulative frequency curve graph show that a new improved expression gave better performance. The new indexes and the cumulative frequency curve graph can surely be used to analyze and assess correlations including the new expression, which is very helpful to evaluate correlations.

1. Introduction

Shear wave velocity (V_s) has been recognized as one of the important soil properties in earthquake and geotechnical engineering (Ohta and Goto, 1978). It has been widely used to define site categories, to assess site conditions, to estimate earthquake ground motion, to evaluate the liquefaction resistance of soils and to implement remedial measures (Borcherdt, 1994; Dobry et al., 2000; Andrus and Stokoe, 2000; Kayen et al., 2013). Correlations and empirical relationships extensively abound in geotechnical engineering and are always used for local regions. There seem to be several reasons. The first and fundamental reason, obviously, is that there is no/little theoretical relationship between the wave velocity parameters (e.g. V_s) and general Cone penetration test-based (CPT-based) parameters (e.g. f_s). The second one is that the use of empirical relationships gives a fast, effective way of predicting the value of a parameter based on the values of some other, possibly more easily determined, parameters. The third is that, in the preliminary stages including feasibility studies, when there are limited funds available for soil exploration, empirical correlations become very valuable (Onyejekwe et al., 2015). The fourth is the space constraints associated with these tests, especially in urban areas. The last but not least reason is that, at the concept design stage of a project, most practitioners are left with the use of correlations and typical values as site investigation data may not be available or limited. Such correlations may be the sole weapon available to the designer when no or poor soil data is available and/or only limited testing has been carried out. In some situations, correlations are even required as a test of reasonableness on the derived design parameters (Ameratunga et al., 2016). Hence, the easiest way to estimate V_s is to use empirical relationships with the common CPT-based parameters (e.g. f_s).

In geotechnical engineering, many design parameters of soil are associated with the piezocone penetration test (CPTU) because not only is it an effective method but also it can provide V_s and other common values, such as cone penetration tip resistance q_c, and sleeve friction f_s.

Common methods for obtaining V_s mainly consist of cross-hole, down-hole, uphole and PS suspension logging (Kitsunezaki, 1980), and the surface wave inversion (SWI) method is also applied as low cost yet providing a knowledge of the elastic soil properties (Mokhtar et al., 1988; Stokoe et al., 1988; Jongmans et al., 1990; Pitilakis et al., 1999; Maheswari et al., 2010). Another increasing approach is termed as seismic CPTU (SCPTU) (Campanella et al., 1986; Lunne et al., 1997; Cai et al., 2010, 2011), through adding sensors to the CPTU.

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Table 1
Correlations between CPT parameters (q_c for CPT, q_t for CPTU) and shear wave velocity.

Applicability	#	Correlation(V_s or V_{s1})	References
All soils	A	$2.62q_t^{0.395}I_C^{0.912}D^{0.124}SF^a$	Andrus et al. (2007)
	B	$[10^{(0.55Ic + 1.68)}(q_t - \sigma_{v0}) / p_a]^{0.5}$	Robertson (2009)
		$[10.1 \log(q_c) - 11.4]^{1.67} (100 f_s / q_c)^{0.3}$	Hegazy and Mayne (1995)
		$118.8\log(f_s) + 18.5$	Mayne (2006)
		$32.3 q_c^{0.089} f_s^{0.1219} D^{0.215}$	Piratheepan (2002)
	C	$V_{s1} = 102 q_{c1}^{0.23}$	Robertson et al. (1992)
	D	$V_{s1} = 135 q_{c1}^{0.23}$	Fear and Robertson (1995)
	E	$V_{s1} = 149 q_{c1}^{0.205}$	Karray et al. (2011)
	F	$V_{s1} = 0.0831 q_{c1N}^{0.103} (\sigma'_{v0}/p_a)^{0.25} e^{1.786Ic}$	Hegazy and Mayne (2006)
Clay	G	$14.13 q_c^{0.359} e_0^{-0.473}$	Hegazy and Mayne (1995)
		$3.18 q_c^{0.549} f_s^{0.025}$	Hegazy and Mayne (1995)
	H	$9.44q_c^{0.435} e_0^{-0.532}$	Mayne and Rix (1995)
		$11.9 q_c^{0.269} f_s^{109} D^{0.127}$	Piratheepan (2002)
	I	$1.75 q_c^{0.627}$	Mayne and Rix (1995)
	J	$0.1 q_c$	Jaime and Romo (1988)
	K	$2.944q_c^{0.613}$	Long and Donohue (2010)
	L	$65.00q_t^{0.150} e_0^{-0.714}$	Long and Donohue (2010)
	M	$1.96(1 + B_q)^{1.202} q_t^{0.579}$	Long and Donohue (2010)
Sand	N	$134.11 + 0.0052 q_c$	Sykora and Stokoe (1983)
	O	$17.48 q_c^{0.33}(\sigma'_{v0})^{0.27}$	Baldi et al. (1989)
	P	$13.18 q_c^{0.192}(\sigma'_{v0})^{0.179}$	Hegazy and Mayne (1995)
		$12.02 q_c^{0.319} f_s^{-0.0466}$	Hegazy and Mayne (1995)
		$25.3 q_c^{0.103} f_s^{0.029} D^{0.155}$	Piratheepan (2002)

Notes: Pa = 100 kPa; SF^a = 0.92 for Holocene and 1.12 for Pleistocene, Stress unit in kPa and depth (D) in meters (m).

CPT-based correlations for evaluating V_s have advanced owning to the contributions of numerous researchers and progressed with the improvement of people's knowledge and experimental devices. There are dozens of correlation equations, and, common representative equations are listed in Table 1. Early equations mainly adopted a linear relationship and single independent variable (e.g., Sykora and Stokoe, 1983; Jaime and Romo, 1988). Jaime and Romo (1988) suggested another correlation, which was a linear relationship as opposed to the nonlinear relationships proposed by other researchers (Sykora, 1987). The exact reason is not yet clear, but may be related to a lack of accurate tools and profound comprehension. Since Baldi et al. (1989) gave an initial correlation in power exponent form for sand, countless correlations have always been proposed (e.g., Hegazy and Mayne, 1995; Long and Donohue, 2010). Primary correlations involved in two variables: q_t (q_c) and f_s (σ_{v0}', $e_0$orB_q), consequent occurred three (Hegazy and Mayne, 1995; Piratheepan, 2002; Andrus et al., 2007) or four variables (Hegazy and Mayne, 2006; Robertson, 2009) and in the log form (Hegazy and Mayne, 1995; Hegazy and Mayne, 2006). Several studies concluded that, however, the use of stressnormalized q_c values in V_s correlations proved to be considerably less accurate than correlations based on non-normalized values (Sykora and Stokoe, 1983; Lodge, 1994; Hasancebi and Ulusay, 2007; Piratheepan, 2002). And numerical investigators (Robertson et al., 1992; Fear and Robertson, 1995; Hegazy and Mayne, 2006; Karray et al., 2011) presented the non-normalized correlation between $V_{s1}$and q_{c1}orq_{c1N} values (see Table 1), in which$V_{s1}$is the shear wave velocity normalized for the vertical effective stress, expressed by:

$$V_{s1} = V_s(p_a/\sigma_{v0}')^{0.25} \tag{1}$$

where$\sigma_{v0}'$is the vertical effective stress (kPa). Cone penetration resistance is often corrected for overburden stress (resulting in the term ofq_{c1}), and the truly normalized cone penetration resistance normalized for overburden stress (q_{c1N}, dimensionless) is given by (Robertson and Wride, 1998; Hegazy and Mayne, 2006):

$$q_{c1N} = (q_c/p_a)(p_a/\sigma_{v0}')^n \tag{2}$$

where$p_a$is a reference pressure in the same units as q_c (i.e., equal to 0.1 MPa for q_c or q_{c1} in MPa). If the value of I_C is < 2.6, n = 0.5, else n = 0.75.

The published CPT–V_s correlation equations presented in Table 1 were generally developed for specific soil types (i.e., "Sand" or "Clay") or for more general "All Soils". Some equations shown in Table 1 are not named for lack of some of the related data. Two methods were evaluated for selecting which correlation equations to use for design. The first method involved using "All Soils" equations for the entire soil profile. The second method involved selection of soil-type dependent correlation equations based on the CPT and SBT. For sandy soils (I_C < 2.05), V_s was estimated using the value from Correlation N (Sykora and Stokoe, 1983) through Correlation P (Piratheepan, 2002) shown in.

Table 1. For intermediate soils (2.05 < I_C < 2.60), V_s was estimated using the average result from Correlation A (Andrus et al., 2007) to Correlation F (Hegazy and Mayne, 2006). For clayey soils (I_C > 2.60), V_s was estimated using the average value through Correlation G (Hegazy and Mayne, 1995) to Correlation M (Long and Donohue, 2010). The soil type-specific method developed, however, used an average of existing correlations for each soil type, which produced spikes (high and low) in the predicted V_s profile as material transitions where differential equations were used for adjacent CPT sublayers. For this reason and ease of implementation, the "All Soils" method was considered to be more desirable (Wair et al., 2012).

Obviously, primary correlations involved two variables: q_t (q_c) and f_s (σ_{v0}', $e_0$orB_q), then gradually there occurred three (Hegazy and Mayne, 1995; Piratheepan, 2002; Andrus et al., 2007) or four variables (Hegazy and Mayne, 2006; Robertson, 2009). Epoch is significant along with other geotechnical parameters such as *Vs* and only Correlation A (Andrus et al., 2007) involves it.

There are so many CPT–V_s correlation equations that how to assess them, how to distinguish them, option variables becomes important. Conventional assessment is the simple application of a correlation coefficient (e.g. Cai et al., 2014) that appears to be general and single. The literature (Onyejekwe et al., 2015; Dikmen, 2009; Maheswari et al., 2010) will give a clue to analyzing and assessing equations.

2. Data

The study area, mainly overlying sensitive clay deposits, is located in Jiangsu Province of eastern China (see Fig. 1). The dataset used in this study consists of seven main sources: Nanjing, Lianyungang, Changzhou, Yancheng, Suzhou, Taizhou and Yangzhou, respectively. A