Shear Wave Velocity Derived from Cone Penetration Tests In Clayey Soil Layers

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ABSTRACT

Based on Cone penetration tests (CPT) data, a number of soil's physical and mechanical parameters can be interpretated, like shear wave velocity, etc. Even though various studies have been conducted and methods are proposed, uncertainties still exist and the applicability of each method needs be further clarified. A case study on the interpretation of CPT results is performed which based on the measured data from an offshore site close to East Sea, China. This paper focus on clayey soil layers and presents an assessment of CPT data interpretation methods for the derivation of clayey soil's shear wave velocity. It shows that Long's method proposed in 2010 (C1) and Cai's method proposed in 2014 (C2) provide better predictions of shear wave velocity. Additionally, values of soil unit weight used in the shear wave velocity derivation can also be interpretated from CPT data since it shows ignorable effect on the interpretated velocity profile.

Keywords: cone penetration test (CPT); soil behaviour type (SBT); shear wave velocity (V_s); clayey soil.

1. Introduction

Cone penetration tests (CPT) are widely used to characterize site conditions for its handiness, multifunctionality and automatization, which are very helpful for offshore sites. Currently, in the design of monopiles for offshore wind farms, subjected to marine environmental loads, the lateral response commonly governs the foundation design. The widely used approach is the p-y curve method recommended by API (RP2A-WSD 2000, Li *et al.* 2017). The initial modulus required in this method is crucial, especially for the analysis of dynamic response. The values of initial modulus can be determined from the small-strain shear modulus, but it is not easy to measure accurately in laboratory tests on samples retrieved from site since this value corresponds to a small strain. Value of initial shear modulus is closely related to soil's density (ρ) and shear wave velocity (V_s) (ASTM D5778), and the later can be measured in lab (like bender element tests) and in-situ (such as cross-hole test, down-hole test, etc.) (GB 50021-2001). However, lab tests often suffer from sample disturbance issues, making it difficult to accurately represent the in-situ characteristics of ground soil and reducing the reliability (Hicher 1996). Therefore, in-situ tests are considered as the better tool. In cases where field shear wave velocity testing equipment is not available or for engineering projects with economic factors need to be considered, the use of established empirical correlations is very helpful (Long and Donohue 2010), like these between V_s between CPT data.

Even though various studies have been conducted and methods are proposed (Mayne 2014), uncertainties still exist and the applicability of each method needs be further clarified. A case study on the interpretation of CPT results was performed, based on the measured data from an offshore site near the East Sea, China. At this site, a series of in-situ cone penetration tests were conducted, and soil samples were retrieved at various depths. From which, shear wave velocity was obtained from down-hole tests on these retrieved soil samples, as well as from the interpretation of CPT results. This paper focus on clayey soil layers and presents an assessment of CPT data interpretation methods for the derivation of cohesive soil's shear wave velocity. Based on the comparison between V_s values obtained by down-hole tests and those derived from CPT data according to various methods, the reliability and applicability of each method are clarified and the most suitable method is recommended.

2. Current methods

2.1. Soil behaviour type (SBT)

To characteristic soil type for each soil layer, CPT works as an efficient tool, and various methods are proposed (Kulhawy and Mayne 1990, Lunne *et al.* 1997, Robertson 2010). Lunne *et al.* (1997) proposed a method to account for the depth effects, which reproduces the cone and shaft resistance in a normalized form:

$$Q = (q_t - \sigma_{v0}) / \sigma'_{v0} \tag{1}$$

$$F_r(\%) = 100 \times f_s / (q_t - \sigma_{v0}) \tag{2}$$

Where Q = Normalized tip resistance, q_t = Corrected tip resistance: $q_t = q_c + u_2(1-a)$, a=0.8, σ_{v0} = Total vertical overburden stress, σ'_{v0} = Effective vertical overburden stress, F_r = Normalized friction ratio, f_s = Sleeve friction.

The normalized cone tip resistance was upgraded by Robertson (2009) by introducing an exponent n:

$$Q_{tn}=(q_{net}/\sigma_{atm})/(\sigma'_{v0}/\sigma_{atm})^{n} \tag{3}$$

Where Q_{tn} = Normalized tip resistance, q_{net} = Net tip resistance: $q_{net}=q_t-\sigma_{v0}$, σ_{atm} = Atmospheric pressure in same units as q_t.

To determine the value of n, CPT material index I_c need be calculated (see Eq (4)), after which, a value of n is estimated through Eq (5). Noted that, iteration is needed which begins with an estimation of n, say n = 1. After several iterations (see Fig 1), convergency is reached and I_c value for each soil layer can be calculated.

$$I_c=\sqrt{(3.47-\log Q_{tn})^2+(1.22+\log F_r)^2} \tag{4}$$

$$n=0.381\cdot I_c+0.05\cdot(\sigma'_{v0}/\sigma_{atm})-0.15\leq 1.0 \tag{5}$$

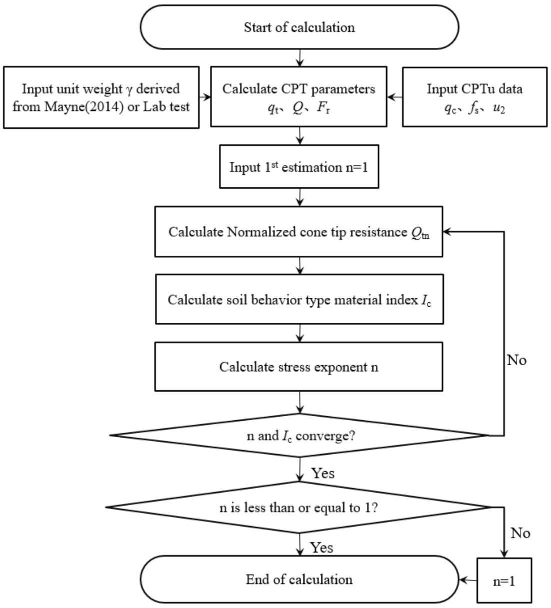

Figure 1. Flow chart for SBT calculation

2.2. Shear wave velocity

Based series of CPT data, several methods are developed to derive shear wave velocity values, which are summarized in Table 1. Since different inputs are need for those methods, flow chart is plotted, see Fig 2, in which methods are labled for clearance.

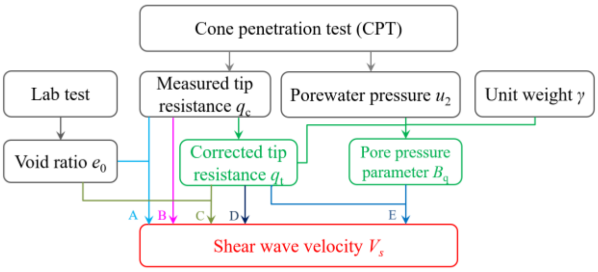

Figure 2. Flow char for V_s calculation.

3. Case study

3.1. General description

The study area belongs to East Sea, China, and the water depth is about 40 m. Series of in-situ piezocone penetration tests were conducted and soil samples were retrieved at various depth. Data of three boreholes were selected for analysis. Fig 3 presents physical and mechanical parameters obtained from laboratory tests on these retrieved soil samples (GB/T 50123-2019、GB 50021-2001), and recorded cone tip resistance, sleeve friction and pore ware pressure on shoulder (u_2), as well as the shear wave velocity profiles measured in-situ through down-hole test.

Table 1. Summary of current methods

Parameter	Method lable	Number of tests	Equation	Site location	Reference
q_c、e_0	A1	31	$V_s=9.44q_c^{0.435}e_0^{-0.532}$	World wide	(Mayne and Rix 1995)
q_c	B1	3	$V_s=0.1q_c$	Mexico	(Jaime and Romo 1988)
	B2	31	$V_s=1.75q_c^{0.627}$	World wide	(Mayne and Rix 1995)
q_t、e_0	C1	10	$V_s=65q_t^{0.150}e_0^{-0.714}$	Norse	(Long and Donohue 2010)
	C2	7	$V_s=90q_t^{0.101}e_0^{-0.663}$	Jiangsu, China	(Cai *et al.* 2014)
q_t	D1	10	$V_s=2.944q_t^{0.613}$	Norse	(Long and Donohue 2010)
	D2	7	$V_s=7.954q_t^{0.403}$	Jiangsu, China	(Cai *et al.* 2014)
q_t、B_q	E1	10	$V_s=1.961q_t^{0.579}(1+B_q)^{1.202}$	Norse	(Long and Donohue 2010)
	E2	7	$V_s=4.541q_t^{0.487}(1+B_q)^{0.337}$	Jiangsu, China	(Cai *et al.* 2014)

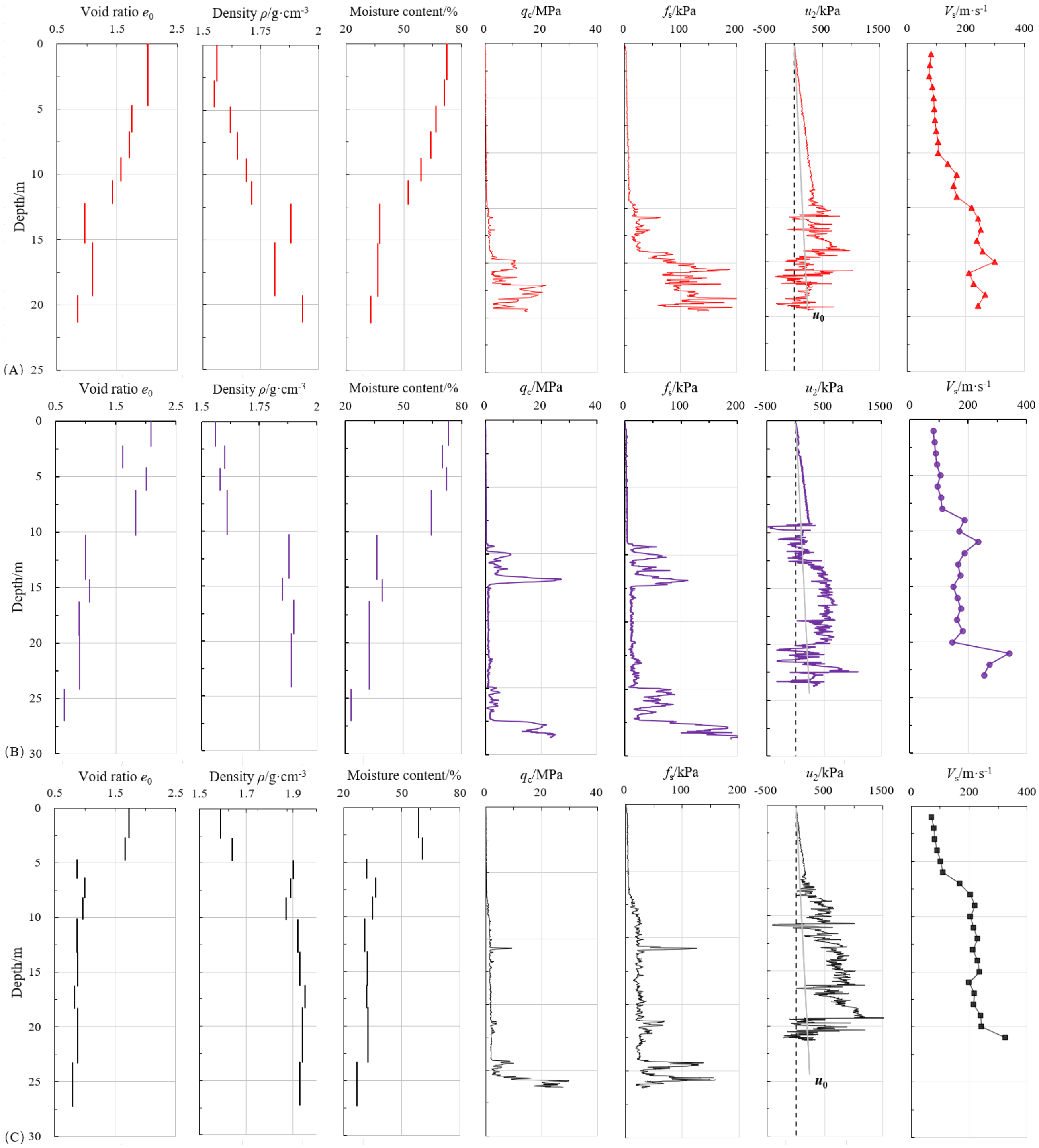

Figure 3. *Date profiles of three boreholes*

3.2. Analysis and discussion

3.2.1. Soil behavior type

Fig 4 shows interpretated profiles of soil behavior type for these three boreholes following the procedure in Fig 1. A value of $I_c = 2.6$ is chosen to classify the clayey soils ($I_c > 2.6$) and sandy soil ($I_c < 2.6$). It can be seen that this site is mainly composed of clayey soils.

3.2.2. Shear wave velocity

Fig 5 shows the comparison of shear wave velocity profiles between measured through in-situ down hole tests and derived from CPT data with methods summarized in Table 1 flowing the procedure given in Fig 2. In general, values of shear wave velocity increase as the depth increasing and this trend agrees well between measured and calculated with these methods. These measured V_s values generally fall in the upper bound of those calculated values with methods in Table 1, that is to say, most of these methods under-estimate ground soils' shear wave velocity, except at a deeper depth.

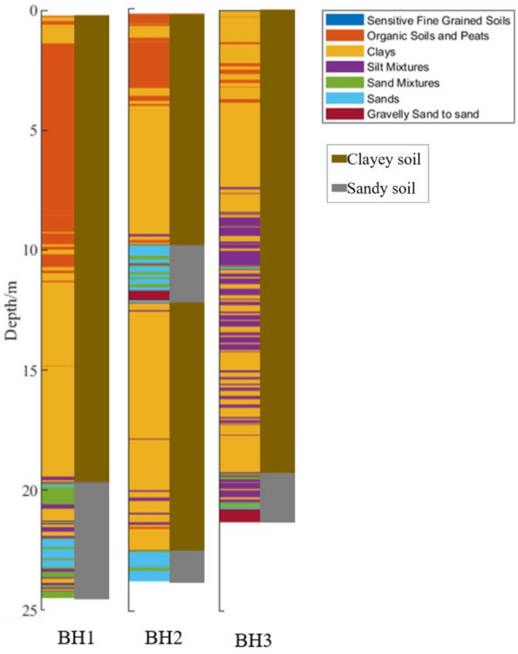

Figure 4. Profiles of soil behaviour type

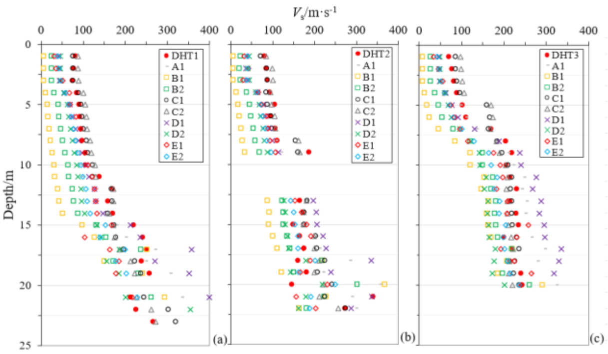

Figure 5. V_s comparison between measured with DHT and derived from CPT data

A further comparison of Vs values between the measured and derived with methos in Table 1 is shown in Fig 6, which indicates that: a) methods B1 and B2 have relative errors up to ±60%, b) methods A1, D1, D2, E1, and E2 produce ±40% differences; c) while methods C1 and C2 make an estimation within an error of ±30%. It may be concluded that methods C1 and C2 make the best estimation, and both can be employed in the derivation of shear wave velocity from the in-situ CPT data.

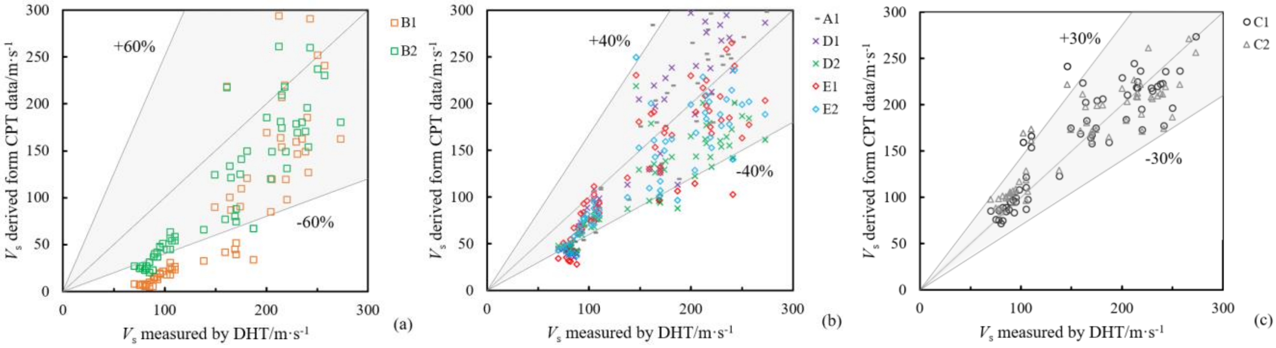

Figure 6. *Errors of shear wave velocity between measured with DHT and derived from CPT data*

3.2.3. Soil unit weight

In the derivation of shear wave velocity from CPT data, soil unit weight for each soil layer may be needed (see methods E1 and E2) and commonly measured on the inevitably disturbed samples retrieved on site. Since correlation between soil unit weight and CPT data is developed, the reliability of a flowchart from CPT data to shear wave velocity should be of interest to engineers. To address this, the commonly used method by Mayne (2014) is adopted to derive the soil unit weight. Fig 7 (a) presents a comparison of soil unit weight between measured in lab and derived from CPT data, which shows that the derived values are generally than those measured in lab, but within an error of ±20%. Based on these soil unit weight values, shear wave velocities are derived with methods E1 and E2 and a comparison is shown in Fig 7 (b). It can be seen that, even though there is an error of ±20% between soil unit weight values, these derived shear wave velocity values show a very well agreement. It may be concluded that in the derivation of V_s with methods E1 and E2, values of soil unit weight produce ignorable effect, and it should be reliable to derive soil's shear wave velocity without lab determined soil unit weight.

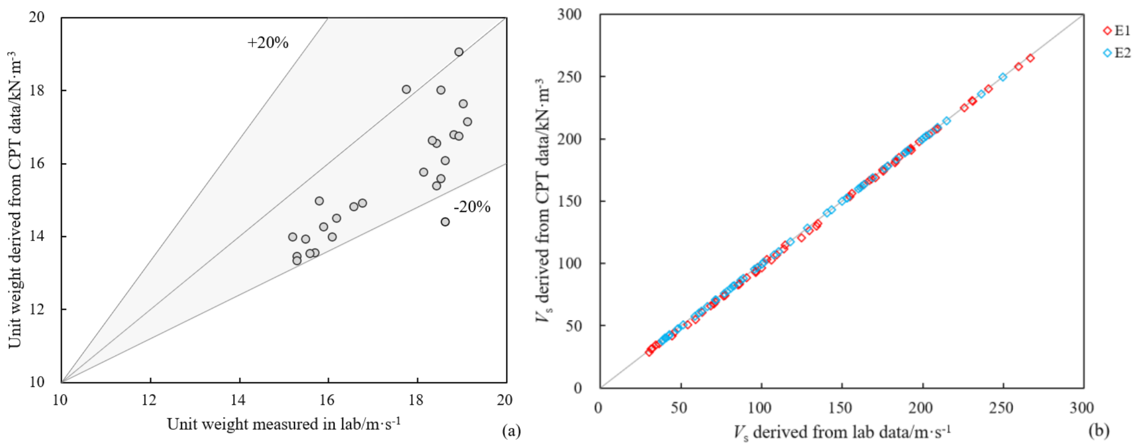

Figure 7. *Comparison of unit weight between measured in lab and derived from CPT data*

4. Conclusions

Based on a case study focusing on an offshore site in East Sea of China, this paper presents an evaluation on current interpretation methods for CPT data recorded at clayey soil layers. By comparison of shear wave velocity between measured with DHT on site and derived from CPT data, main findings and recommendations are made:

Long's method proposed in 2010 (C1) and Cai's method proposed in 2014 (C2) produced better prediction of shear wave velocity. The difference in soil unit weight between measured in lab and derived from CPT data is no more than 20%, and as a result, the calculated shear wave velocity is nearly the same. Therefore, in the absence of on-site borehole test data, it is recommended to estimate soil unit weight based on CPT data.

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