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Enhancing the CPT correlation with the small strain shear stiffness of sands

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Stress normalization

Abstract The cone penetration test (CPT) is a valuable geotechnical insitu test. Yet, the CPT correlations with the small strain shear modulus and seismic shear wave velocity still need more research to enhance their accuracy. In this study, the stress normalizations for the net cone tip resistance and the small strain shear modulus are scrutinized. Subsequently, enhanced CPT correlations with the small strain shear modulus and the seismic shear wave velocity for sands are presented. The proposed approach utilizes published databases of CPT in sands and recent researches that quantify the small strain shear modulus using sand gradation parameters. Four case histories are analyzed using the suggested correlation and the results confirm that the presented approach is a promising enhancement to the CPT correlations with the small strain shear modulus and seismic shear wave velocity in sands.

1. Introduction

Determination of cohesionless soil stiffness relies mainly on the correlation of the soil moduli with the penetration tests such as the SPT and the CPT because of the recognizable difficulties to obtain undisturbed samples from such formations. Specifically, the CPT is considered a reliable, repeatable and cost-effective geotechnical in situ test in sands [1,2].

The CPT may be equipped with geophones to measure the velocity of the shear wave V_s generated from a source placed at the ground surface. In such case, the test is termed as the seismic cone penetration test (SCPT). The small strain shear modulus G_0 is determined at the depth of velocity measurement using the following relationship:

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

where ρ is the soil density, which equals to the soil unit weight divided by the gravity acceleration [3].

The small strain shear modulus G_0 represents the shear modulus at shear strains less than 10^{-6}. It applies to different types of loading (viz., monotonic, cyclic, static and dynamic) and different types of drainage (viz., drained and undrained conditions) [4,5].

The small strain shear modulus G_0 and the interrelated shear wave velocity V_S are considered important parameters in geotechnics. They are commonly utilized in the following geotechnical studies:

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Table 1 Selected previous CPT-V_S/CPT-G_0 correlations.

No.	Reference	CPT-V_s/CPT-G_0 Correlations	Units[a]
1	Hegazy & Mayne [16]	$V_s = 0.0831 Q_{tn} \exp(1.7861 I_c) \left(\frac{\sigma'_v}{p_a}\right)^{0.25}$ In calculation of the normalized net tip resistance Q_{tn} (Eq. (3)), the stress exponent n should be equal to 0.5	V_s: m/s
2	Mayne [17]	$V_s = 18.5 + 118.81 \log(f_s)$	V_s: m/s f_s: kPa
3	Andrus et al. [14]	$V_s = 2.27 q_t^{0.412} I_c^{0.989} z^{0.033}$	V_s: m/s q_t: kPa z: m
4	Robertson [18]	$V_S = [10^{(0.55 I_c + 1.68)}(q_t - \sigma_v)/p_a]^{0.5}$ For an average unit weight of 18 kN/m^3, the small strain shear modulus G_0 is given by the following: $G_0 = 0.018 \times 10^{(0.55 I_c + 1.68)}(q_t - \sigma'_v)$	V_s: m/s[b]
5	McGann et al. [19]	$V_s = 18.4 q_t^{0.144} I_c^{0.0832} z^{0.278}$	V_s: m/s q_t: kPa f_s: kPa z: m
6	Ahmed et al. [20]	$G_0 = 6700 \sigma'_v \exp(-1.4 I_c)$	[b]

[a] Specific units are to be used, as indicated, since the related correlations are derived empirically from databases with variables having the same units.
[b] A consistent set of units are to be used in both sides of the correlation.

(1) Dynamic and seismic analysis of foundations (e.g., [6,7]).
(2) Determination of the liquefaction susceptibility (e.g., [8,9]).
(3) Determination of the load-deformation relationships for foundations under operative loads (e.g., [10,11]).
(4) Soil-structure interaction of underground structures (e.g., [12,13]).

Therefore, relating the penetration tests to the small strain modulus G_0 and the shear wave velocity V_S were frequently addressed in many previous studies.

The direct measurement of shear wave V_S using the SCPT allows an accurate determination of the small strain shear modulus G_0. Yet, there is still a crucial need to rigorously correlate G_0 and V_S with the basic measurements of the cone test (i.e., the tip resistance q_t and the skin friction f_s). These correlations are commonly utilized when the available shear wave measurements are limited while the CPT penetrations are abundant. Additionally, the CPT is simpler, cheaper and faster than the SCPT. Hence, the CPT is more appealing to many geotechnical engineers to be incorporated in geotechnical site investigations than the SCPT [14].

2. Previous CPT-V_S/CPT-G_0 correlations

Robertson & Campanella [1], Yu [15] and others stated that there are no comprehensive closed-form solutions to the problem of the cone penetration in sands. Therefore, the CPT correlations are typically obtained by means of regression analyses of databases of the CPT resistances and the measured soil parameters. Numerous correlations were envisaged to relate the CPT resistances to either the shear wave velocity V_s or the small strain shear modulus G_0. Some of the recent and common CPT correlations are listed in Table 1.

The following definitions are interrelated to Table 1: σ_v and σ'_v are the total and the effective overburden stress, respectively; p_a is the atmospheric pressure (≈100 kPa). The behavior index I_c, the normalized net tip resistance Q_{tn}, the friction ratio F_R and the stress exponent n are estimated as follows [21,18]:

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

$$Q_{tn} = \left(\frac{q_c - \sigma_v}{p_a}\right) \Big/ \left(\frac{\sigma'_v}{p_a}\right)^n \tag{3}$$

$$F_R = 100\left(\frac{f_s}{q_c - \sigma_v}\right) \tag{4}$$

$$n = 0.381(I_c) + 0.05\left(\frac{\sigma'_v}{p_a}\right) - 0.15 \leqslant 1.00 \tag{5}$$

The obtained shear wave velocity V_s from the CPT-V_s correlations can be converted into the small strain shear modulus G_0 using the relationship between the shear wave velocity V_S and the small strain shear modulus G_0 given in Eq. (1).

3. Database of CPT and undisturbed sand samples

This study utilizes a database that was presented by Mayne [4]. It comprises the geotechnical properties and the CPT resistances for 15 high-quality undisturbed samples of siliceous sands from Japan, Canada, Norway, China and Italy. Table 2 lists the samples and their depth from the ground surface depth z, the ground water depth, fines content FC (in decimals), uniformity coefficient C_u, unit weights, effective vertical stress σ'_v, the small strain shear modulus G_0 and cone resistances q_t and f_s. The database of sands includes natural alluvial deposits, hydraulically placed fills, and tailings from mining operations. Fig. 1 shows that the database samples are classified as clean

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