A Global Statistical Correlation between Shear Wave Velocity and Cone Penetration Data

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A Global Statistical Correlation between Shear Wave Velocity and Cone Penetration Data

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Abstract

Shear wave velocity (V_s) and cone penetration data are collected from sites worldwide. The data represent different soil types including sands, clays, intermediate soils, and mine tailings. The statistical correlations between V_s and different cone parameters were examined. The soil behavior type index (I_c) represents most of the variability of the V_s data. Regression models are fitted and a global statistical correlation between normalized V_s and I_c is developed for different soils. The derived correlation is verified at a selected site where the soil stratigraphy is relatively complex.

Introduction

The shear wave velocity and shear modulus (G_{max}) are fundamental soil parameters. They are important in determining soil dynamic behavior and liquefaction susceptibility (Youd and Idriss 2001), as well as in static loading situations (Burland, 1989). The V_s can be measured using different in-situ tests such as seismic cone penetration test (SCPT), seismic dilatometer test (SDMT), downhole test (DHT), crosshole test (CHT), and spectral analysis of surface wave (SASW). Also, different empirical correlations have been developed between V_s and cone penetration test (CPT) data. Baldi et al. (1989) correlated V_s in Italian sands with cone tip resistance (q_c) and the effective overburden stress (σ'_{vo}). Rix & Stokoe (1991) modified the above study and estimated G_{max}/q_c as a function of $q_c/(\sigma'_{vo})^{1/2}$. Mayne & Rix (1995) found that V_s in clays is statistically correlated with q_c and void ratio, e_o. Hegazy & Mayne (1995) updated the above correlations in sands and clays using additional data.

More recently, Suzuki et al. (1998) found that normalization of the V_s to the corrected cone tip resistance in Japanese sites had a trend with the soil behavior type index (I_c). In this paper, a global statistical correlation is developed to estimate V_s in any soil type using cone data. A best-fit regression analysis is performed to reduce the variance of the residuals.

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Database

Shear wave velocity and CPT data were compiled from 73 sites representing different soil types including sands, clays, soil mixtures and mine tailings. The V_s data were measured using SCPT, DHT, CHT and SASW. A list of 31 clay sites is summarized in Mayne and Rix (1993). A list of 30 cohesive and cohesionless sites is summarized in Hegazy and Mayne (1995). Table 1 includes a list of 12 new sites added to the above databases.

V_s-Cone Data Trends

The trends of different cone data including q_c and sleeve friction (f_s) with V_s were examined. The q_c and f_s data depend on the soil type, strength, stress history and index properties (Hegazy and Mayne 2002). The V_s measurements are also functions of soil type and behavior. Therefore, V_s can be predicted using q_c and f_s. Figure 1 shows a statistical correlation between q_c and V_s. The cone tip resistance data approximately represents 52% of the V_s variability. Figure 2 shows the correlation between f_s and V_s. Figure 2 indicates that f_s represents 49% of the V_s variability. Therefore q_c and f_s should be used together to predict V_s. Robertson and Fear (1998) introduced a soil behavior type index (I_c) as a function of q_c, f_s and vertical effective stress (σ'_{vo}). The correlation between V_s and I_c is discussed in the following section.

V_s-I_c Correlation

Simple regression analysis was performed with V_{s1}/q_{c1N} as dependent parameter and I_c as an independent parameter. V_{s1} is the corrected V_s to a reference overburden stress according to Robertson et al. (1992):

$$V_{s1} = V_s \left(\frac{P_a}{\sigma'_{vo}} \right)^{0.25} \tag{1}$$

The normalized cone tip resistance (q_{c1N}) is determined below according to Youd and Idriss (2001). The soil behavior type index (I_c) is considered as follows (Robertson and Fear 1998):

$$I_c = [(3.47 - \log q_{c1N})^2 + (\log F + 1.22)^2]^{0.5} \tag{2a}$$

where q_{c1N} and F are expressed as follows:

$$F = \frac{f_s}{(q_c - \sigma_{vo})} * 100\% \tag{2b}$$

$$q_{c1N} = Q = \frac{(q_c - \sigma_{vo})}{\sigma'_{vo}} \tag{2c}$$

Table 1. List of new sites, soil types and references*

Site	Soil type	Reference
Tonegawa, Japan	silt to silty sand	Matsuo and Tsutsumi 1998
Edogawa, Japan	silt to silty sand	Matsuo and Tsutsumi 1998
Natorigawa, Japan	sand	Matsuo and Tsutsumi 1998
Moss landing area, CA,USA	sand	Boulanger et al. 1997
A site in Japan	clay, silt, sand	Suzuki et al. 1998
Venice, Italy	clay, silt, sand	McGillivray & Mayne 2004
Amherst, MA, USA	varved soft clay	SCPT data from this study
Memphis, TN, USA	soft clayey silt, sand fill	
Camilla, GA, USA	silty clay (weathered)	
Emerald Mine Tailings, PA	mine tailings	
Cumberland Tailings, PA	mine tailings	
Auburn, AL	silty sand, sandy silt	

Notes: 1. Shear wave velocity data were measured using SCPT. *2. Additional to databases compiled by Mayne & Rix (1993); Hegazy & Mayne (1995).

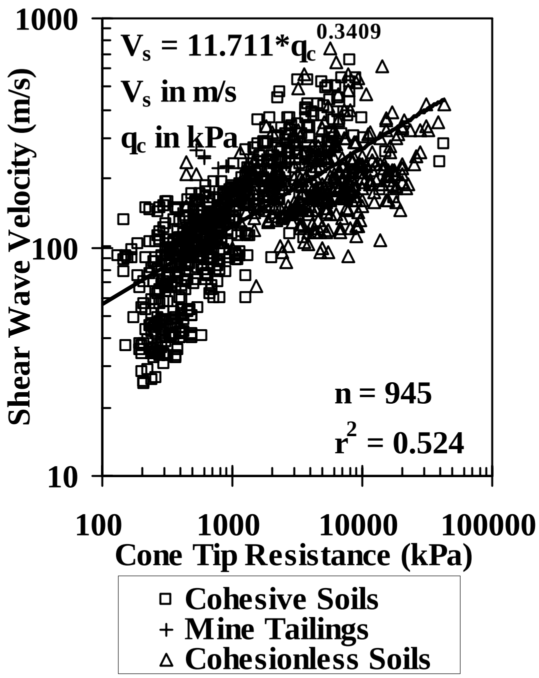

Figure 1. V_s-q_c correlation for all soil types

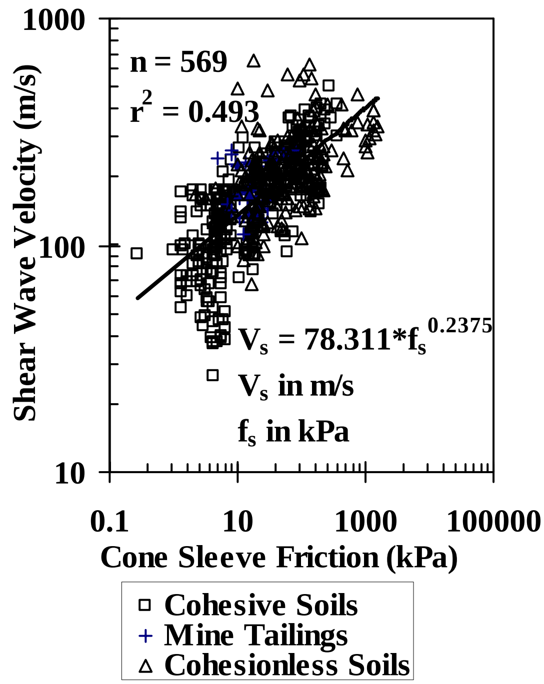

Figure 2. V_s-f_s correlation for all soil types

A value of I_c greater than 2.6 indicates a cohesive soil. If the value of I_c is less than 2.6, I_c is re-determined using q_{c1N} as follows:

$$q_{c1N} = \left(\frac{q_c}{P_a}\right)\left(\frac{P_a}{\sigma'_{vo}}\right)^{0.5}, \quad P_a = 100\ kPa \tag{3}$$

If I_c above is greater than 2.6, I_c is re-determined considering q_{c1N} as follows:

$$q_{c1N} = \left(\frac{q_c}{P_a}\right)\left(\frac{P_a}{\sigma'_{vo}}\right)^{0.75} \tag{4}$$

Figure 3 shows the best-fit regression results between V_{s1}/q_{c1N} and I_c which is expressed in the following proposed correlation ($n = 558$, $r^2 = 0.854$):

$$\frac{V_{s1}}{q_{c1N}} = 0.0831 * e^{(1.786 * I_c)} \tag{5}$$

The shear wave velocity (V_s) in m/s is predicted as follows:

$$V_s = 0.0831 * q_{c1N} * \left(\frac{\sigma'_{vo}}{P_a}\right)^{0.25} * e^{(1.786 * I_c)} \tag{6}$$

In the above equations, q_c, f_s, σ_{vo} and σ'_{vo} are in kPa and V_s is in m/s.

Verification

The above correlation was applied to compare the measured and predicted V_s at the Treporti test site near Venice, Italy. The soil stratigraphy at the site is fairly complex with intermixed Venetian sediment of clays, silts and sands (McGillivray and Mayne 2004). Figure 4 indicates a good agreement between the measured in-situ and predicted values of V_s except at the shallowest depths. A complete match between measured and predicted V_s values may not be expected for the reasons cited herein. A V_s measurement using SCPT is an average value between the depths of two successive measurements (about 1 m apart) however a q_c reading represents a soil resistance at a specific depth (at 2 cm intervals). Despite use of a worldwide V_s-SCPT database, the derived regression correlation is a function of the data used to develop it and cannot explain all the variability of natural soil deposits. Also, measured V_s values are usually reported at the same depth of the cone tip however a wave receiver is typically mounted above the cone tip. Therefore, there is a shift between the measured and predicted V_s values, unless a depth correction equal to the distance between the cone tip and the receiver is considered.

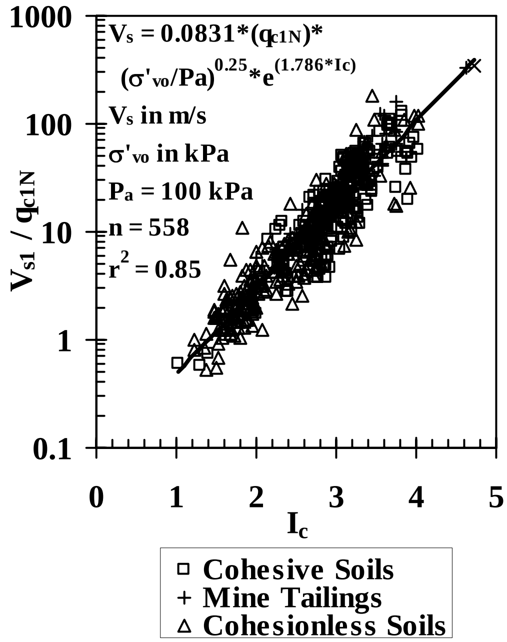

Figure 3. Recommended global V_s correlation as a function of I_c.

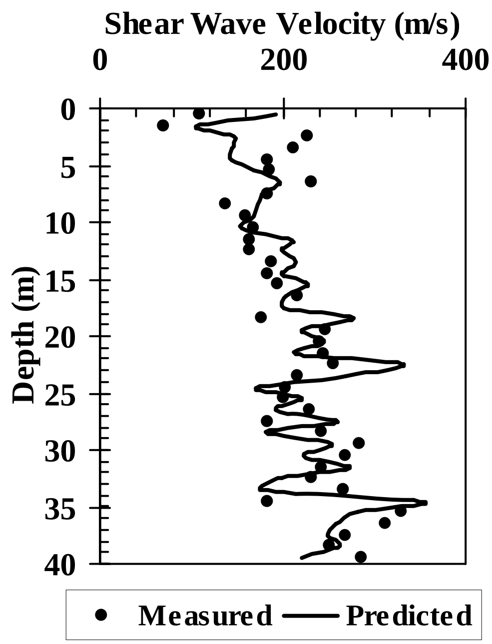

Figure 4. Comparison between measured and predicted V_s at a site in Venice, Italy (Measured data from McGillivray and Mayne 2004).

Conclusions

Statistical correlations between V_s and several cone parameters were evaluated for different soil types including clays, silts, sands, and mine tailings. The cone tip resistance and sleeve friction data were separately found to explain about 50% of the V_s data variability. The best fit was obtained between the ratio V_{s1}/q_{c1N} and I_c where r^2 was 85%. The proposed global statistical correlation to predict V_s was verified where the measured and predicted V_s values were well compared at a selected site where the soil stratigrahy was relatively complex. The proposed statistical expression is useful to provide estimates of V_s in the absence of direct in-situ measurements or to check on anomalous or uncertain values of shear wave velocity.

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