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PREDICTING SHEAR-WAVE VELOCITY FROM CONE PENETRATION RESISTANCE

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ABSTRACT

Empirical equations for predicting the small-strain shear-wave velocity, V_S, of soils of different geologic age from cone penetration resistance are presented in this paper. The equations are determined using data from 229 soil layers in California, South Carolina and Japan. Of the 229 soil layers, 72 are of Holocene age, 113 of Pleistocene age, and 44 of Tertiary age. Variables considered in the development of the equations include: cone tip and sleeve resistances, depth, overburden pressure, soil behavior type index, and geologic age. It is found that V_S is on average 22-26 % greater in the Pleistocene soils and 129-137 % greater in the Tertiary-age Cooper Marl than in the Holocene soils with the same tip resistance. These results clearly indicate the need to consider geologic age, as well as cementation, when predicting V_S from cone measurements. The new equations are particularly useful where it is not economically feasible to measure V_S at all desired locations.

Keywords: Cone penetration test, ground response, in situ tests, shear waves, velocity

INTRODUCTION

Shear modulus, or shear-wave velocity, is a required property to evaluate the dynamic response of soil due to earthquake shaking, as well as machine foundation vibration. At low shear strain levels (less than about 10^{-4} %), the shear modulus in soils is constant and at its maximum value, G_{max}. Values of G_{max} for ground response analysis are commonly determined from in situ small-strain shear-wave velocity, V_S, measurements using the equation:

$$G_{max} = r V_S^2 \tag{1}$$

where r is the mass density (or total unit weight divided by the acceleration of gravity) of the soil.

Although direct measurements of V_S are always preferred over estimates, relationships with penetration resistance are useful for some projects. For example, the number of V_S measurements available for developing regional ground shaking hazard maps is usually limited. Relationships with the more abundant penetration measurements can provide timely and economical inputs required for regional and preliminary site-specific ground responses analyses.

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A concern with estimating V_S from penetration resistance is that the former is a small strain measurement, whereas the latter is a large strain measurement. The factors controlling behavior at small and large strains may not be exactly the same. As discussed by Schneider et al. (2004), V_S in sands is controlled by the number and area of grain-to-grain contacts. The number and area of particle contacts depends on relative density, effective stress state, rearrangement of particles with time, and cementation. On the other hand, penetration resistance in sands is controlled by the interaction of particles being sheared by and rotating around the penetrometer. This behavior depends primary on relative density and effective stress state, particularly in the horizontal direction, and to a lesser degree by age and cementation. Thus, although strong relationships between V_S and penetration resistance exist, some variation should be expected.

Relationships between cone penetration test (CPT) and V_S, or G_{max}, measurements have been investigated since the early 1980s (e.g., Robertson and Campanella, 1983; Sykora and Stokoe, 1983; Bellotti et al., 1986; Baldi et al., 1989; Lo Presti and Lai, 1989; Rix and Stokoe, 1991; Robertson et al., 1992; Hegazy and Mayne, 1995; Mayne and Rix, 1995; Fear and Robertson, 1995; Andrus et al., 2004). These investigations have shown that cone tip resistance, cone sleeve friction, confining stress, depth, soil type, and geologic age are factors influencing the relationship. One limitation of the previous relationships is most of them were developed for either sands or clays, with no intermediate range of soil types. Also, most of the previous relationships are for relatively young deposits. Presented in this paper are new regression equations developed using 229 data pairs and considering both soil type and geologic age.

DATABASE

Of the 229 data pairs, 80 are from California (Mitchell et al., 1994; Boulanger et al., 1997; Fuhriman, 1993; Hryciw et al., 1991; Piratheepan, 2002; Holzer et al., 2005); 143 from South Carolina (S&ME, 1998-2003; WPC, 1999-2004; Ellis, 2003; Mohanan, 2006); and 6 from Japan (Iai, 1997; Piratheepan, 2002). A plot of V_S versus cone tip resistance for the 229 data pairs separated by geologic age is presented in Figure 1. Geologic ages are inferred from information provided in the project reports or conversations with the investigators. There are 72 data pairs from Holocene-age (<10,000 years) deposits, 113 from Pleistocene-age (10,000 – 1.8 million years) deposits, and 44 from the Tertiary-age (1.8 – 60 million years) Cooper Marl in South Carolina. It can be seen in the figure that generally V_S increases with geologic age for a given cone tip resistance.

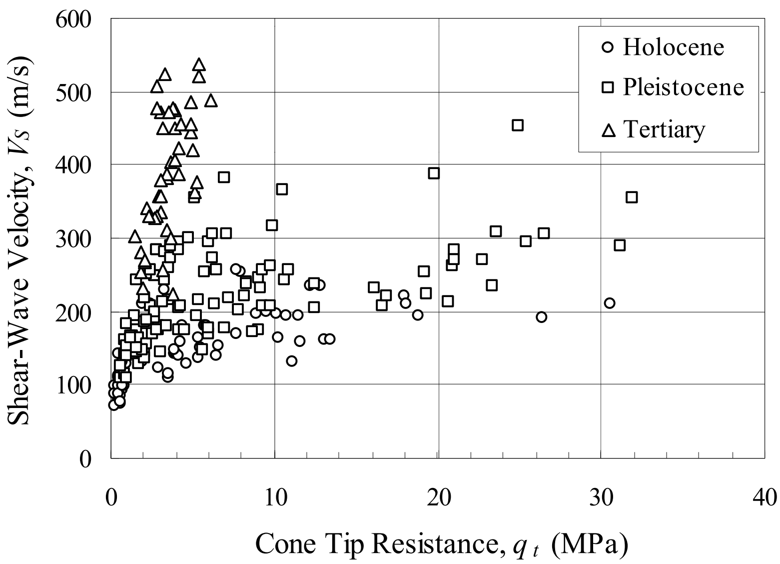

Figure 1. Comparison of measured V_S and cone tip resistance separated by geologic age.

The criteria used for selecting the data pairs are: (1) Measurements are from below the ground water table where reasonable estimates of effective stress can be easily made. (2) Measurements are from thick, uniform soil layers identified using the CPT measurements. A distinct advantage of the CPT is that a nearly continuous profile of penetration resistance is obtained for detailed soil layer determination. (3) CPT locations are within 5 m of the V_S test locations. (4) At least two V_S measurements, and the corresponding test intervals, are within the uniform layer identified by the CPT. (5) Time history records used for V_S determination exhibit easy-to-pick shear wave arrivals. Values of V_S determined from difficult-to-pick shear-wave arrivals are not used. When the time history records are not available, exceptions to Criterion 5 are allowed if there are several V_S measurements within the layer that follow a consistent trend. By adopting these criteria, scatter in the data due to soil variability and measurement error is reduced.

Cone Tip Resistance and Soil Behaviour Type Index

All CPT measurements plotted in Figure 1 are from electrical cone penetrometers. Fifty-three of the data pairs (20 Holocene and 33 Pleistocene) were determined by non-piezocones. The rest were determined by piezocones. For the piezocone measurements, cone tip resistances were corrected for the effect of pore water pressure acting behind the tip (Lunne et al., 1997). This correction was particularly significant in fine-grained soils. No pore pressure corrections were needed for the non-piezocone measurements.

Average cone resistances are determined over the selected interval of V_S measurements. The average is calculated using the electronic CPT data files, when available. For the few cases where the electronic data files are not available, average resistances are estimated from the graphical profiles.

Some applications of CPT measurements require correcting tip resistances to a reference overburden stress. The correcting equation proposed by Robertson and Wride (1998) can be expressed as:

$$q_{t1N} = \left(\frac{q_t}{P_a}\right)\left(\frac{P_a}{\sigma'_v}\right)^n \qquad (2)$$

where q_{t1N} is the normalized cone tip resistance, q_t is the measured cone tip resistance corrected for pore pressure if based on piezocone measurements, P_a is the reference stress of 100 kPa, σ'_v is the effective vertical stress, and n is an exponent dependant on grain size characteristics. The value of n ranges from 0.5 for clean sands to 1.0 for clays (Olsen, 1997).

Because samples are usually not collected during cone investigations, the soil behavior type index by Robertson (1990) is used. This soil behavior type index, I_c, is computed by (Robertson and Wride, 1998):

$$I_c = \left[(3.47 - \log Q)^2 + (\log F + 1.22)^2\right]^{0.5} \qquad (3)$$

where Q and F are normalized cone tip resistance and friction ratio, respectively. Ranges of I_c defining the soil behavior type zones are roughly: < 1.31 for gravelly sand to dense sand; 1.31-2.05 for clean sand to silty sand; 2.05-2.6 for silty sand to sandy silt; 2.60-2.95 for clayey silt to silty clay; 2.95-3.60 for silty clay to clay; and >3.60 for organic soils.

Shear-Wave Velocity

Values of V_S were determined from seismic CPT measurements for 209 of the 229 data pairs. For the other twenty data pairs, 14 are from crosshole (California) and 6 from suspension logger (Japan) measurements. Only seismic CPT measurements deeper than 3 m are considered to insure that the shear-wave travel path had a significant vertical component. Also, where possible, V_S from seismic CPTs based on the psuedo-interval method (Patel, 1981; Campanella and Stewart, 1992) is used. Concerning the crosshole tests, measurements that might have been influenced by wave refraction along an adjacent stiffer layer are not included in the average. Each test method involves a significant component of wave propagation or particle motion in the vertical direction. Therefore, use of V_S based on different methods is considered acceptable.

Similar to the overburden stress correction used for penetration resistance, it has been proposed to correct measured V_S using the following equation (Sykora, 1987; Robertson et al., 1992):

$$V_{S1} = V_S \left(\frac{P_a}{s'_v} \right)^{0.25} \tag{4}$$

where V_{S1} is the stress-corrected shear-wave velocity, and V_S is the measured shear-wave velocity. As explained by Andrus and Stokoe (2000), application of Equation 4 implicitly assumes a constant coefficient of earth pressure, K'_o, for all deposit types. It also assumes that V_S is measured with both the direction of particle motion and the direction wave propagation polarized along principal stress directions and that one of those directions is vertical.

Site and Soil Layer Characteristics

Characteristics of the compiled CPT-V_S data pairs are summarized in Table 1. Values of I_c range from 1.19 to 4.00 for the Holocene data and 1.16 to 3.25 for the Pleistocene data. The types of geologic deposits tested include: hydraulic fill, compacted and uncompacted fills, alluvial/fluvial, distal alluvial fan, eolian, lacustrine, beach, estuarine, and tidal marsh.

Table 1. Characteristics of the CPT-V_S data

Geologic Age	Percentage of Data Pairs by Soil Behavior Type Index			Percentage of Data Pairs by Average Depth of Measurements		
	I_c = 1-2	I_c = 2-3	I_c = 3-4	D = 0-10 m	D = 10-20 m	D = >20 m
Holocene	40	28	32	100	-----	-----
Pleistocene	34	58	8	51	46	3
Tertiary (Cooper Marl)	-----	100	-----	5	56	39

For the Cooper Marl data, all values of I_c lie within the range of 2.01 to 2.91. The Cooper Marl occurs throughout much of the Charleston, South Carolina region. It dates at about 30 million years before present. The upper part of the Marl, where all the measurements are from, has been characterized as a phosphatic limestone consisting of 60-75% calcium carbonate, 5-25 % quartz sand, 10-30 % clay, and 1-5 % phosphatic sand and pebble. The calcium carbonate is generally in the form of skeletal remains of microscopic marine organisms. It exhibits an overconsolidation ratio of 3 to 6 (Camp, 2004).

About 92 % of the Holocene and Pleistocene data have an average measurement depth less than 14.5 m and a layer thickness less than 6.3 m. Over 90 % of all the data pairs are from sites where the depth to groundwater is less than 4 m.

Values of s'_v are calculated using soil densities reported by the investigator(s). When no densities were reported, typical values for soils with similar description are assumed. In most cases, the assumed densities are 1.76 Mg/m^3 (110 lb/ft^3) for soils above the groundwater table and 1.92 Mg/m^3 (120 lb/ft^3) for soils below the groundwater table.

REGRESSION ANALYSIS

The equations for predicting V_S (or V_{S1}) are determined from nonlinear regression analysis by power curve fitting first for the Holocene data, and then for the Pleistocene and Tertiary data. The decision to use power curve fitting is based primarily on results of previous studies. Various combinations of measured tip resistance or normalized tip resistance, sleeve friction or normalized sleeve friction, effective overburden stress or depth, and soil behavior type were initially considered (Piratheepan, 2002; Ellis, 2003; Andrus et al. 2003). Only selected equations having the lower standard deviation of the residuals (or errors) and the higher coefficient of determination are presented below.

Holocene-Age Soils

Based on the 72 Holocene data pairs, the recommended best-fit equation for predicting V_S in m/s is:

$$V_S = 2.27\, q_t^{0.412}\, I_c^{0.989}\, D^{0.033} ASF \tag{5}$$

where q_t is in kPa, I_c is dimensionless, D is depth below the ground surface in m, and ASF is an age scaling factor with value of 1.0 for Holocene soils. The 95 % confidence intervals for the coefficient and exponents in Equation 5 are 2.27 $\pm$ 0.85, 0.412 $\pm$ 0.034, 0.980 $\pm$ 0.149 and 0.033 $\pm$ 0.052.

The small exponent on D and the relatively large confidence interval associated with it indicates marginal significance of this term in Equation 5. This result is somewhat surprising given the well-established influence of effective confining pressure on V_S based on laboratory tests. On the other hand, Holzer et al. (2005) studied several different natural deposits in Oakland, California and noted V_S increasing with depth only in the Bay mud, which also exhibited a decreasing void ratio with depth. It appears that factors other than depth often dominate the variation of V_S in natural deposits.

Using the same 72 data pairs corrected to the reference overburden stress, the recommended best-fit equation for predicting V_{S1} in m/s is:

$$V_{S1} = 16.5\, q_{t1N}^{0.411}\, I_c^{0.970} ASF \tag{6}$$

where q_{t1N} is dimensionless; and the 95 % confidence intervals are 16.5 $\pm$ 4.4, 0.411 $\pm$ 0.039 and 0.970 $\pm$ 0.160. It is interesting to note that the exponents in Equations 6 and 5 are practically the same. Presented in Table 2 are the regression statistics for Equations 5 and 6.

Table 2. Statistics and scaling factors for regression equations

Geologic Age	Relationship	Number of Samples, *n*	Age Scaling Factor, *ASF*	Scaling Factor, *SF*	Residual Standard Deviation, *s* (m/s)	Coefficient of Determination, R^2
Holocene	Equation 5	72	1.00	-----	22	0.779
	Equation 6	72	1.00	-----	24	0.758
	Equation 7	72	-----	0.92	23	0.709
	Equation 8	72	-----	0.88	23	0.596
Pleistocene	Equation 5	113	1.22	-----	45	0.171
	Equation 6	113	1.25	-----	42	0.002
	Equation 7	113	-----	1.12	45	0.430
	Equation 8	113	-----	1.11	44	0.371
Tertiary (Cooper Marl)	Equation 5	44	2.29	-----	78	0.179
	Equation 6	44	2.37	-----	65	0.174
	Equation 9	44	-----	-----	67	0.397
	Equation 10	44	-----	-----	59	0.315

The standard deviation of the errors, *s*, reflects how much the data fluctuate from the developed equation. It is defined as the square root of [Σ(measured V_S – predicted $V_S)^2$]/(n - 2), where n is the number of samples. An *s* value of 22 m/s indicates that 68 % of the data fall within 22 m/s of the equation. The coefficient of determination, R^2 is a measure of how much the total variation is explained by the equation. It is defined as the ratio of the deviation due to regression to the total variation in the dependent variable, which is velocity, and can range between 0 and 1.0. The closer R^2 is to 1.0, the more the regression equation is said to explain the total variation. Equation 5 provides a slightly better fit of the Holocene data than does Equation 6, with the lowest value of *s* (22 m/s) and the highest value of R^2 (0.779).

A comparison of measured and calculated V_{S1} using Equation 6 for the Holocene data separated by I_c is presented in Figures 2. It can be seen in the figure that V_{S1} is equally over and under predicted by Equation 6.

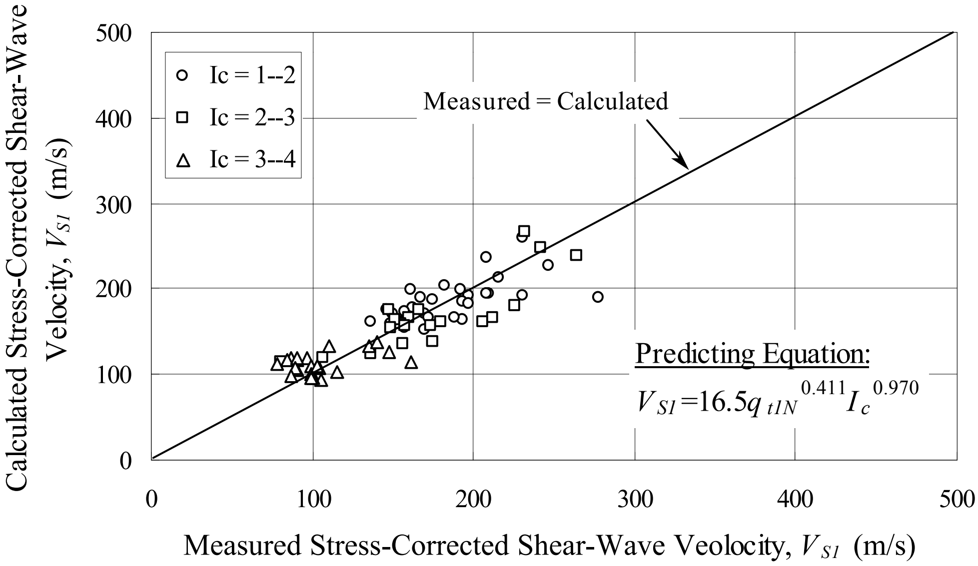

Figure 2. Comparison of measured and calculated V_{S1} using Equation 6 for the Holocene data.

Pleistocene-Age Soils

Values of *ASF* are determined for the 113 Pleistocene data pairs by dividing the measured V_S by the calculated V_S for each data pair using Equations 5 and 6, and then averaging the results. As given in Table 2, the *ASF* values are 1.22 and 1.25 for Equations 5 and 6, respectively. These values indicate that V_S is 22-25 % higher in the Pleistocene deposits than V_S in the Holocene deposits with the same cone penetration resistances.

Values of *s* given in Table 2 for the Pleistocene soils and Equations 5 and 6 indicate that 64 % of the scatter in the data is within 42-45 m/s of the mean velocity. The R^2 values indicate that only 0.2-17 % of the total variability is accounted for using these equations. Hence, Equations 5 and 6 do not model the Pleistocene data pairs well, even with the best-fit values of *ASF*. Hence, the regression analysis is repeated considering both Holocene and Pleistocene data pairs.

Based on the combined Holocene and Pleistocene data set, the best-fit regression equation for predicting V_S in m/s is:

$$V_S = 2.62\, q_t^{0.395}\, I_c^{0.912}\, D^{0.124} SF \tag{7}$$

where SF is a scaling factor; and the 95 % confidence intervals are 2.62 $\pm$ 0.86, 0.395 $\pm$ 0.031, 0.912 $\pm$ 0.137 and 0.124 $\pm$ 0.041. The SF term is different from ASF because the reference age for SF is the average of the combined Holocene and Pleistocene data, whereas the reference age for ASF is the average of just the Holocene data. For the data pairs corrected to the reference overburden stress, the best-fit equation for predicting V_{S1} in m/s is:

$$V_{S1} = 19.6\, q_{t1N}^{0.396}\, I_c^{1.006} SF \tag{8}$$

where the 95 % confidence intervals are 19.6 $\pm$ 4.4, 0.396 $\pm$ 0.031 and 1.006 $\pm$ 0.137. It is interesting to note that the coefficients and exponents associated with Equations 7 and 8 are within the 95 % confidence interval of the coefficients and exponents associated with Equations 5 and 6, except for the exponent on D in Equation 7.

Values of SF in Equations 7 and 8 are determined for the Holocene and Pleistocene groups by dividing the measured V_S by the calculated V_S and averaging the results. As listed in Table 2, SF is 0.88-0.92 for the Holocene data and 1.11-1.12 for the Pleistocene data. These values indicate that V_S in Pleistocene deposits is 22-26 % higher than V_S in Holocene deposits with the same cone penetration resistances, which agrees well with Equations 5 and 6 with ASF.

While the s values for Equations 7 and 8 are essentially the same values for Equations 5 and 6 and the Pleistocene data (see Table 2), the R^2 values are improved from 0.2-17 % to 37-43 %. Thus, Equations 7 and 8 are considered better for Pleistocene deposits. Although the s value for Pleistocene soils is about 2 times greater than the s value for Holocene soils, the median velocity has also increase. The s value is about 15 % of the median velocity for the Holocene data and about 20 % of the median velocity for the Pleistocene data.

A comparison of measured and predicted V_S for the Pleistocene-age soils using Equation 8 is shown in Figure 3. It can be seen in the figure that V_{S1} for the Pleistocene soils is fairly well modeled by Equation 8, although there is some over prediction at lower values of V_{S1} and under prediction of higher values of V_{S1}. This over and under prediction may be due to measurements from younger and older Pleistocene deposits that are not completely represented by one SF value.

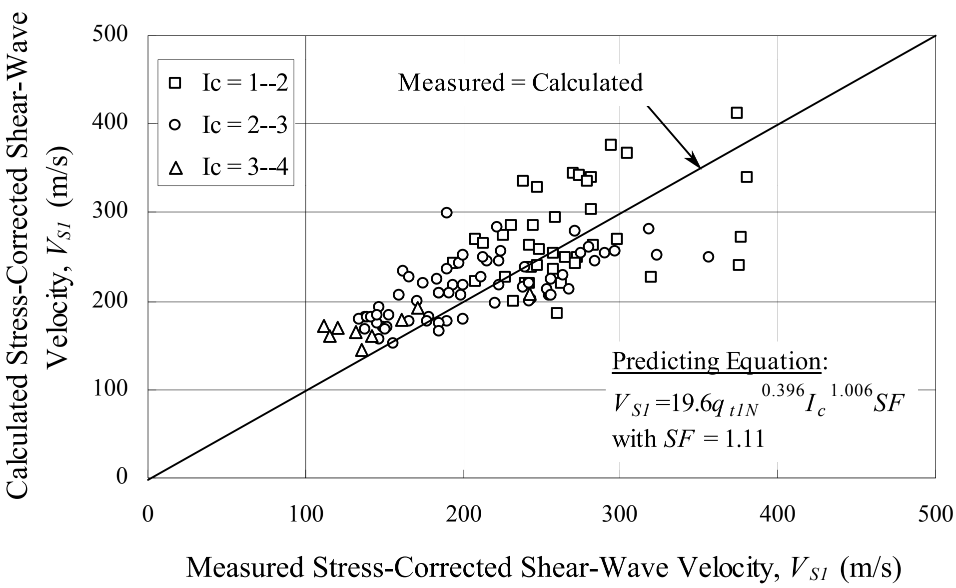

Figure 3. Comparison of measured and calculated V_{S1} using Equation 8 for the Pleistocene data.

Tertiary-Age Cooper Marl

Values of *ASF* are determined for the 44 Cooper Marl data pairs using Equations 5 and 6. These values are 2.29 and 2.37, respectively (see Table 2). They indicate that V_S is 129-137 % higher in the Marl than in Holocene deposits with the same cone penetration resistances. It is likely that this significant difference is related to the high carbonate content of the Marl, and is not typical of all Tertiary deposits. The low R^2 values of 0.174-0.179 (see Table 2) indicate that the Marl data are not well modeled by Equations 5 and 6.

Additional analysis was performed on the Cooper Marl data using Equation 7 and 8. However, values of s and R^2 were not significantly improved. Also, regression analysis was conducted using a modified I_c relationship suggested by Lewis and his colleagues (WSRC, 2000) based on cone resistance and pore pressure measurements. This modified I_c was considered because it better predicts soil type in the Marl (Li et al., 2007). However, the resulting equations had a small exponent (nearly 0) on I_c, indicating that I_c is not significant in the regression (Mohanan, 2006).

The final regression on the Marl data pairs is performed without considering I_c. The recommended best-fit equation for predicting V_S in m/s is:

$$V_S = 13.0\, q_t^{\,0.382}\ D^{0.099} \tag{9}$$

where the 95 % confidence intervals for the coefficient and exponents are 13.0 $\pm$ 9.2, 0.382 $\pm$ 0.092 and 0.099 $\pm$ 0.081. For predicting V_{S1} in m/s, the recommended best-fit equation is:

$$V_{S1} = 115.2\, q_{t1N}^{\,0.338} \tag{10}$$

where the 95 % confidence intervals are 115.2 $\pm$ 29.1 and 0.338 $\pm$ 0.075. The s and R^2 values associated with Equations 9 and 10 (see Table 2) indicate an improvement over Equations 5 and 6. The s values of 59-67 m/s are about 16-17 % of the median velocity for the Marl data.

Shown in Figure 4 is the variation of measured and calculated V_S using Equation 10 and the Marl data. It can be seen in the figure that the data are slightly over predicted at lower V_S and slightly under predicted at higher V_S.

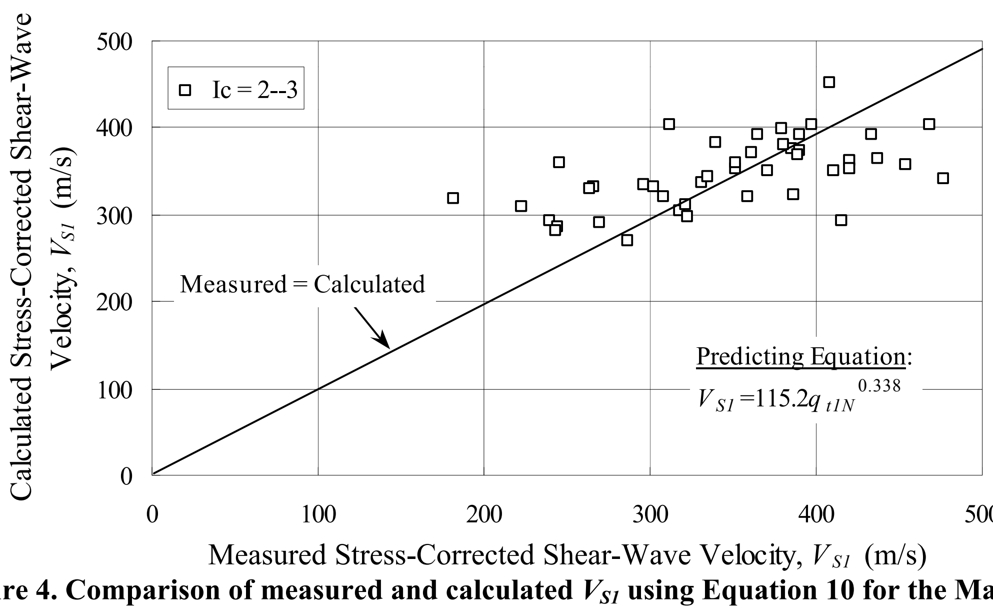

Figure 4. Comparison of measured and calculated V_{S1} using Equation 10 for the Marl data.

COMPARISON WITH PREVIOUS RELATIONSHIPS FOR HOLOCENE SANDS

Summarized in Table 3 are seven CPT-V_S relationships proposed for Holocene sands based on stress-corrected measurements, including Equation 6 developed as part of this study. Baldi et al. (1989) used CPT calibration chamber and V_S resonant column measurements on freshly deposited silica sand from Ticino, Italy to develop their relationship. They then compared their relationship with seismic CPT measurements in Po River sand and Gioia Turo sand with gravel and found good agreement. The sandy soils at the two field sites had ages ranging from about 3,000 years to 20,000 years at a maximum depth of 30 m.

Table 3. Selected CPT-V_S equations proposed for Holocene sands

Reference	Original Equation with V_S or V_{S1} in m/s	Assumptions for Adjusting Equation	Adjusted Equation with V_{S1} in m/s	Approximate Range of q_{t1N} Data Used
Baldi et al. (1989)	$V_S=277q_c^{0.13}s'_v{}^{0.27}$ where q_c and s'_v in MPa	s'_v=0.1 MPa; $q_{t1N}=q_{c1}/P_a$	$V_{S1}=110q_{t1N}^{0.13}$	Not available
Rix and Stokoe (1991)	$G_{max}/q_c=1634[q_c/(\sigma'_v)^{0.5}]^{-0.75}$ where G_{max}, q_c and s'_v in kPa	s'_v=100 kPa; r=18.2 kg-s^2/m^2; $q_{t1N}=q_{c1}/P_a$	$V_{S1}=123q_{t1N}^{0.125}$	20 to 420
Robertson et al. (1992)	$V_{S1}=60.3q_{c1}^{0.23}$ where q_{c1} in bars	$q_{t1N}=q_{c1}/P_a$	$V_{S1}=60.3q_{t1N}^{0.23}$	20 to 150
Fear and Robertson (1995)	$q_{c1}=(V_{S1}/135)^{4.35}$ where q_{c1} in MPa	$q_{t1N}=q_{c1}/P_a$	$V_{S1}=79.5q_{t1N}^{0.23}$	Not available
Hegazy and Mayne (1995)	$V_S=13.18q_c^{0.192}s'_v{}^{0.179}$ where q_c and s'_v in kPa	s'_v=100 kPa; $q_{t1N}=q_{c1}/P_a$	$V_{S1}=72.8q_{t1N}^{0.192}$	Not available
Andrus et al. (2004)	$(V_{S1})_{cs}=62.6(q_{c1N})_{cs}^{0.231}$	$(q_{c1N})_{cs}=q_{t1N}$	$V_{S1}=62.6q_{t1N}^{0.231}$	30 to 330
This Study, Equation 6	$V_{S1}=16.5q_{t1N}^{0.411}I_c^{0.970}$	I_c=1.3 I_c=1.6 I_c=1.9 I_c=2.2	$V_{S1}=21.3q_{t1N}^{0.411}$ $V_{S1}=26.0q_{t1N}^{0.411}$ $V_{S1}=30.8q_{t1N}^{0.411}$ $V_{S1}=35.5q_{t1N}^{0.411}$	166 to 332 71 to 224 48 to 138 30 to 129

Rix and Stokoe (1991) carried out CPT calibration chamber and V_S resonant column measurements on freshly deposited washed mortar sand. They also considered crosshole and CPT (mechanical cone) measurements from three different Holocene sand deposits at the Heber Road site in the Imperial Valley of Southern California. The washed mortar sand classified as poorly graded sand to gravelly sand with fines content (*FC*, silt and clay) less than 1 %. The Heber Road sands classified as silty sand with *FC* ranging from 4-14 %.

Robertson et al. (1992) and Fear and Robertson (1995) developed relationships using seismic CPT measurements from the Fraser River Delta region of British Columbia and a tailings sand site in Alaska, respectively. The Fraser River Delta deposits consisted of young, uncemented silica clean sand. The Alaska sand contained about 30 % fines and was composed of a large amount of carbonate shell material. Both sets of measurements were made by the seismic CPT techniques using a standard 10 cm^2 electric cone.

Hegazy and Mayne (1995) developed their relationship using data from 24 sand sites. The V_S measurements were determined by different in situ measurement techniques (i.e., seismic cone, crosshole, downhole, or spectral analysis of surface waves).

Andrus et al. (2004) compiled CPT-V_S data pairs from various Holocene sand deposits, many of which are the same ones considered in this study. They based their relationship on normalized cone tip resistances corrected to an equivalent clean sand ($I_c \leq 1.64$) value using the procedure outlined in Robertson and Wride (1998). All of the sand layers had $FC < 20$ % or $I_c < 2.25$.

Presented in Figure 5 are the seven CPT-V_S relationships plotted over the ranges of q_{t1N} used to develop them. Where the range of q_{t1N} is not available, question marks are noted in the figure. It can be seen that the relationships by Rix and Stokoe (1991) and Fear and Robertson (1995) plot above the other previous relationships. The field data considered by Rix and Stokoe (1991) were based on mechanical cone measurements, while the other studies were primarily based on electrical cone measurements. Anagnostopoulos et al. (2003) showed significant difference in resistances measured by the two types of cone penetrometers, which might explain the position of the Rix and Stokoe (1991) relationship. The relationship by Fear and Robertson (1995) is based on field measurements in sand with FC of 30 % and carbonate shell material. A FC of 30 % is approximately equivalent to an I_c of 2.5 (Robertson and Wride, 1998). Thus, Equation 6 developed in this study agrees well with, and explains some variation in, previous relationships proposed for Holocene sands.

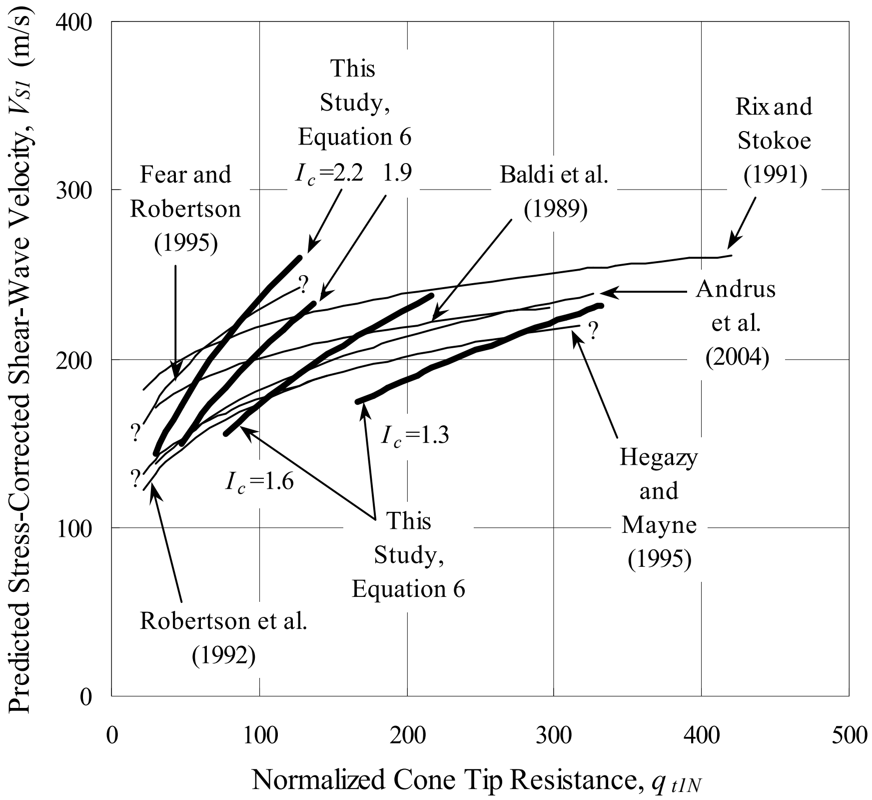

Figure 5. Comparison of CPT-V_S relationships proposed for Holocene sands.

CONCLUSIONS

Regression analyses are performed on 229 data pairs to develop CPT-V_S relationships that consider soil type and geologic age. The soil behavior type index by Robertson (1990) is used because sample information is usually not available at CPT sites. Also, the soil behavior type index appears to be slightly more significant in the regression than sleeve resistance. Values of V_S are found to be 22-26 % higher in the Pleistocene soils and 129-137% higher in the Tertiary-age Cooper Marl, than in the Holocene soils with the same cone penetration resistance. The new relationships provide a viable way to estimate V_S from CPT measurements for regional and preliminary ground response analyses.

Particular care and engineering judgment should be exercised when applying the relationships to sites with conditions different from the database, because it is likely that the age scaling factors will differ from region to region. Therefore, some local measurements of V_S should be conducted to determine the appropriateness of the age scaling factors in other Pleistocene and Tertiary soil deposits.

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