Shear Wave Velocity – Penetration Resistance Correlations for Ground Shaking and Liquefaction Hazards Assessment

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Investigations Undertaken

The goal of this project is to develop improved regression equations between small-strain shear-wave velocity (V_S) and penetration resistance from the Cone Penetration Test (CPT) and Standard Penetration Test (SPT). The annual project summary for last year documented initial findings for the V_S-CPT regression analyses. This summary documents findings for the V_S-SPT regression analyses.

Sixty-three data pairs of V_S and SPT blow count have been compiled as part of this project. The compiled data are from measurements made by various investigators documented in project reports and published papers. Available information about the soil type, fines content, plasticity, coefficient of uniformity, deposit type, and age corresponding to the V_S measurements have also been compiled.

The general criteria used for selecting the V_S and SPT data pairs are as follows: (1) All measurements are from below the ground water table where reasonable estimates of effective stress can be made. (2) All measurements are from thick, uniform soil layers identified using CPT measurements. A distinct advantage of the CPT is that a nearly continuous profile of penetration resistance is obtained for detailed soil layer determination. By requiring V_S and SPT data to be from only thick, uniform soil layers, scatter in the data due to soil variability is minimized. When no CPT measurements are available, exceptions to Criterion 2 are allowed if there are several V_S and SPT measurements within the layer that follow a consistent trend. (3) At least two V_S measurements, and the corresponding test intervals, are within the uniform layer. (4) Time history records used for V_S determination exhibit easy-to-pick shear (S)-wave arrivals. Thus, values of V_S determined from difficult-to-pick S-wave arrivals are not used. When time history records are not available, exceptions to Criterion 4 are allowed if there are several V_S measurements within the layer that follow a consistent trend. In this study, nearly all the V_S measurements used are based on the crosshole, downhole, or seismic CPT techniques.

Results

Of the 63 V_S-SPT data pairs, 34 are from California, 13 are from Taiwan, 10 are from Japan, and 6 are from Canada. The California, Japan, and Canada data are all from Holocene-age (<10,000 years) soil deposits. Although surficial soils at the Taiwan sites are also Holocene in age, no age information is currently available for the subsurface soils. Therefore, only the data from California, Japan, and Canada are considered in the development of the regression equations. The data from Taiwan are used to evaluate the developed equations.

The soil properties considered in the regression analyses include: uncorrected S-wave velocity (V_S), stress-corrected S-wave velocity (V_{S1}), energy-corrected blow count (N_{60}), energy- and stress-corrected blow count ($(N_1)_{60}$), depth (D), fines content (FC), coefficient of uniformity (C_U), and median grain size (D_{50}). Grouping the data by FC and considering arbitrary combinations of the soil properties, a total of 34 different regression equations are derived. Listed in Table 1 are the 6 regression equations that seem most useful. Also listed in Table 1 are the number of data pairs, coefficient of determination (R^2), and standard deviation error (SDE) associated with each equation. Although a few of the other regression equations not listed in Table 1, with more independent variables, provided slightly higher R^2 and lower SDE values, the differences are not significant. The fact that the equations based on uncorrected measurements (Equations 1-3) provide somewhat better fits than the equations based on stress-corrected measurements (Equations 4-6) may be explained by the extra independent variable, D, in Equations 1-3.

Comparisons between measured S-wave velocities and predicted S-wave velocities using Equations 3 and 6 are presented in Figures 1 and 2, respectively. The plotted data exhibit a uniform scatter about the "predicted = measured" line, confirming the success of the regression equations to provide good fits of the compiled data for Holocene soils with FC < 40 %.

Table 1. Regression equations for uncemented, Holocene-age sandy soils.

Regression Equation for Predicting V_S or V_{S1} [a] (m/s)		Number of Data pairs	R^2	SDE (m/s)	Equation Number
FC < 10 %	$V_S = 66.7(N_{60})^{0.248} D^{0.138}$	25	0.823	14.8	1
FC = 10-35 %	$V_S = 72.3(N_{60})^{0.228} D^{0.152}$	10	0.951	8.4	2
FC = 0-40 %	$V_S = 72.9(N_{60})^{0.224} D^{0.130}$	39	0.788	15.5	3
FC < 10 %	$V_{S1} = 95.5(N_1)_{60}^{\ 0.226}$	28	0.688	17.5	4
FC = 10-35 %	$V_{S1} = 103.4(N_1)_{60}^{\ 0.205}$	13	0.878	11.7	5
FC = 0-40 %	$V_{S1} = 101.8(N_1)_{60}^{\ 0.205}$	45	0.719	16.7	6

[a] N_{60} and $(N_1)_{60}$ in blows/0.3 meter, and D in meters.

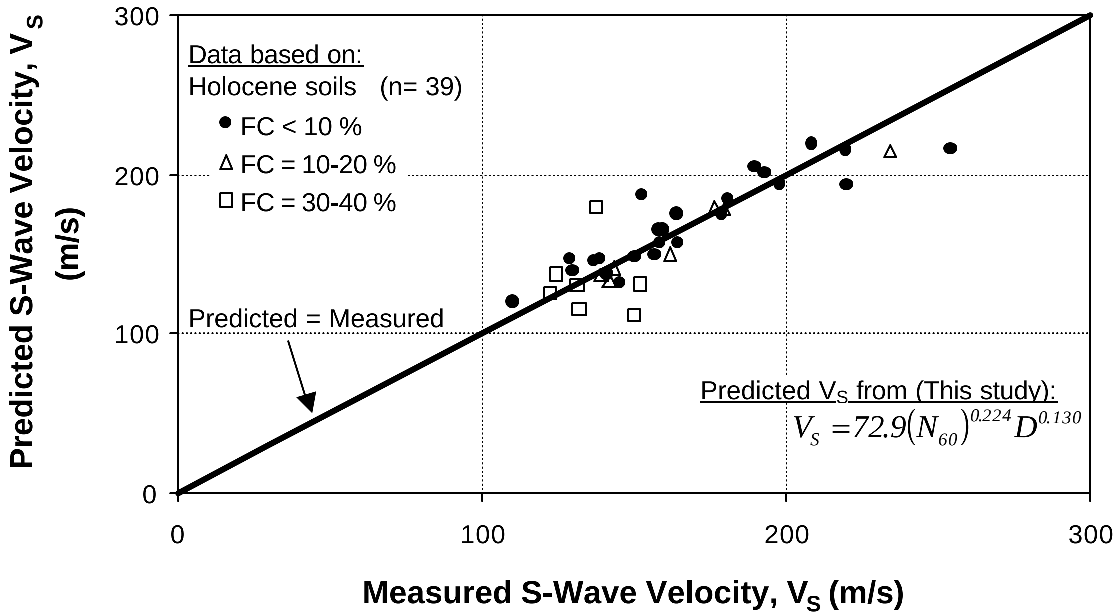

Figure 1. Comparison of measured and predicted V_S as a function of blow count and depth for Holocene sandy soils with fines content less than 40 %.

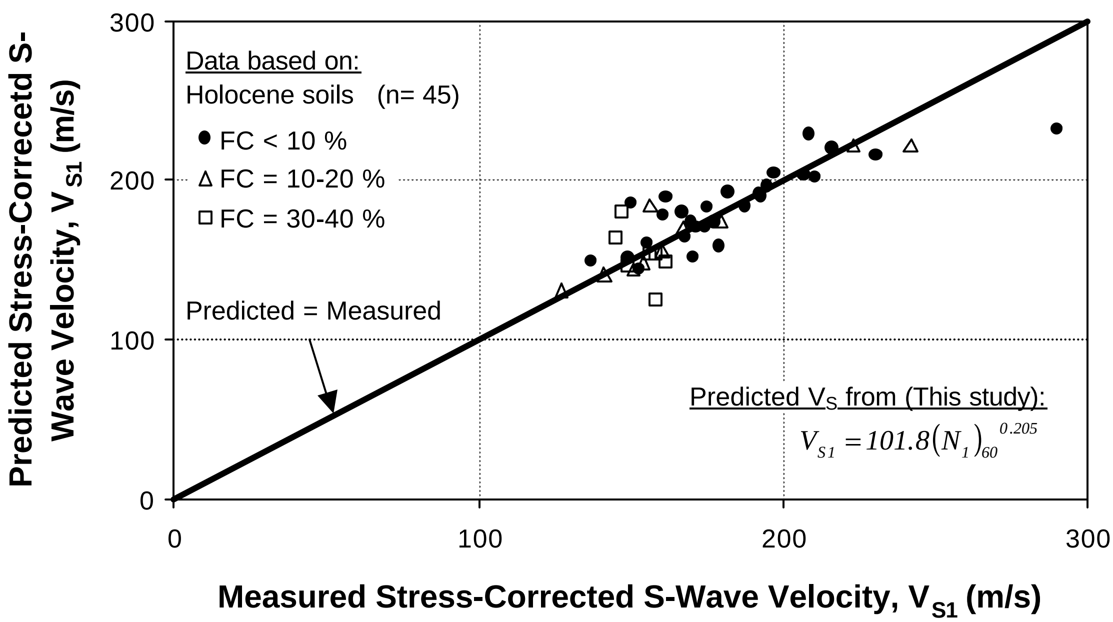

Figure 2. Comparison of measured and predicted V_{S1} as a function of corrected blow count for Holocene sandy soils with fines content less than 40 %.

Equations 3 and 6 are plotted in Figures 3 and 4, respectively, along with several earlier regression equations. Also plotted in the figures are the compiled data from California, Japan, and Canada. As shown in Figure 3, Equation 3 compares fairly well with the Ohta and Goto (1978) regression equation for fine sands and D = 10 m. It appears from the plotted data that the Ohta and Goto equation over-predicts V_S for $N_{60} < 20$. In Figure 4, Equation 6 compares well with the regression equations by Yoshida et al. (1988) for fine sand, Fear and Robertson (1995) for Ottawa sand, and Andrus and Stokoe (2000) for uncemented, Holocene-age sands with less than 10 % non-plastic fines. On the other hand, there is significant difference between these equations and the regression equation proposed by Fear and Robertson (1995) for Alaska sand. Fear and Robertson describe Alaska sand as tailings composed of large amount of carbonate shell material. They suggest that the shell material significantly increased its compressibility, which resulted in lower penetration resistances. An alternative hypothesis is that the high concentration of carbonate resulted in a weakly cemented soil skeleton with significantly higher V_S measurements.

The results summarized in Table 1 suggest that fines content may influence both the regression coefficient and exponents. This finding contradicts the earlier regression equations, which imply that fines content only influences the coefficient. More data are needed to determine regression equations for soils with fines content over 40 %, as well as soils with geologic age older than Holocene.

Using the 13 data pairs compiled from Taiwan sites, an evaluation of Equation 3 is presented in Figure 5. The predicted and measured values of V_S compare well, exhibiting a SDE value of 20 m/s. This SDE value is only 5 m/s higher than the SDE value determined for Equation 3 and the data used to develop it (see Table 1). Because of the good comparison and the fact that most of the data are from depths less than 10 m, the soils are likely Holocene in age.

Non-Technical Summary

Prediction of ground shaking response at soil sites requires knowledge of stiffness of the soil, expressed in terms of V_S. While it is preferable to determine V_S directly from field tests, it is often not economically feasible to make V_S measurements at all locations. Thus, to take advantage of the more abundant penetration measurements, correlations between V_S and penetration resistance are needed. The result presented above support the findings of earlier studies that blow count and depth (or overburden pressure) are significant parameters in V_S-SPT correlations. In addition, the results suggest that fines content influences the regression equations differently than previously assumed. The regression equations developed in this study provide a viable way to estimate V_S from SPT blow count for regional ground shaking hazard mapping and preliminary site-specific ground response analysis. They also provide an approach to comparing liquefaction assessment procedures based on V_S and SPT measurements.

Reports Published

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Piratheepan, P., and Andrus, R.D. (2001), "Estimating shear-wave velocity from cone penetration resistance and geologic age," *Program and Abstracts*, 73rd Annual Meeting of the Eastern Section – Seismological Society of America, Columbia, SC, October 14-16.

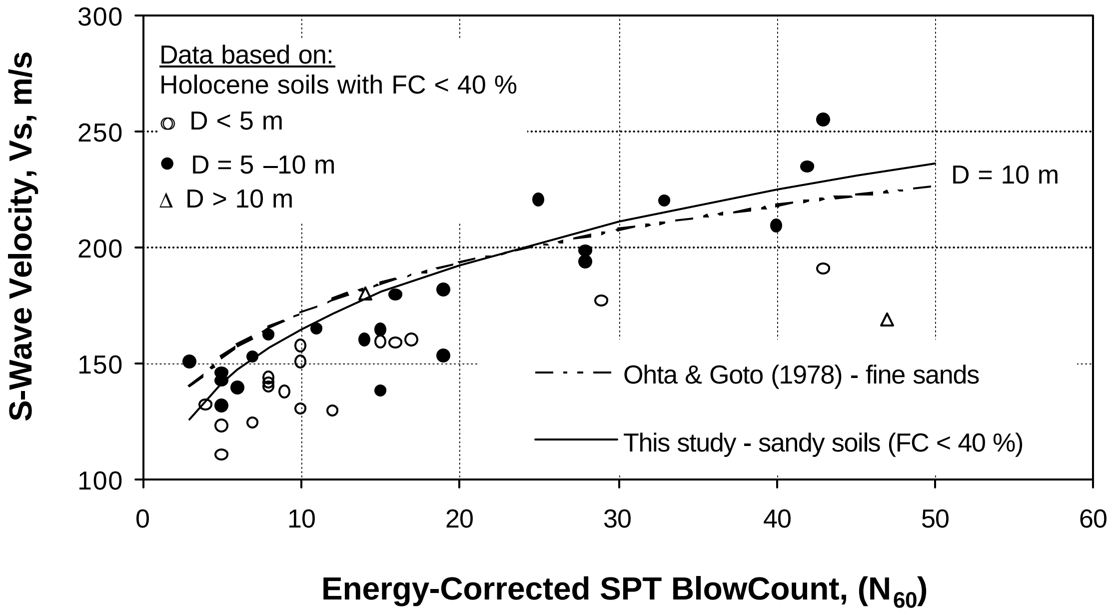

Figure 3. Comparison of V_S-SPT regression equation developed in this study with the Ohta and Goto (1978) regression equation of similar form for D = 10 m, along with compiled data for Holocene sandy soils with fines content less than 40 %.

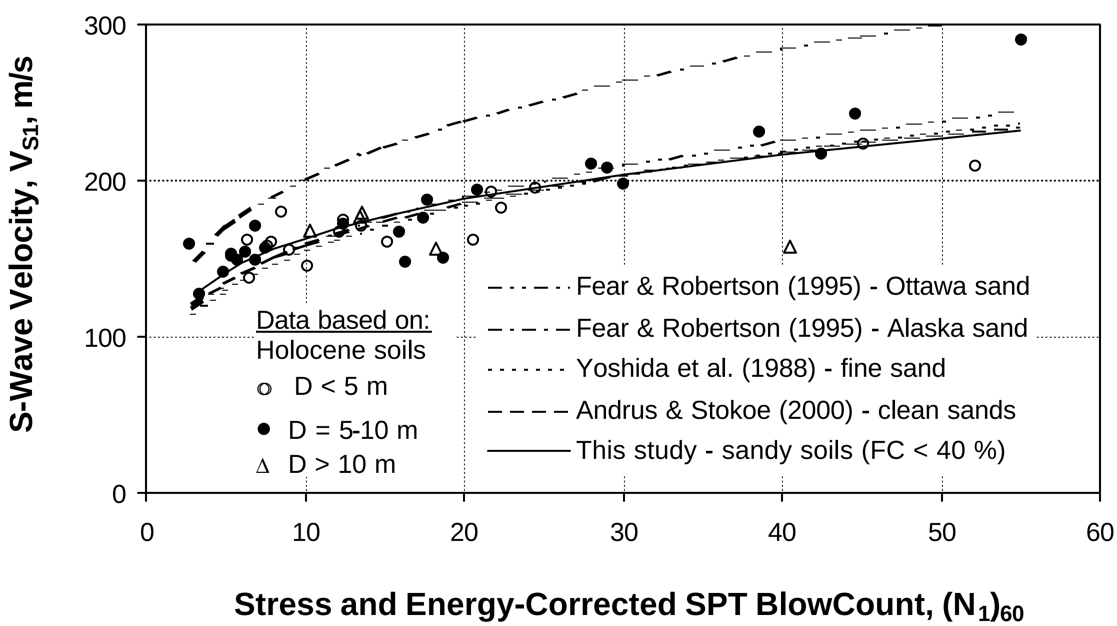

Figure 4. Comparison of V_S-SPT regression equation developed in this study with earlier regression equations of similar form, along with compiled data for Holocene sandy soils with fines content less than 40 %.

Availability of Processed Data

The processed data in hard copy format are available in Piratheepan (2002). The processed data in electronic format are available from the PI. Professor Andrus can be reached at the telephone number and e-mail address listed on the first page of this summary report.

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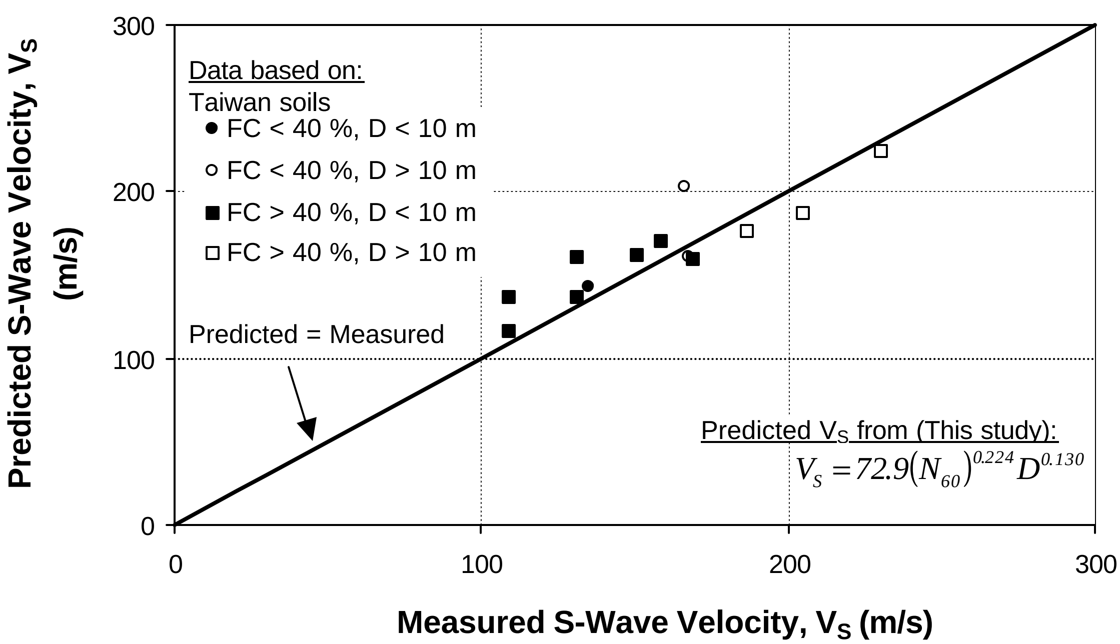

Figure 5. Comparison of measured and predicted V_S as a function of blow count and depth for Taiwan soils.