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

USGS Grant 01HQGR0007

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Program Element: I
Keywords: geotechnical, borehole geophysics, shear wave velocity

Investigations Undertaken

The goal of this project is to develop improved correlations between small-strain shear wave velocity (V_S) and penetration resistance from the Cone Penetration Test (CPT) and Standard Penetration Test (SPT). This report documents initial findings for the V_S-CPT correlations.

Shear wave velocity and CPT data have been compiled from primarily sites in California, as well as sites in Japan and Canada. With the assistance of Thomas Holzer, Michael Bennett, John Tinsley, and Thomas Noce, about half of the data were compiled from measurements made by the U.S. Geological Survey in Oakland and Alameda, California. Additional data were compiled 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 has also been compiled.

The general criteria used for selecting the V_S and CPT data 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 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. By requiring V_S and CPT data to be from only thick, uniform soil layers, scatter in the data due to soil variability can be minimized. (3) At least two V_S measurements, and the corresponding test intervals, are within the uniform layer identified by the CPT. (4) Time history records used for V_S determination exhibit easy-to-pick shear wave arrivals. Thus, 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 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

Because samples are usually not collected during cone testing, the soil behavior type chart based on normalized cone tip resistance and friction ratio by Robertson (1990) is used in grouping the compiled data. A simplified version of Robertson's chart is shown in Figure 1. Plotted on the chart are the compiled data. This chart is divided into six regions: 2, organic soils; 3, silty clay to clay; 4, clayey silt to silty clay; 5, silty sand to sandy silt; 6, clean sand to silty sand; and 7, gravelly sand to dense sand. In addition, a normally consolidated region that trends with the position of the numbers subdivides the six regions. According to Robertson, soils plotting above the normally consolidated region tend to be over consolidated and older. Below the normally consolidated region, soils generally exhibit higher sensitivity. It is interesting to note that the data for Holocene-age (<10,000 years) soils plot in all regions of the chart, while the data for Pleistocene-age (10,000 to 1.5 million years) soils correctly plot only in the upper right regions of the chart. However, there are exceptions to the soil classes predicted by the chart, as suggested by the compiled data with known soil class plotted in Figure 2.

For purposes of developing the V_S-CPT correlations, data points plotting in the regions for behavior types 6-7 and classifying as sands (SW, SP, SP-SM, SM), if sample information is available, are grouped as sands. Data points plotting in the regions for behavior types 3-4 and classifying as clays (ML, MH, CL, CH), if sample information is available, are grouped as clays.

Plotted in Figures 3 and 4 are the compiled data based on uncorrected V_S and uncorrected cone tip resistance for sands and clays, respectively. Also, plotted in the figures are proposed V_S-CPT correlations determined by statistical regression modeling of the plotted data. The correlations are defined by:

$$V_S = 26.3(q_c)^{0.199}(f_s)^{0.003}\,\text{ASF} \qquad \text{for sands} \qquad (1)$$

$$V_S = 14.3(q_c)^{0.280}(f_s)^{0.108}\,\text{ASF} \qquad \text{for clays} \qquad (2)$$

where V_S is shear wave velocity in m/s, q_c is uncorrected cone tip resistance in kPa, f_s is uncorrected cone sleeve friction in kPa, and ASF is a age scaling factor. Based on the modeling of the Holocene soils, the coefficient of determination r^2 is 0.61 for Eq. (1), and 0.88 for Eq. (2). The general form of Eqs. 1 and 2 is similar to correlations proposed by Hegazy and Mayne (1995), with the ASF term added. Values of ASF for the compiled data are given in Table 1. These equations provide a useful approach to estimating V_S for use in ground response analysis at sites where it is not economically feasible to make direct V_S measurements.

Proposed correlations based on stress-corrected V_S and normalized cone tip resistance for sands and clays are shown in Figures 5 and 6, respectively. These correlations are defined by:

$$V_{S1} = 77.4(q_{c1N})^{0.178}\,\text{ASF} \qquad \text{for sands} \qquad (3)$$

$$V_{S1} = 50.2(q_{c1N})^{0.428}\,\text{ASF} \qquad \text{for clays} \qquad (4)$$

where V_{S1} is stress-corrected V_S in m/s, and q_{c1N} is normalized q_c as defined by Robertson and Wride (1998) the coefficient of determination r^2 is 0.60 for Eq. (3), and 0.82 for Eq. (4). It is expected that r^2 will improve somewhat when a sleeve friction term is added. Equation (3) provides a useful approach to comparing simplified liquefaction assessment procedures based on V_S and CPT for sands.

Table 1 – Age Scaling Factors for the Proposed V_S-CPT Correlations.

Geologic Age	ASF for Sands	ASF for Clays
Holocene (<10,000 years)	1.00	1.00
Pleistocene (10,000 to 1.5 million years)	1.44 Equation 1 1.41 Equation 3	1.18 Equation 2 1.27 Equation 4

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 results presented above clearly show that soil type and geologic age are two important factors that influence the correlation between V_S and cone penetration resistance. Previous published V_S-cone penetration resistance correlations do not consider geologic age, or are limited to relatively young soil deposits. Thus, the proposed correlations represent a significant improvement over the earlier correlations.

Reports Published and to be Published

Piratheepan, P. (2002), "Correlations between shear wave velocity and penetration resistance," *M.S. Thesis*, Clemson University, Clemson, SC (in preparation).

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.

Availability of Processed Data

All processed data are available from the PI in hard copy and electronic formats. Professor Andrus can be reached at the telephone number and e-mail address listed above. A hard copy of the processed data will also be available in Piratheepan (2002). In addition, the entire data set compiled by the U.S. Geological Survey from testing Oakland and Alameda, California, is available from Dr. Thomas Holzer. Dr. Holzer can be reached at 650-329-5637 and by e-mail at tholzer@usgs.gov.

References

Hegazy, Y.A., and Mayne, P.W. (1995), "Statistical correlations between V_S and cone penetration data for different soil types," *International Symposium on Cone Penetration Testing, Linkoping*, Sweden, October 4-5, 173-178.

Robertson, P.K. (1990), "Soil classification using the cone penetration test," *Canadian Geotechnical Journal*, 27, 151-158.

Robertson, P.K., and Wride, C.E. (1998), "Evaluating cyclic liquefaction potential using the cone penetration test," *Canadian Geotechnical Journal*, 35, 442-459.

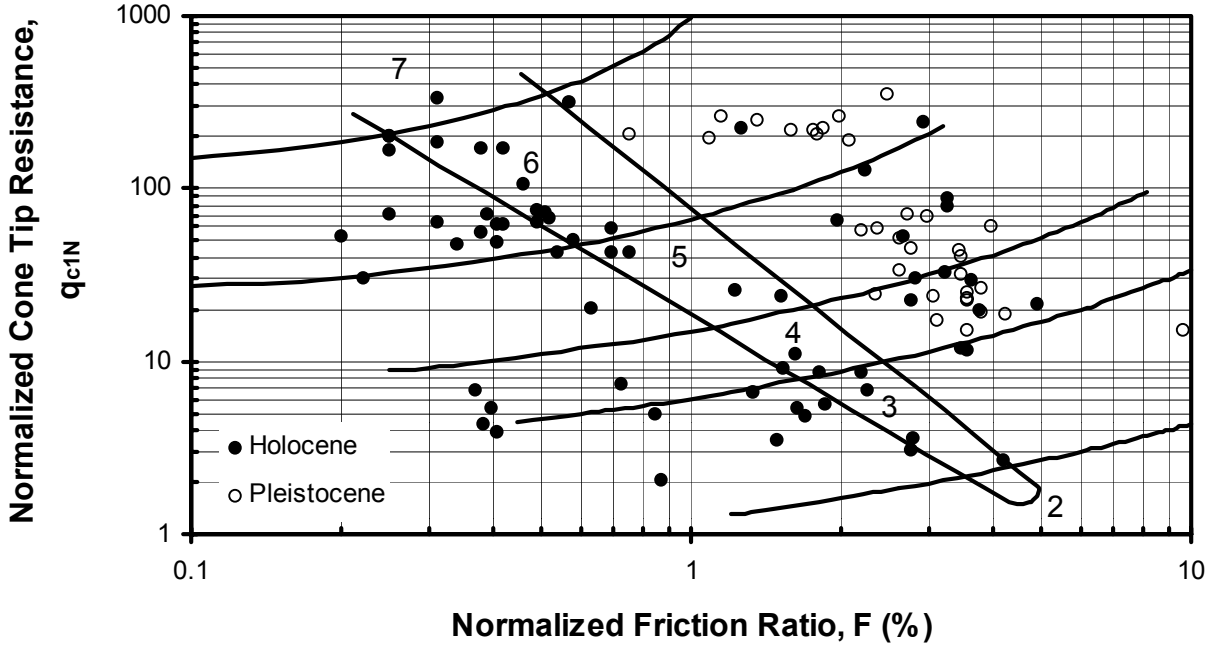

Figure 1. Soil behavior type chart by Robertson (1990) with data compiled for this study.

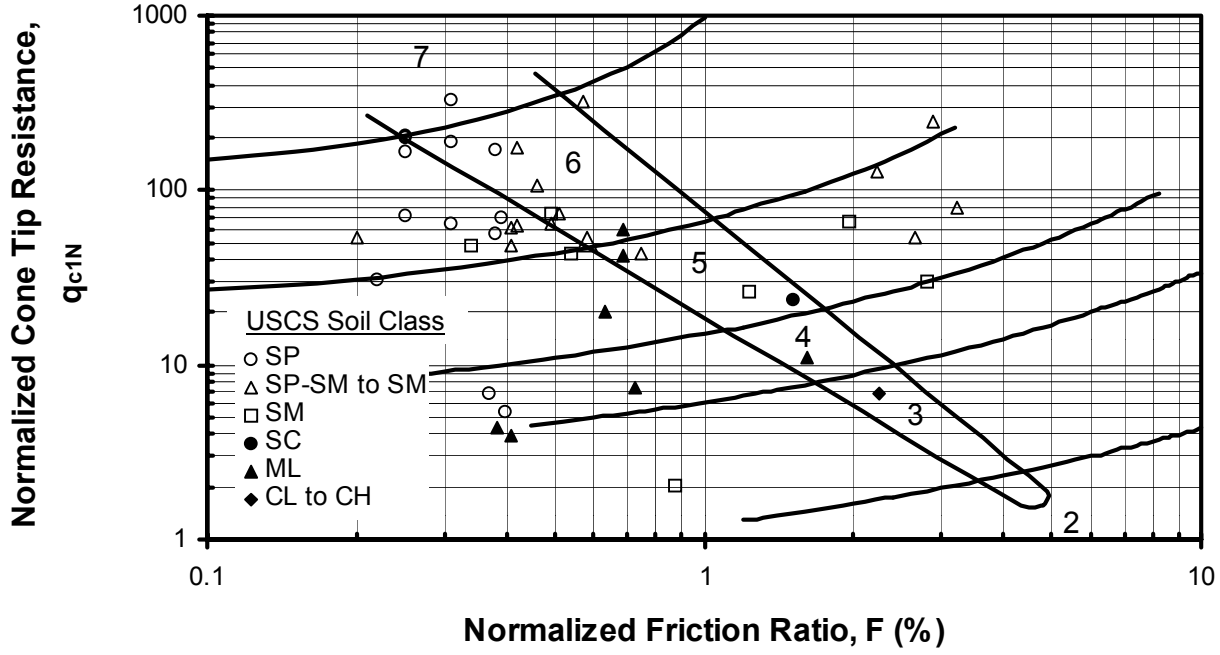

Figure 2. Soil behavior type chart by Robertson (1990) with data compiled for this study of known USCS soil class.

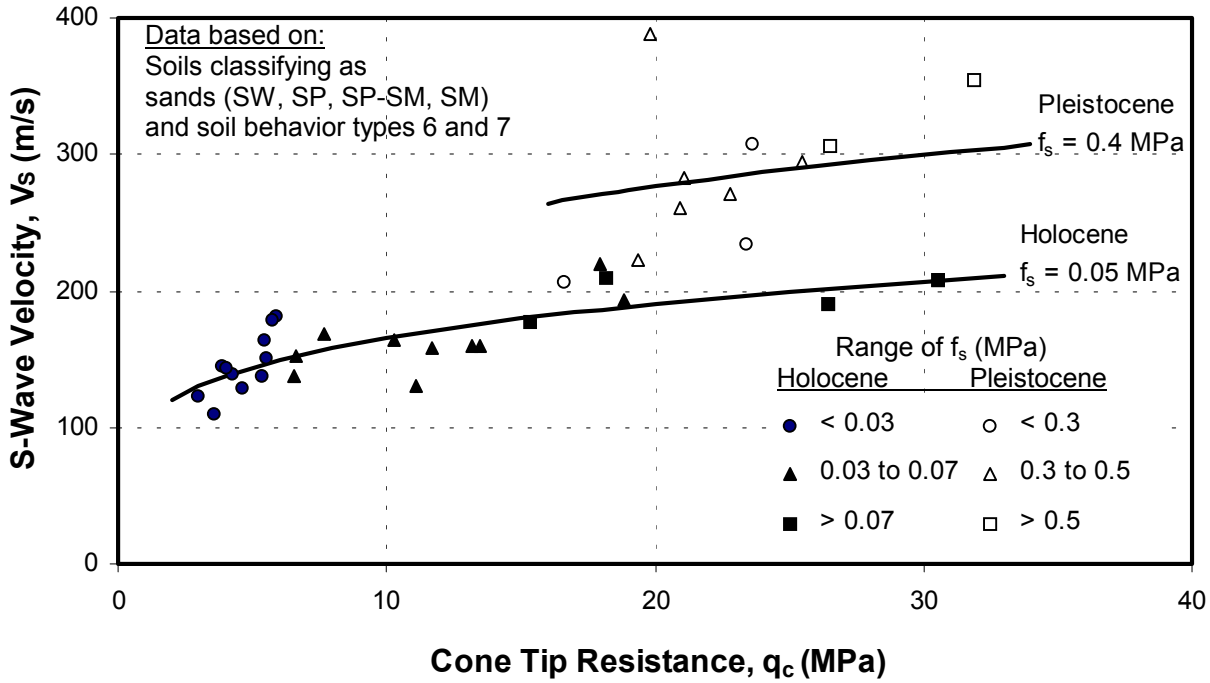

Figure 3. Preliminary correlations between uncorrected V_S and q_c proposed in this study for sands along with compiled data.

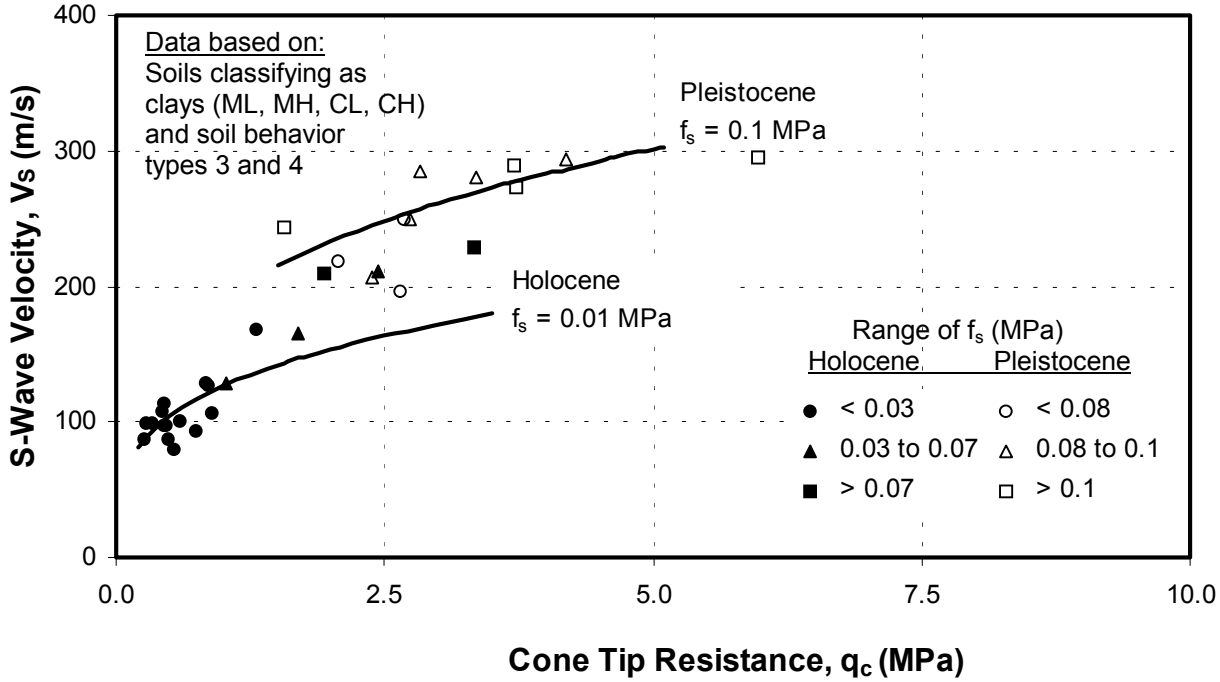

Figure 4. Preliminary correlations between uncorrected V_S and q_c proposed in this study for clays along with compiled data.

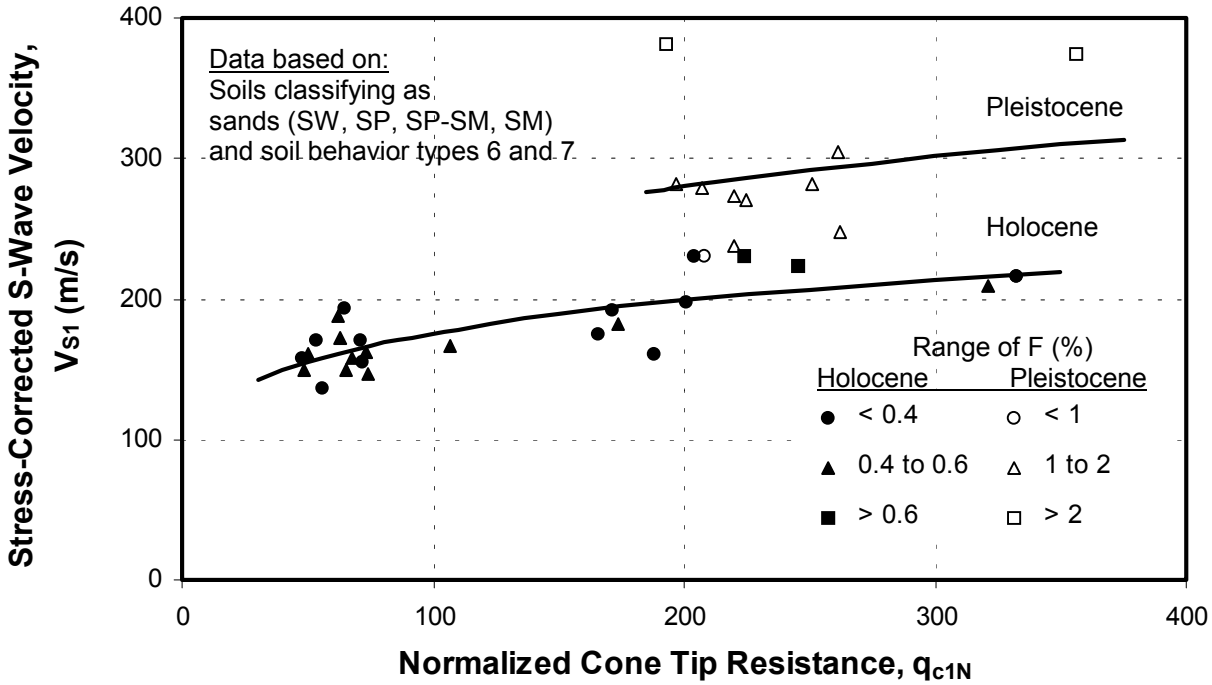

Figure 5. Preliminary correlations between stress-corrected V_S and normalized q_c proposed in this study for sands along with compiled data.

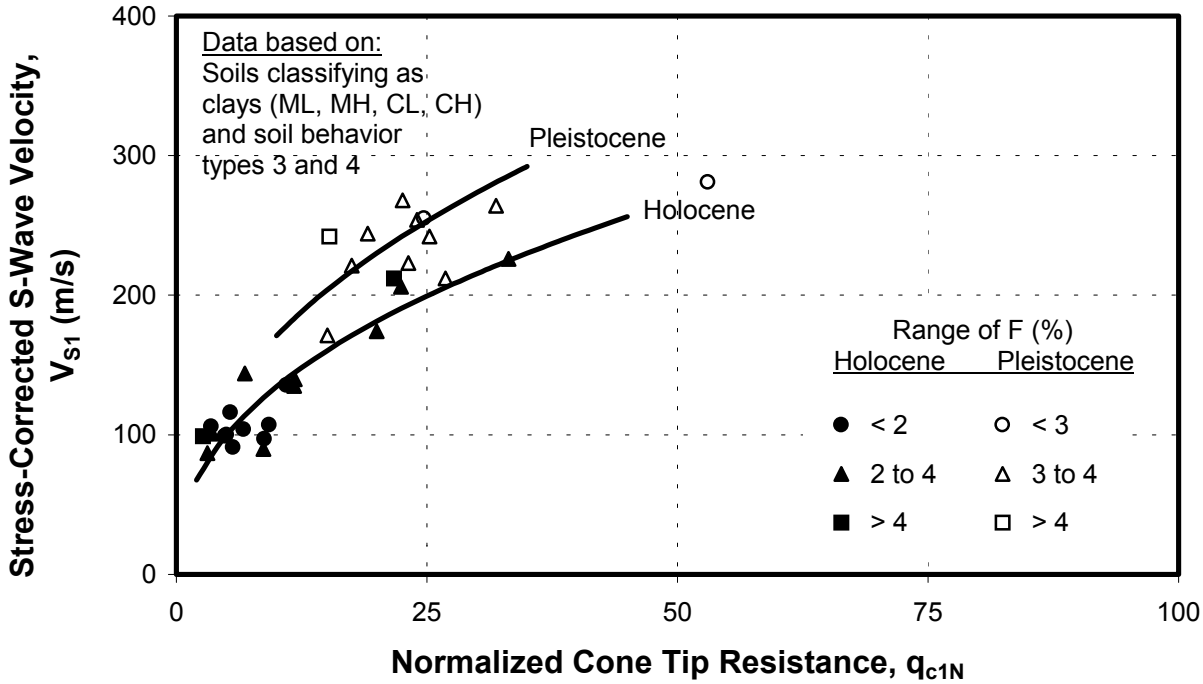

Figure 6. Preliminary correlations between stress-corrected V_S and normalized q_c proposed in this study for clays along with compiled data.