CPT Stress Normalization and Prediction of Soil Classification

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SYNOPSIS: An updated CPT soil classification chart is presented based on a new cone penetration resistance normalization technique. This chart was developed using a very large database of CPT/boring data together with an improved understanding of how to predict soil strength. The new normalization technique is based on the Stress Focus concept. The Stress Focus is an in situ point at a vertical effective stress in the range of approximately 100 to 300 atm (10 to 30 MPa) where sand densities and strength have values independent of the initial relative density at lower stress states. As a result, the trends of cone resistance (for different relative densities) with vertical effective stress can be described using an variable stress exponent.

1. INTRODUCTION

The CPT soil characterization chart shown in Figure 1 was developed in 1987 using a limited CPT/boring database (Olsen and Malone, 1988). The soil type boundaries, word descriptions, and Soil Classification Number (SCN) concept from this chart have been used by numerous writers over the last seven years (Robertson, 1990, ARA, 1992, etc.,). The Stress Focus concept, to be presented in this paper, describes how cone resistance is exponentially related to by vertical effective stress. The Stress Focus concept was deduced from the results of high pressure tests, CPT/SPT chamber tests, and field CPT tests in uniform in situ soil layers. It provides the basics for a new comprehensive stress normalization technique using CPT data. A new CPT soil characterization chart is also presented based on the new stress normalization technique, a much larger database of CPT/boring data, and finally a better ability to predict soil strength.

2. THE STRESS FOCUS

The basis of the new stress normalization concept is the observation that sand has the same strength at very high pressures (the Stress Focus) irrespective of the initial relative density. The Stress Focus is a unique point which occurs at a vertical effective stress between 100 atm (10 MPa or 100 tsf) and 300 atm (30 MPA) as shown in Figure 2. It is because a given sand compresses to the same density and strength (at the Stress Focus) from all initial states.

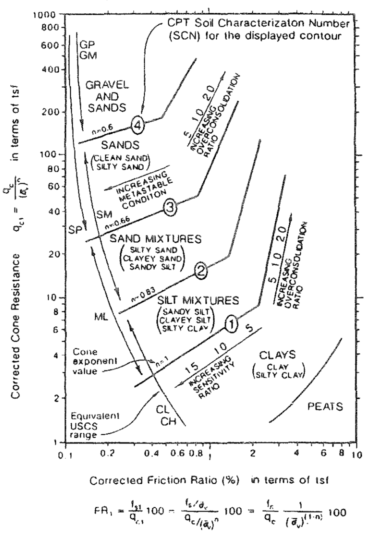

Figure 1. The 1987 CPT Soil Characterization Chart (Olsen, 1988)

Failure envelope curvature reduces available strength with increased confining stress until the Stress Focus is achieved. At the Stress Focus, all initial relative densities have an available friction angle equal to that of initially loose sand at high confining stress.

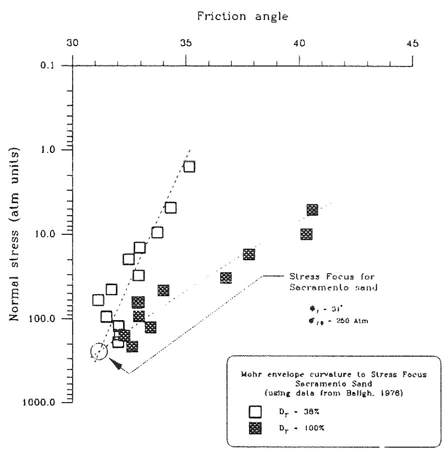

Figure 2. Strength decrease to the Stress Focus for Sacramento sand in terms of friction angle and overburden stress (Olsen, 1994) (data from Baligh, 1976)

The CPT calibration chamber trends shown in Figure 3 were established by Baldi, Bellotti, Ghionna, Jamiolkowski, and Pasqualini (1981) based on many CPT chamber test results. When these curves were replotted, using log scales as shown in Figure 4, they pointed to a Stress Focus. These same trends were also demonstrated using individual relative density chamber tests at various overburden stresses (Olsen, 1994). The cone resistance versus stress curves trending to a Stress Focus is caused by failure envelope curvature and cavity expansion effects.

The normalized cone resistance, q_{c1e}, (Olsen, 1994) is defined by Equation 1 and can be used to describe the non-linear trend of cone resistance with vertical effective stress to the Stress Focus.

$$q_{c1e} = \frac{q_c - \sigma_{total}}{\left(\sigma'_v\right)^c} = \frac{\left(q_c\right)_{net}}{\left(\sigma'_v\right)^c} \qquad (1)$$

where

σ'_v = Vertical effective stress (atm units)
q_c = Measured cone Resistance (atm units)
q_{c1e} = Normalized cone resistance
σ_{total} = Total vertical stress (atm units)
c = Cone resistance stress exponent

The normalized cone resistance, q_{c1e}, has a 1 subscript to represent normalization to one atmospheric (100 KPa) vertical effective pressure ; the e subscript signifies that a variable stress exponent (based on the Stress Focus concept) was used for normalization.

The CPT cone resistance Stress Focus can now be generalized as shown in Figure 5 (Olsen, 1994). CPT soundings start penetration by failing the surfical soil using shallow bearing capacity failure. At the critical depth boundary, penetration is controlled by compression and cavity expansion. Surface expression failure can be defined by limit equilibrium theories (Terzaghi 1943, Durgunoglu & Mitchell, 1975) and have a linear relationship between bearing stress and vertical effective stress. Cavity expansion can be expressed as an exponential

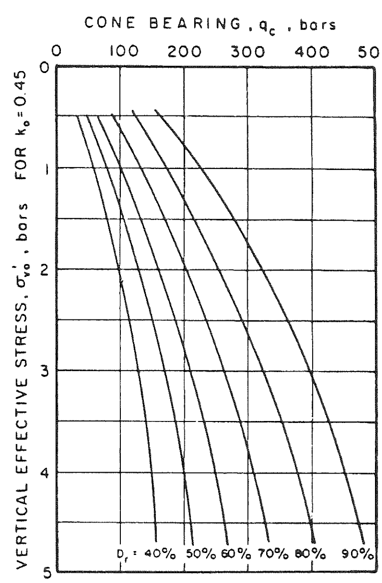

Figure 3. Trends of cone resistance versus effective stress for Ticino sand (Baldi, Bellotti, Ghionna, Jamiolkowski, and Pasqualini, 1981)

relationship between bearing stress and vertical effective stress. The cone resistance stress exponent, c, decreases as the sand relative density increases (Olsen, 1994) and can be estimated as shown below using the relative density (D_r);

$$c = 1 - \left(D_r - 10\%\right)0.007 \qquad (2)$$

The cone resistance at the Stress Focus is q_{cf} and the vertical effective stress at the Stress Focus is σ'_{fc}. The Stress Focus location (q_{cf} and σ'_{fc}) is soil type dependent; both parameters decrease as the soil type changes from sand to clay (Olsen, 1994).

3. PREDICTION OF THE STRESS EXPONENT USING THE CPT

Data from uniform in situ layers allowed establishment of cone resistance stress exponent contours on the CPT soil characterization chart (Olsen, 1994). An example of one such uniform layer is shown in Figure 6 together with the computer displayed q_{c1e} (equivalent q_c at σ'_v=1 atm), c (log-log slope), and soil layer limits from the database. The stress exponent, c, is equal to the linear chart measured slope over one log vertical effective stress cycle. A stress exponent of 0 corresponds to a vertical line, while a exponent of 1 (linear scale) represents a line with a slope of one horizontal log scale to one vertical log scale. Normalized sleeve friction resistance parameters (f_{s1e} and s) for each uniform soil layer were also required to assign values to the CPT soil characterization chart. However; the sleeve is the more difficult of the two measurements. Data from several uniform soil layers could not be used because normalized sleeve friction parameters could not be established with adequate confidence.

Nonetheless, approximately 65 excellent uniform layers (from 240 potential uniform soil layers) were available to establish contours of cone resistance stress exponent, c, on the CPT soil characterization chart (Figure 7). In situ data points having the highest level of confidence were given most weight during establishment of the contours. Chamber test exponent trends were also used as a guide during establishment of exponent contours.

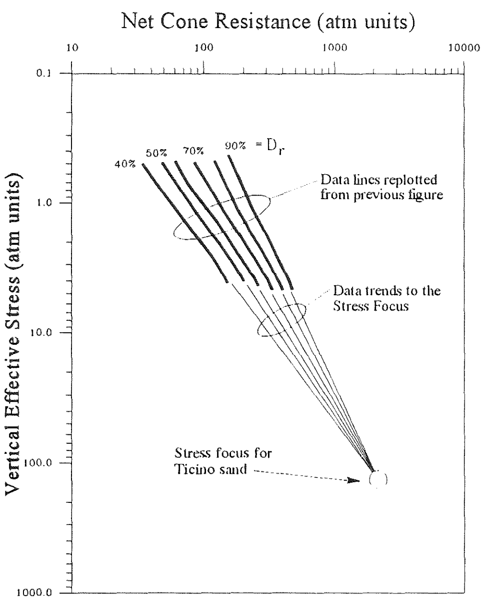

Figure 4. Replotting of Baldi, et.al., 1981 data curves in terms of $\log_{10}$ net cone resistance versus Log_{10} vertical effective stress

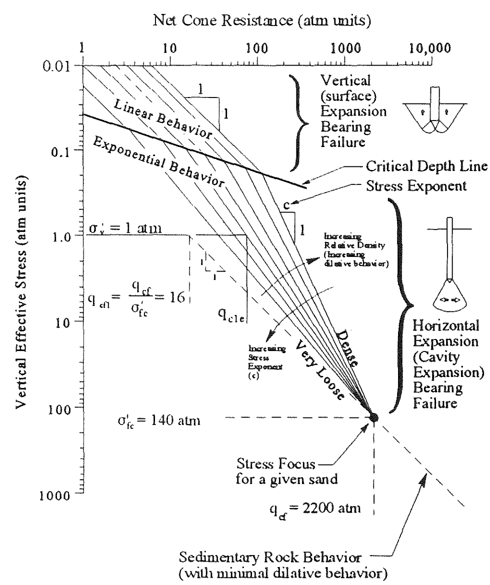

Figure 5. Annotated description of the cone resistance Stress Focus together with bearing stress partitioned into surface bearing capacity failure and cavity expansion failure (Olsen, 1994)

The cone resistance stress exponent contours in Figure 7 exhibit several predictable trends; 1) high values for loose sands, 2) very low values for over consolidated sands, 3) values of approximately 1.0 (and slightly lower) for normally consolidated clays, 4) values slightly below unity (i.e., 0.75 to 0.9) for slightly over consolidated clays, and 5) values as high as 1.2 for unstable silty clay mixtures. These stress exponent contours are used to determine the stress exponent for normalization of the cone resistance (Equation 1). However, an iterative solution is required. Initially, a stress exponent is assumed for Equation 1; the resulting q_{c1e} and calculated friction ratio are used to determine the chart-based contour stress exponent from Figure 7. If, the chart-based stress exponent does not equal the assumed stress exponent; a new assumed value must be tried. Approximately 3 to 9 iterations are usually required until the chart-based value is sufficiently close to the assumed value (Olsen, 1986, 1988, 1994).

A vertical effective stress of one atmosphere typically occurs at a depth of 7 to 10 metres (23 to 33 feet) where the measured values of q_c, f_s, V_s, SPT are approximately equal to their normalized values, q_{c1e}, f_{s1e}, V_{s1}, N_1. However; near the ground surface (i.e. 1 metres), and at great depth (i.e. 40 metres), use of an improper stress normalization technique will yield incorrect normalized values by a factor greater than two. This procedure (Olsen, 1994) represents the most advanced available normalization technique. However, the use of a constant stress exponent (i.e. 0.61) for normalization can be justified for general investigations within the depth range of 4 to 12 metres.

4. THE NEW CPT SOIL CHARACTERIZATION CHART

The new CPT soil characterization chart in Figure 8 is a significant improvement over the 1988 version (Figure 1) for three reasons: 1) an improved stress normalization has been developed, 2) a larger CPT/boring database (by a factor of 5) is available, and 3) an improved understanding of how to predict strength has been developed (Olsen, 1994).

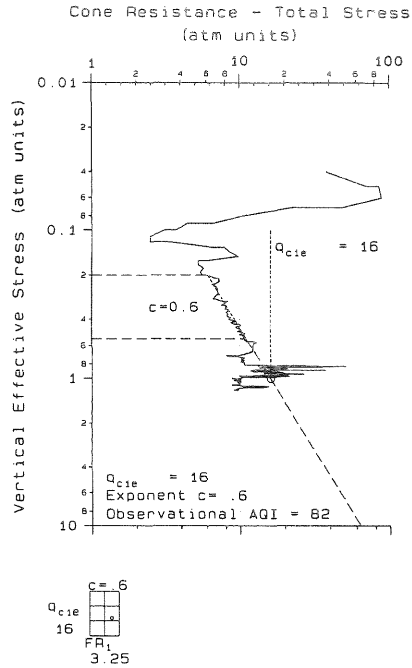

Figure 6. Uniform silty clay layer in the Aftchafalya River (Dredging study)

CPT predicted strength contours on the CPT soil characterization chart allowed improved positioning of the soil classification contours. The stress exponent, c, for sand (see Figure 5) is a better descriptor of strength than relative density. Relative density is a poor strength index because it's highly dependent on the testing procedure and does not account for the stress state. Stress exponent contours on the CPT soil characterization chart are shown in Figure 7 and 8. CPT-predicted contours of normalized undrained strength for clay (Olsen, 1994) also have the same shape as the stress exponent contours within the clay portion of the soil classification chart. This is additional verification that the stress exponent is a strength index. Any soil type (at σ'_v=1 atm) will have a known range of strengths and likewise, each CPT soil classification zone must also have a range of normalized strengths. Strength contours therefore cannot be parallel to soil classification contours and as a result should be approximately perpendicular. CPT soil classification contours should therefore be

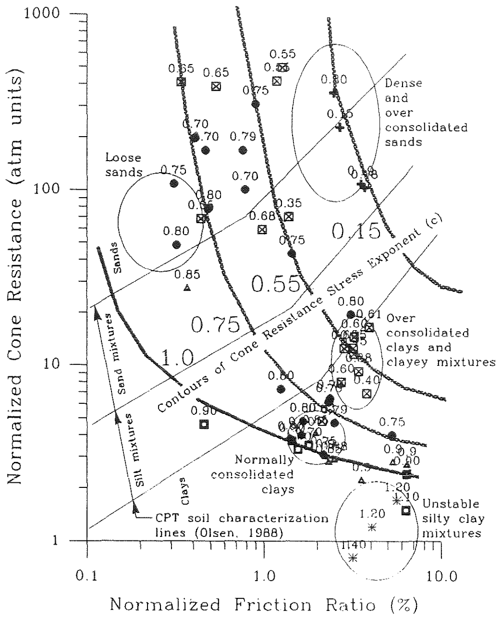

Figure 7. Contours of cone resistance stress exponent based on data from in situ uniform soil layers with constant relative strength (i.e. constant sand friction angle or constant clay c/p ratio) (Olsen, 1994)

approximately perpendicular to normalized strength contours

The CPT Soil Classification Number (SCN) (Olsen, 1988) scaling on the CPT soil characterization chart (see Figure 1) has been changed to improve SCN understanding; SCN=0 now represents a pure silt, SCN=1 represents a fine sand or low silt content silty sand, and finally SCN= -1 represents the boundary between silty clay and clayey silt. As a result, SCN's greater than 1 represent sand and SCN's less than -1 represent clay. The boundary between normally consolidated and over consolidated are also shown in Figure 8 together with trends for increasing over consolidation. Soil classification descriptions are also shown near SCN boundaries. Cone resistance stress exponent contours (from Figure 7) are also included for use with Equation 1.

5. CONCLUSIONS

The Stress Focus concept provides the basis for a new CPT cone resistance stress normalization technique. This technique takes into account the fact that the cone resistance is exponentially effected by vertical effective stress (as observed in CPT chamber tests). Evaluation of data from uniform in situ soil layers provided the comprehensive correlations required for prediction of the stress exponent when using field CPT data. An updated CPT soil characterization chart was developed based on the improved stress normalization concept, a larger database of CPT/boring data, and better tools for prediction of strength.

6. REFERENCES

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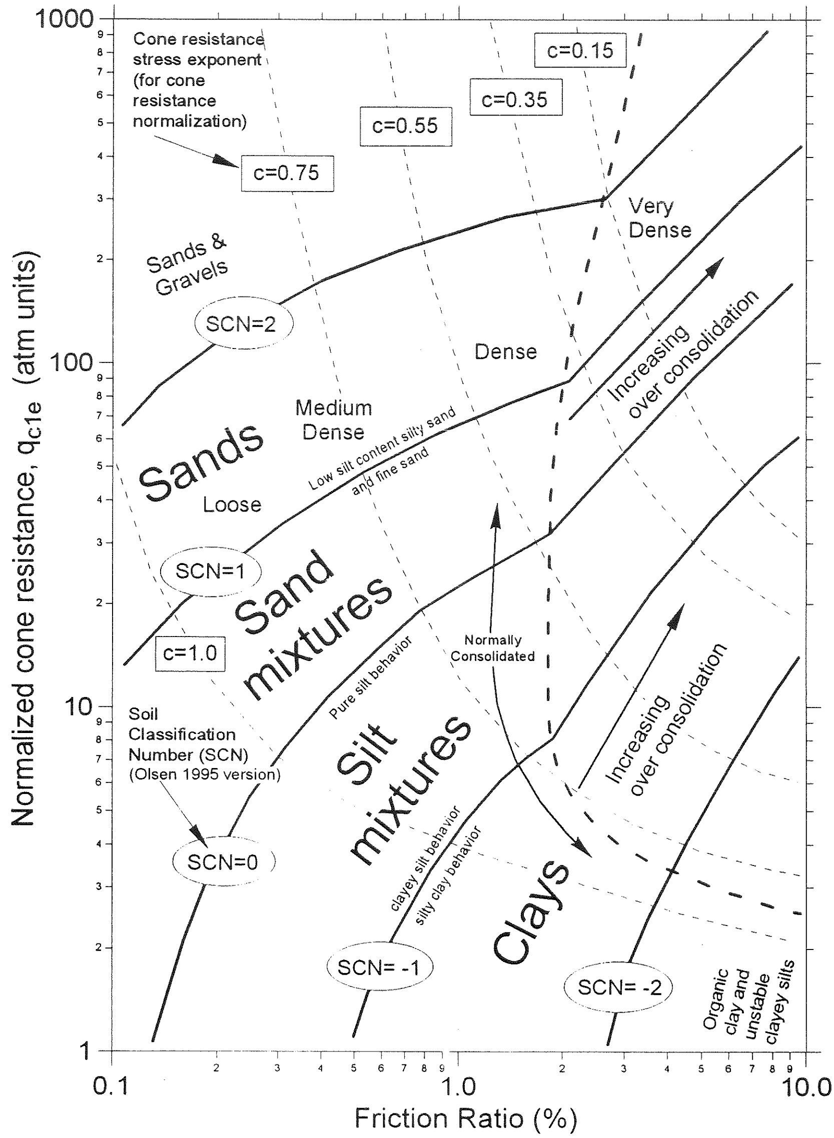

Figure 8. Updated CPT soil charaterization chart developed using a better understanding of stress effects, a larger CPT/boring database and based on improved techniques for prediction of soil strength.