Estimating soil unit weight from CPT

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ABSTRACT: With increasing use of computer software to aid in the interpretation of CPT results, it is common to calculate overburden stresses based on estimated soil unit weights. There are existing methods to estimate soil unit weight based on soil behavior type (SBT) derived from CPT results. Methods have also been developed to estimate soil unit weight using shear wave velocity and DMT results. Using links between shear wave velocity and CPT results, as well as links between CPT and DMT results, a new correlation is proposed to estimate soil unit weight based directly on CPT results (q_t and f_s). The resulting correlation is evaluated using published case records and appears to provide reasonable estimates of soil unit weight.

1 INTRODUCTION

The total unit weight (γ) of each soil layer is required to estimate the overburden stress. Correct evaluation of total and effective overburden stresses is important in many correlations between Cone Penetration Test (CPT) results and geotechnical parameters. In particular, for CPT in soft clays soils, a reliable assessment of unit weight is critical for the correct evaluation of net cone resistance. The unit weight is best measured by obtaining undisturbed samples. However, for many soils and for low risk projects, it can be difficult and costly to obtain undisturbed samples in all soil layers. An alternate approach is to estimate the soil unit weight directly from CPT results.

The objective of this paper is to present a new correlation between soil unit weight and CPT results to aid in efficient CPT data processing and interpretation. The correlation is evaluated using published case records.

2 EXISTING RELATIONSHIPS

Larsson & Mulabdić (1991) developed a chart for Swedish clays based on net cone resistance (q_t-σ_{vo}) and normalized pore pressure [$B_q = (u_2-u_0)/(q_t-\sigma_{vo})$]. Lunne et al (1997) suggested a method to estimate soil unit weight based on soil behaviour type (SBT) using the non-normalized CPT charts proposed by Robertson et al (1986). The Lunne et al (1997) values are shown in Table 1. Although the Lunne et al (1997) method provides reasonable values for soil unit weight, the SBT zones cover a wide range of soil density and therefore do not fully capture the change in soil unit weight due to variations in soil density.

Table 1. Approximate soil unit weight (γ) based on soil behaviour type (after Lunne et al., 1997)

Soil Behaviour Type (SBT)*	Approximate unit weight, γ (kN/m^3)
1	17.5
2	12.5
3	17.5
4	18.0
5	18.0
6	18.0
7	18.5
8	19.0
9	19.5
10	20.0
11	20.5
12	19.0

*SBT based on charts by Robertson et al., (1986)

Mayne (2007) showed that soil unit weight changes with both corrected cone resistance (q_t) and sleeve friction (f_s) and suggested a correlation between soil dry unit weight and normalized cone resistance for uncemented, unaged quartz to siliceous sands. However, Mayne (2007) cautioned that the correlation was a modest one and was a function of mineralogy and cementation. Mayne (2007) suggested that the best correlation was between soil unit weight and normalized shear wave velocity, V_{s1}, as follows:

$$\gamma = 4.17 \ln(V_{s1}) - 4.03 \qquad (1)$$

where $V_{s1} = V_s (p_a/\sigma'_{vo})^{0.25}$
σ'_{vo} = in-situ effective vertical stress
p_a = atmospheric pressure in same units as σ'_{vo}

An initial value of γ is assumed in order to start the process, since effective overburden stress (σ'_{vo}) depends on γ.

Equation 1 has the disadvantage that it requires the measurement of shear wave velocity (V_s) and requires some iteration. Recently, Robertson (2009a) presented an updated correlation between normalized CPT results and normalized shear wave velocity for a wide range of soils. Although direct measurement of V_s is preferred over estimates, relationships with cone measurements are useful for smaller low risk projects, where V_s measurements are not always taken.

Marchetti (1980) suggested that soil unit weight could be estimated from DMT results using a combination of DMT I_D and E_D. For a given soil type (based on I_D), soil unit weight increases with increasing E_D. Following the example of Marchetti (1980), for a given soil type (based on CPT friction ratio, R_f), soil unit weight should increase with increasing cone resistance, q_t. Robertson (2009b) suggested a correlation between CPT and DMT results, such that it is possible to link the Marchetti (1980) correlation between DMT results and soil unit weights with CPT results.

3 PROPOSED NEW CORRELATION

By combining recent experience and correlations between shear wave velocity and soil unit weight (Mayne, 2007), as well as DMT results and soil unit weight (Marchetti, 1980) and simplifying, it is possible to develop approximate contours of soil unit weight in terms of dimensionless CPT cone resistance (q_t/p_a) and friction ratio ($R_f = (f_s/q_t)100$), where p_a is atmospheric pressure in the same units as the corrected cone resistance. The resulting simplified correlation between soil unit weight and CPT results is shown on Figure 1.

Figure 1 allows an estimate of soil unit weight based only on CPT direct measurements, q_t (or q_c) and f_s. The chart has been made dimensionless by using (q_t/p_a) and γ/γ_w, where γ_w is the unit weight of water in same units as γ. The contours on Figure 1 show the correct trend of increasing soil unit weight with increasing cone resistance and sleeve friction values, as suggested by Mayne (2007). Included on Figure 1 are the approximate SBT boundaries used by Robertson et al. (1986) to illustrate how the soil unit weight can vary within a SBT zone.

The contours of soil unit weight shown in Figure 1 can be approximated using the following simplified equation:

$$\gamma/\gamma_w = 0.27 [\log R_f] + 0.36 [\log(q_t/p_a)] + 1.236 \qquad (2)$$

Where R_f = friction ratio = $(f_s/q_t)100$ %
γ_w = unit weight of water in same units as γ
p_a = atmospheric pressure in same units as q_t

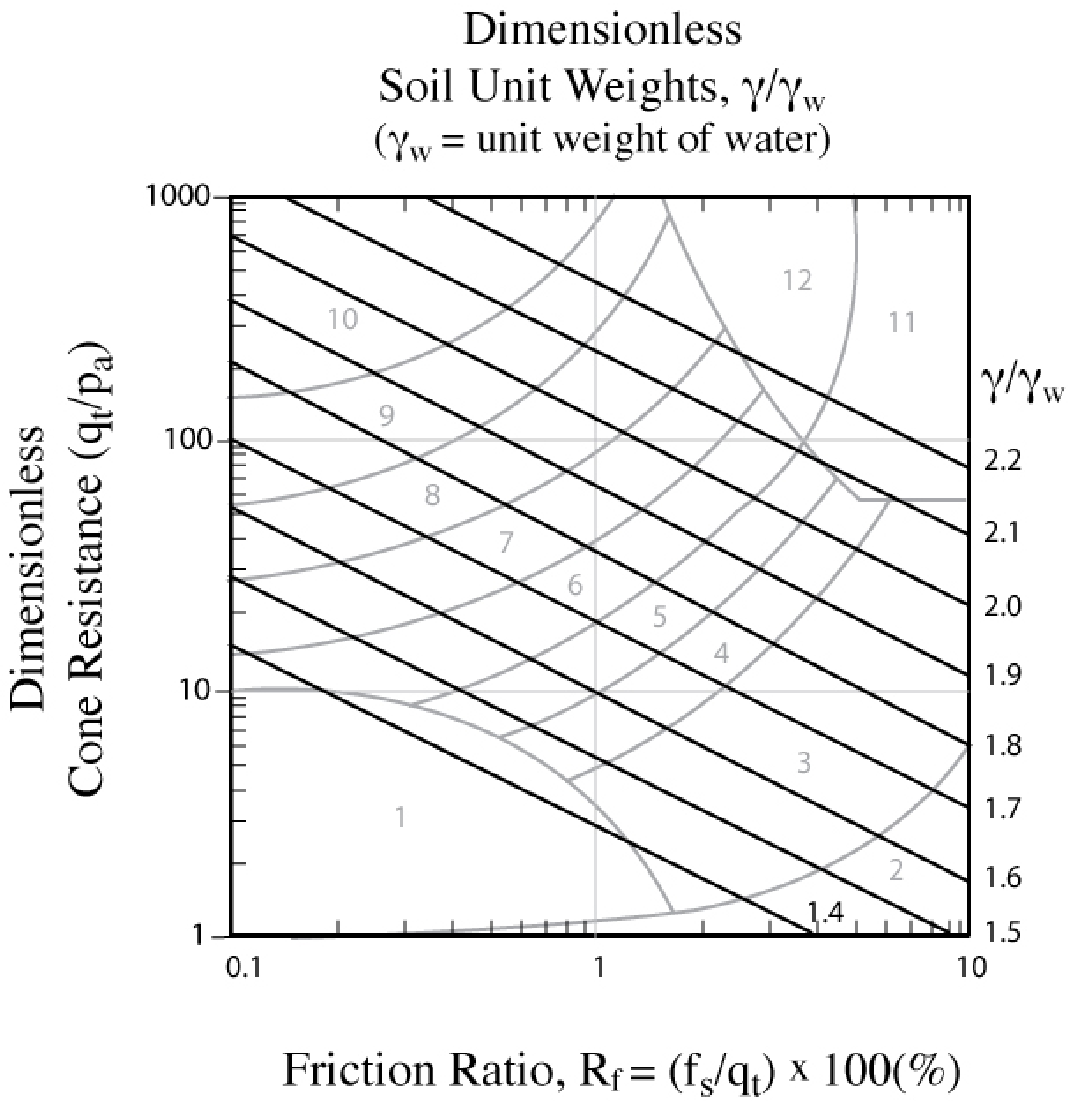

Figure 1 Proposed relationship between CPT results and soil unit weight

The average specific gravity (G_s) for most soils is in the range 2.6 to 2.7. However, some soils can have specific gravity values outside this range, which would influence the suggested average correlation shown in Figure 1 and equation 2. If disturbed samples are available and specific gravity values obtained, the relationship can be modified to the more general form:

$$\gamma/\gamma_w = [0.27\ [\log R_f] + 0.36\ [\log(q_t/p_a)] + 1.236]\ G_s/2.65 \qquad (3)$$

4 COMPARISON WITH PUBLISHED RECORDS

Data have been collected from sites around the world where CPT results and average soil unit weights have been published and/or were available. A summary of the data is presented in Table 2.

Table 2. Published records for CPT and soil unit weights

No.	Site Name	Soil	Depth Range (m)	Dimensionless Unit Weight γ/γ_w	CPT Range q_t/p_a	CPT Range R_f (%)
1a	McDonald's Farm, Canada	Deltaic sand	5 - 12	1.7 – 1.9	40 – 120	0.3 – 0.6
1b	McDonald's Farm, Canada	Soft silty clay	17 - 30	1.5 – 1.6	7 – 12	1.5 - 2.5
2	Bothkennar, UK	Soft clay	3 - 15	1.6 – 1.7	3 - 10	1.0 – 2.0
3	Amherst, USA	Soft varved sensitive clay	6 – 10	1.6 – 1.7	5 – 7	1.0 – 1.5
4	Ford Center, IL, USA	Soft glacial clay	7 - 16	2.0*	8 - 15	1.3– 1.7
5a	Venice Lagoon, Italy	Medium dense sand	4 - 5	1.8	30 – 50	0.3 – 0.5
5b	Venice Lagoon, Italy	Soft clayey silt	29 - 30	1.8	20	2.0 – 3.0
6	Burswood, Perth	Soft clay	3 – 15	1.5	1.5 – 5	1.0 – 3.0
7	Baton Rouge, USA	Stiff fissured clay	10 – 30	1.9	20 – 40	1.5 – 3.5
8	Georgia Pied-mont, USA	Stiff silty sand to sandy silt – residual soil	4 – 12	1.6 – 1.8	30 – 55	1.4 – 2.2
9	Cooper Marl, USA	Stiff ce-mented silt	20 - 30	1.8	20 – 50	0.6 – 1.2
10	Bangkok, Thail-and	Soft clay	4 – 8	1.5 – 1.7	3 - 4	2.5 – 3.0
11	Cowden, UK	Very stiff clay	4 – 10	1.8 – 1.9	20 – 25	1.5 – 2.5
12	Brent Cross, UK	Very stiff clay	2 – 10	1.8 – 1.9	15 - 30	2.0 – 2.5
13	Madingley, UK	Very stiff clay	2 - 12	1.9 – 2.0	15 - 40	3.5 – 6.0
14	Pisa Clay, Italy	Sensitive clay	12 - 20	1.7 – 1.8	11 –1 7	1.0 – 1.5
15	UNCC, Florida, USA	Sand to silty sand	3 - 5	1.8 - 1.9	50 - 100	0.4 – 0.7
16	CANLEX, Cana-da	Loose sands	3 - 37	1.6 – 1.8	15 – 90	0.3 – 1.0
17	Onsoy, Norway	Sensitive clay	2 - 20	1.5 – 1.6	3 – 10	1.0 – 3.0
18	Holmen, Norway	Loose sand	5 - 20	1.7 – 1.8	20 - 50	0.3 – 0.6

*Specific Gravity, G_s = 2.80

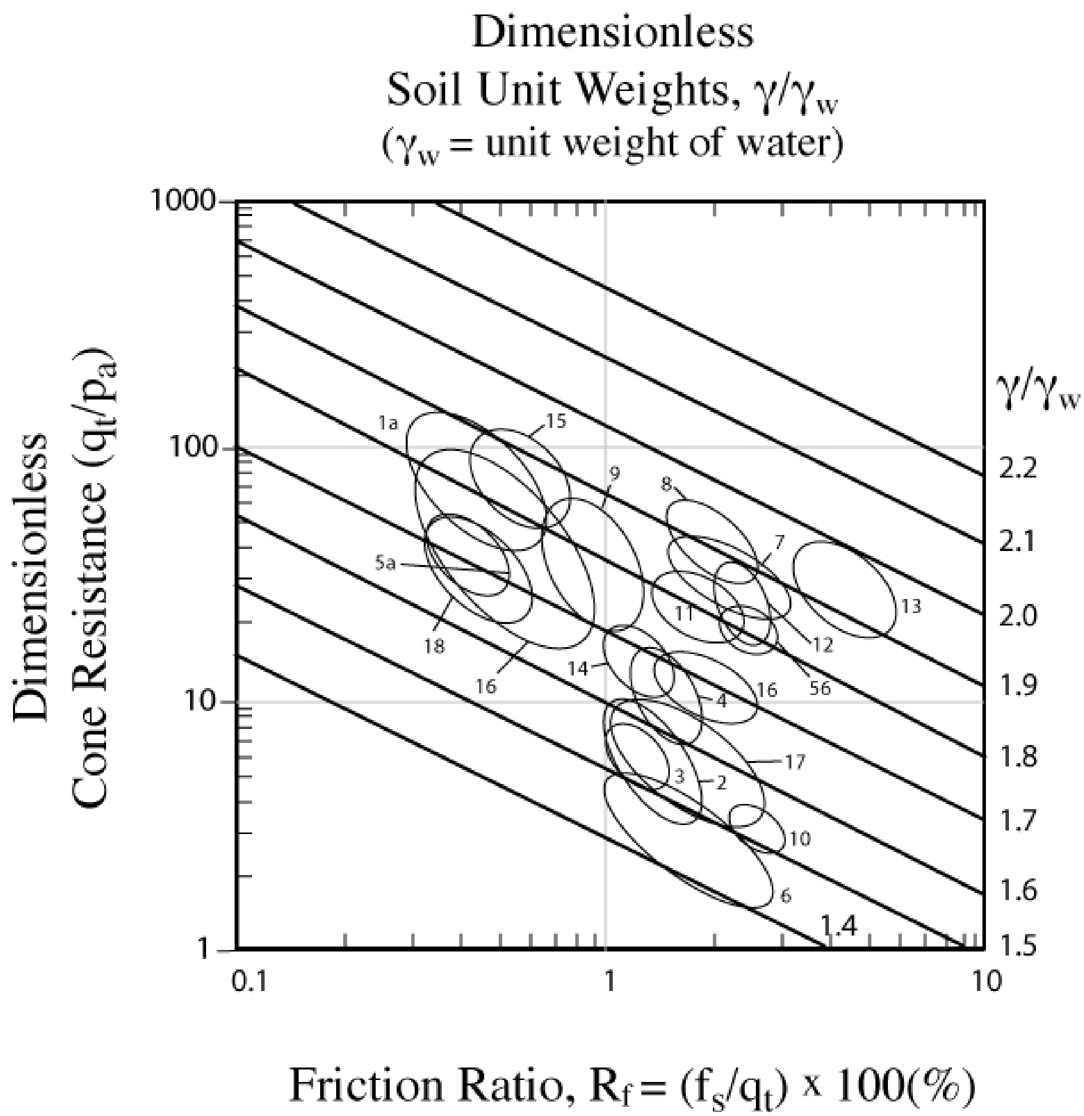

Figure 2. Published records of sites with soil unit weights (see Table 2 for sites)

Figure 2 shows the published records of CPT values over the suggested contours of soil unit weight. The CPT results from the published sites cover a wide range of soils from sands to soft clays, where $1.5 < q_t/p_a$, 120 and $0.3\% < R_f < 6\%$ and $1.5 < \gamma/\gamma_w < 2.0$.

In general, soil unit weight values were obtained from samples in nearby boreholes. Although individual values at each depth within a profile could be presented, the plots become crowded and confusing with many data points. Comparison between individual values from nearby profiles at the same depth often show considerable scatter due to variations in soil stratigraphy and consistency since many sites are not uniform. Hence, adjacent data from the same depth may not always represent the same soil. When there are a large number of sites for comparison it is common to compare values obtained at the same depth within relatively uniform sections of a deposit. Sand deposits tend to be highly variable in consistency (e.g. relative density and grain characteristics) and plots of individual data points from nearby in-situ tests can show large scatter. To simplify the presentation of comparison data a range of values are shown that represent the approximate average values within each relatively uniform section of a deposit. Some sites have more than one relatively uniform deposit within the profile and these are represented by a set of values for each uniform deposit. Presentation of average values also aids in the inclusion of published records where digital results were not available and where only estimates of average values were made from published plots. Figure 3 compares the measured soil unit weights with those estimated using equation 2. In general, the comparison is good.

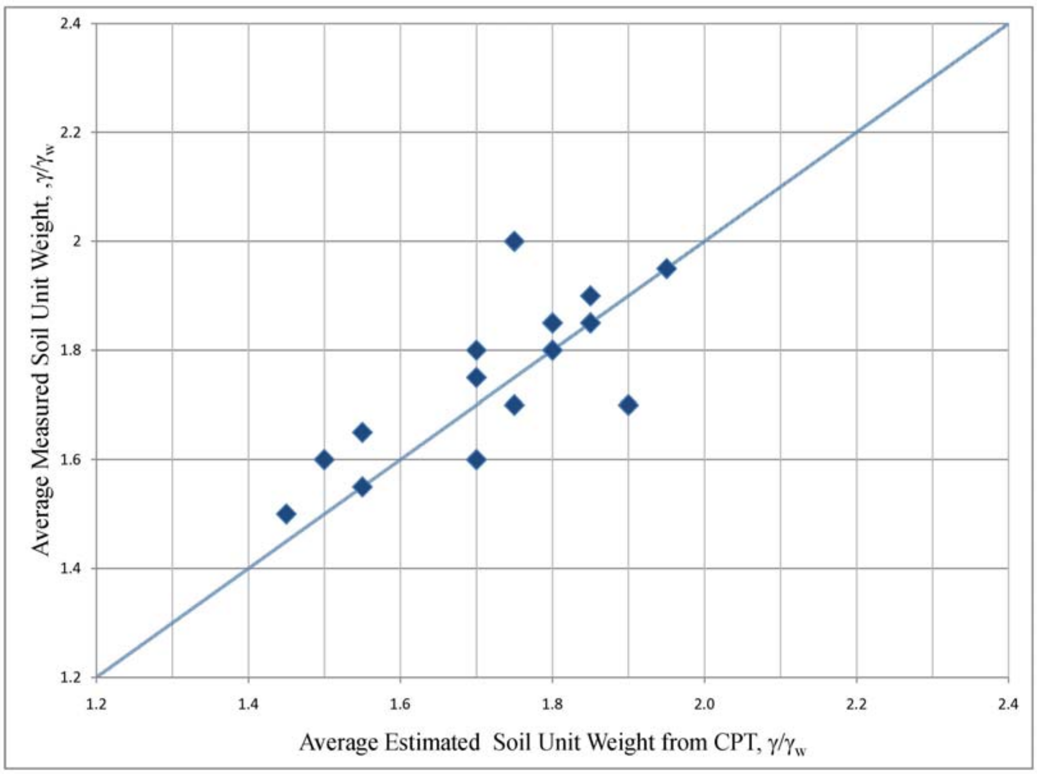

Figure 3. Comparison between measured and CPT-estimated soil unit weights

5 SUMMARY

With increasing use of computer software to aid in the interpretation of CPT results, it is common to calculate overburden stresses based on estimated soil unit weights. Using existing links between shear wave velocity and CPT results, as well as links between CPT and DMT results a new correlation is proposed to estimate soil unit weight based directly on CPT results (q_t and f_s). The resulting correlation is evaluated using published case records and appears to provide reasonable estimates of soil unit weight.

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