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Soil unit weight estimation from CPTs

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ABSTRACT: Soil unit weight is needed during the post-processing of CPT data in order to calculate total and effective vertical overburden stresses, net cone resistance (q_t-σ_{vo}) for the evaluation of undrained shear strength and modulus, as well as the normalized parameters (Q_t, F_r, and B_q) used in soil behavioral type classification systems. A compiled database from documented field test sites in a variety of soil types was used to explore and develop direct relationships between measured unit weights and CPT readings. A consistent trend emerged for total unit weight in terms of sleeve friction and effective overburden stress.

1 INTRODUCTION

An initial step in geotechnical analyses is the calculation of the initial geostatic stress conditions, including overburden stress: The total overburden stress (σ_{vo}) is calculated from the accumulation of total soil unit weights (γ_t) with depth according to:

$$\sigma_{vo} = \int \gamma_t \ dz \tag{1}$$

The total overburden stress is of critical importance as it determines the effective vertical overburden stress ($\sigma_{vo}' = \sigma_{vo} - u_0$), as well as the interpretation of many other geotechnical parameters (e.g., K_0, OCR, ϕ', G, D', ...) from the CPTu data (Mayne, 2007a, b). In particular, for soundings advanced into soft clays and silts, a reliable assessment of unit weight is critical for the proper evaluation of the net cone resistance. Obtaining unit weight directly and reliably from CPT measurements has obvious advantages and would fit requirements for efficient, safe and sustainable geotechnical practice, when compared to undisturbed sampling and laboratory testing.

The best means to obtain the unit weight of soil layers is via undisturbed sampling, such as thin-walled push-in tubes, piston-type samplers, or special block sampling, in order to minimize issues of sample disturbance on clays and silts (e.g. Tanaka 2000; Lunne et al. 2006). Undisturbed sampling of clean sands is now possible using special one-dimensional freezing methods (Mayne, 2006), but at great expense associated with time and special costly equipment. Measured mass and volume of the undisturbed samples directly provide the unit weight.

The soil unit weight can be calculated from fundamental indices on the basis of index relationships which for saturated soils is given by:

$$\gamma_{sat} = \frac{G_s + e}{1 + e} \cdot \gamma_w \tag{2}$$

where G_s = specific gravity of solids, e = void ratio = $G_s \cdot w$ (for saturation S = 1), w = water content, and γ_w = unit weight of water. Therefore, by measuring in-place water content with an assumed G_s (e.g., 2.70), the unit weight may be surmised.

For immediate results, indirect in-situ methods for ascertaining soil unit weights are available through electrical resistivity probes (Nelissen, 1988), gamma ray penetrometers (Sully & Eschesuria 1988), radioactive isotope modules (Mimura et al. 1995), and dielectric measurements (Shinn, et al. 1998). However, their use requires specialized devices, some with hazardous materials, which adds appreciable burdens in terms of time, costs, and/or safety during deployment. Therefore, a key objective of this study was to explore direct CPTu methods for assessing unit weights of geomaterials from the basic penetrometer readings (q_t, f_s, and u_2) and thus obtain a faster post-processing of the net cone resistance, at least for preliminary analyses and on-site post-processing of data.

2 AVAILABLE CPT RELATIONSHIPS

In earlier studies, Sully & Eschesuria (1988) found a relationship between γ_t and q_c for one sand deposit. Larsson & Mulabdić (1991) developed a chart for Swedish clays that grouped γ_t in zones defined by plotting net cone resistance (q_t-σ_{vo}) vs. normalized porewater pressure: $B_q = (u_2-u_0)/(q_t-\sigma_{vo})$. Młynarek et al. (1995) showed a family of dry density curves from q_c and σ_{vo}' for alluvial and fluvioglacial sands. Plant et al. (1997) showed a rough and scattered trend between γ_t and net cone resistance in Hong Kong clays. Lunne et al. (1997) presented a table of assigned unit weights for each of the 12 zones or soil behavioral types (SBT) established by Robertson et al. (1986), however no data are shown in support of those values.

3 UNIT WEIGHT-SHEAR WAVE TRENDS

A global and fundamental relationship exists between total unit weight and shear wave velocity in soils. This is because shear wave velocity strongly depends upon void ratio and effective stress state (Tatsuoka & Shibuya, 1992; Stokoe & Santamarina, 2000), as well as other factors, including fabric, structure, cementation, and ageing. Using data compiled from various soil types, Burns & Mayne (1996) showed that the total unit weight can be expressed as a power function in terms of effective overburden stress and shear wave velocity (n = 438; r^2 = 0.820; S.E.Y. = 0.115; where n = number of data sets, r^2 = coefficient of determination, and S.E.Y. = standard error of the dependent variable):

$$\gamma_{sat}(\mathrm{kN/m^3}) = 6.87 \frac{(V_s\ \mathrm{m/s})^{0.227}}{(\sigma_{vo}'\ \mathrm{kPa})^{0.057}} \tag{3}$$

A later study with additional data (Mayne 2001) further confirmed a relationship between γ_t and V_s, using depth (z) in lieu of σ_{vo}' (n = 727; r^2 = 0.808; S.E.Y. = 1.05):

$$\gamma_{sat}(kN/m^3) \quad = \quad 8.32 \cdot \log(V_s \ m/s) - 1.61 \cdot \log(z \text{ meters}) \tag{4}$$

Thus, use of the seismic piezocone test (SCPTu) which provides four measurements with depth (q_t, f_s, u_2, and V_s) has the capability to provide reasonable and reliable values of γ_t profiles from its shear wave measurements.

An alternative version to the above can be developed in terms of stress-normalized shear wave velocity (V_{s1}), where the unit weight is estimated from (Mayne 2007a):

$$\gamma_{sat} \quad = \quad 4.17 \cdot \log_e(V_{s1}) - 4.03 \tag{5}$$

where $V_{s1} = V_s\,(m/s)/(\sigma_{vo}'/\sigma_{atm})^{0.25}$ where σ_{atm} = 1 bar = 100 kPa = atmospheric pressure. An initial value of γ_t is assumed in order to start the process, as effective overburden stress (σ_{vo}') depends on γ_t. Eq (5) has the advantage of accounting for layered profiles with either higher or lower density materials with depth compared with (4).

In the cases where only conventional piezocone tests (CPTu) are available, the shear wave velocity could be estimated from the penetrometer readings, then used in (3) or (4) to estimate γ_t. For instance, Baldi et al. (1989) developed a correlation for sands, Mayne & Rix (1995) presented a relationship for clays, and Andrus et al. (2007) included age as an important factor for such relationships. Hegazy & Mayne (1995) addressed assorted and mixed soil types, finding:

$$V_s\,(m/s) \ = \ [10.1 \cdot \log q_t - 11.4]^{1.67} \ \ [f_s/q_t \cdot 100]^{0.3} \tag{6}$$

While these correlations offer possible linkages from CPT to V_s and then from V_s to γ_t, they do so with increased uncertainty and less reliability.

4 UNIT WEIGHT - SCPTu DATABASE

Towards the goals of this study, a careful assembly of a geomaterial database included a wide range of soil types (sands, silts, clays, calcareous soils, tills, etc) that contained all necessary variables for consideration. As a minimum, these parameters included: γ_t, V_s, and CPT measurements of q_t, f_s, and u_2 that were input to facilitate graphical and statistical evaluations. Table 1 lists the 39 sites that were compiled herein, also noting their location and approximate reference source citations. Table 2 contains an additional listing of 5 sites where the unit weight and CPT data were available for consideration, but specific shear wave results were not known.

The compiled database confirmed the γ_t relationship with V_s and σ_{vo}' given by (5), as seen in Figure 1. Separate curves are shown for effective overburden stresses corresponding to σ_{vo}' = 10, 100, and 1000 kPa. Also clear is the need to exclude "unusual" geomaterials such as highly calcareous soils (Cooper Marl) or diatomaceous geomaterials, including Japanese mudstone and Mexico City clay.

5 DIRECT UNIT WEIGHT - CPT TRENDS

For the next task, a direct relationship between unit weight and CPT readings was sought by conducting a comprehensive series of multiple regression analyses using both arithmetic and logarithmic scaling. The full suite of regression attempts are not included herein, as they were too numerous for discussion. In the fitting of the data from Table 1 by linking (4) and (6), a multiple regression analysis of some success was found with the results:

$$\gamma_t\,(\mathrm{kN/m^3}) = 11.46 + 0.33 \log(z) + 3.10 \log(f_s) + 0.70 \log(q_t) \tag{7}$$

where q_t and f_s are in units of kPa and depth z is input in meters. The relationship provided the following regression statistics: n = 215; $r^2 = 0.720$; S.E.Y. = 1.31. As noted earlier, the use of σ_{vo}' is preferred over depth z, as the former can better account

Table 1. List of test sites with unit weight, shear wave velocity, and CPT data

No.	Site	Location	Type Soil	Reference	Proceedings/Journal Citation
1	Amherst NGES	Massachusetts, USA	soft varved clay	DeGroot & Lutenegger (2003)	Characteriz. & Engrg Prop.of Natural Soils
2	Anchorage	Alaska, USA	stiff clay	Mayne & Pearce (2005)	Frontiers in Offshore Geotechnics, Perth
3	Ariake	Japan	soft clay	Ohtsubo et al. (2007)	Characteriz. & Engrg Prop.of Natural Soils
4	Bangkok AIT	Thailand	soft clay	Shibuya (2003)	Characteriz. & Engrg Prop.of Natural Soils
5	Bothkennar	Scotland, UK	soft clay	Hight et al. (2003)	Characteriz. & Engrg Prop.of Natural Soils
6	Brent Cross	England, UK	fissured London clay	Lunne et al. (1986)	Canadian Geotechnical Conference
7	Burswood	Western Australia	soft clay	Chung (2005)	PhD Thesis, Univ. Western Australia
8	Calgary	Alberta, Canada	clay till	Mayne & Woeller (2008)	BGA Intl. Conf. Foundations, Dundee
9	Cooper Marl	South Carolina, USA	calcareous clay	Camp (2004)	GeoSupport 2004, ASCE GSP 124
10	Cowden	England, UK	clay till	Powell Butcher (2003)	Characteriz. & Engrg Prop.of Natural Soils
11	Drammen	Norway	soft clay	Lunne & Lacasse (1998)	Characterization of Natural Clays, Japan
12	Dublin	Ireland	boulder clay	Long and Menkiti (2007)	Characteriz. & Engrg Prop.of Natural Soils
13	Edo River	Japan	natural sand	Mimura (2003)	Characteriz. & Engrg Prop.of Natural Soils
14	Evanston NGES	Illinois, USA	soft clay	Finno (2000)	Natl. Geotech.Experim. Sites, GSP 93
15	Fucino	Italy	calcareous clay	Brignoli et al. (1995)	Symp. on Cone Penetration Testing, SGF
16	Gioia Tauro	Italy	natural sand	Ghionna & Porcini (2006)	Characteriz. & Engrg Prop.of Natural Soils
17	Highmont	Canada	mine tailing sand	Robertson et al (2000)	Canadian Geotechnical Journal
18	Holmen	Norway	natural sand	Lunne et al. (2003)	Characteriz. & Engrg Prop.of Natural Soils
19	J-pit	Canada	mine tailing sand	Robertson et al (2000)	Canadian Geotechnical Journal
20	Kidd	Canada	mine tailing sand	Robertson et al (2000)	Canadian Geotechnical Journal
21	Lilla Mellosa	Sweden	soft clay	Larsson & Mulabdic 1991	Piezocone Tests in Clay, SGI Report 42
22	LL Dam	Canada	mine tailing sand	Robertson et al 2000	Canadian Geotechnical Journal
23	Madingley	England, UK	fissured Gault clay	Lunne et al. 1986	Characteriz. & Engrg Prop.of Natural Soils
24	Massey	Canada	natural sand	Robertson et al (2000)	Canadian Geotechnical Journal
25	Mildred L.	Canada	mine tailing sand	Robertson et al (2000)	Canadian Geotechnical Journal
26	Natori	Japan	natural sand	Mimura (2003)	Characteriz. & Engrg Prop.of Natural Soils
27	Noto	Japan	diatom. mudstone	Matsumoto et al. (1996)	J. Geotechnical & Geoenvironmental Engrg
28	Onsoy	Norway	soft clay	Lunne (2003)	Characteriz. & Engrg Prop.of Natural Soils
29	Opelika	Alabama, USA	residual sandy silt	Mayne & Brown (2003)	Characteriz. & Engrg Prop.of Natural Soils
30	Pentre	England, UK	silt deposit	Lambson et al. (1993)	Large Scale Piles Clay, Thomas Telford
31	Pisa Pancone	Italy	soft clay	LoPresti (2003)	Characteriz. & Engrg Prop.of Natural Soils
32	Sarapui	Rio, Brazil	very soft clay	Almeida et al. (2003)	Characteriz. & Engrg Prop.of Natural Soils
33	Ska Edeby	Sweden	soft clay	Larsson & Mulabdic (1991)	Piezocone Tests in Clay, SGI Report 42
34	Texas NGES	USA	stiff clay	Briaud et al. (2001)	J. Geotechnical & Geoenvironmental Engrg
35	Tone River	Japan	natural sand	Mimura (2003)	Characteriz. & Engrg Prop.of Natural Soils
36	Treporti	Italy	stratified soils	Simonini (2007)	Characteriz. & Engrg Prop.of Natural Soils
37	Troll Offshore	North Sea	soft clay	Lunne et al. (2007)	Characteriz. & Engrg Prop.of Natural Soils
38	Yodo River	Japan	natural sand	Mimura (2003)	Characteriz. & Engrg Prop.of Natural Soils
39	Yorktown	Virginia, USA	calc.sandy clay	Mayne (1989)	Foundation Engineering, ASCE GSP 22

Table 2. List of additional sites with unit weight and CPT readings.

No.	Site	Location	Type Soil	Reference	Proceedings/Journal Citation
40	Betuwe Railway	The Netherlands	peat	den Haan (2007)	Characteriz. & Engrg Prop.of Natural Soils
41	Hibernia	North Atlantic	natural sand	Thompson & Long (1989)	Canadian Geotechnical Journal
42	Kowloon	Hong Kong, China	sand fill	Lee et al. (2002)	J. Geotechnical & Geoenvironmental Engrg
43	Mexico City	Mexico	soft clay	Cruz & Mayne (2006)	Proc.GeoShanghai, ASCE GSP 149
44	Recife RRS2	Brazil	soft clay	Coutinho (2007)	Characteriz. & Engrg Prop.of Natural Soils

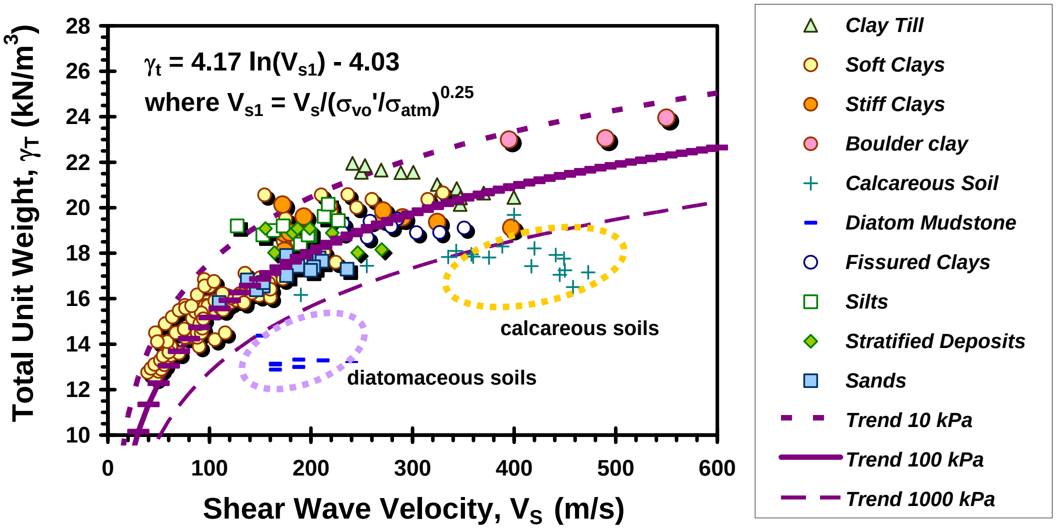

Figure 1. Total unit weight trend with V_s and σ_{vo}' for various geomaterials

for layered deposits and unit weight variance with depth. Therefore, higher order regressions were investigated to include σ_{vo}' with all three readings of the piezocone in an attempt to improve the statistics, including an increase in coefficient of determination (r^2) and decrease in the standard error of the dependent variable (S.E.Y.). This produced the regression presented in Figure 2 and expressed ($n = 207$; $r^2 = 0.718$; S.E.Y. = 1.08) in dimensionless form:

$$\gamma_t = 1.81\cdot\gamma_w\cdot\left(\frac{\sigma_{vo}'}{\sigma_{atm}}\right)^{0.05}\cdot\left(\frac{q_t-\sigma_{vo}}{\sigma_{atm}}\right)^{0.017}\cdot\left(\frac{f_s}{\sigma_{atm}}\right)^{0.073}\cdot(B_q+1)^{0.16} \qquad (8)$$

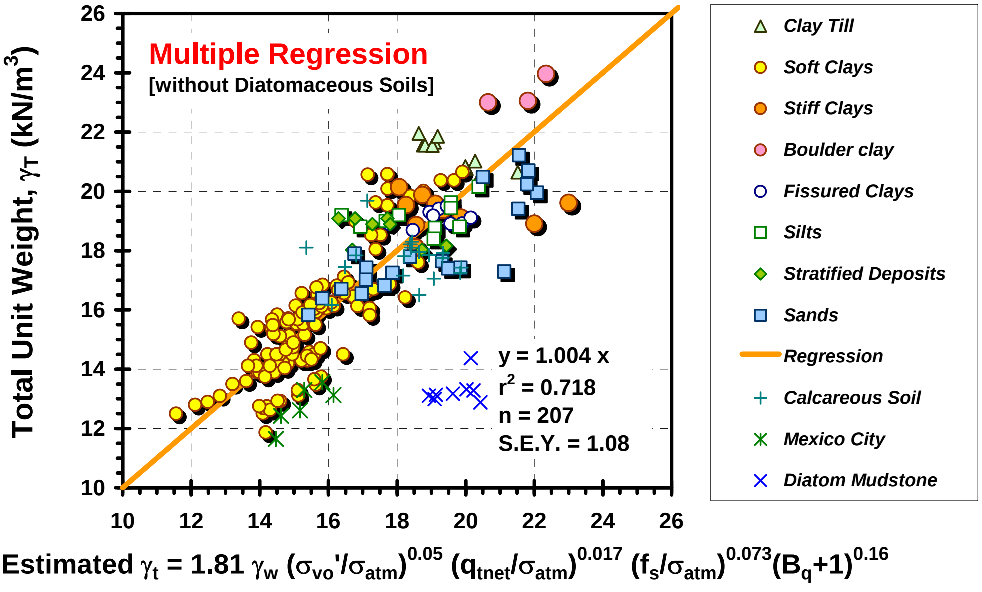

Figure 2. Multiple regression relationship for total unit weight with effective overburden stress and CPT readings. (Note: excludes diatomaceous soils)

where $B_q = (u_2-u_o)/(q_t-\sigma_{vo})$ = normalized excess porewater pressure parameter. Note these exclude diatomaceous soils (Japanese mudstone and Mexico City clay).

Upon further investigation, it became apparent that sleeve friction and σ_{vo}' alone sufficed to produce reasonable estimates of γ_t, thereby not requiring a reliance on q_t or u_2 readings, at no loss in statistical significance (Figure 3). The resulting expression ($n = 207$; $r^2 = 0.737$; S.E.Y. = 1.08)

$$\gamma_t = 1.95 \cdot \gamma_w \cdot \left(\frac{\sigma_{vo}'}{\sigma_{atm}}\right)^{0.06} \cdot \left(\frac{f_s}{\sigma_{atm}}\right)^{0.06} \tag{9}$$

In the event that the cone sleeve has unequal end areas, it would be important to correct the measured reading to the total sleeve resistance, even if only an approximation is used (Lunne et al. 1997).

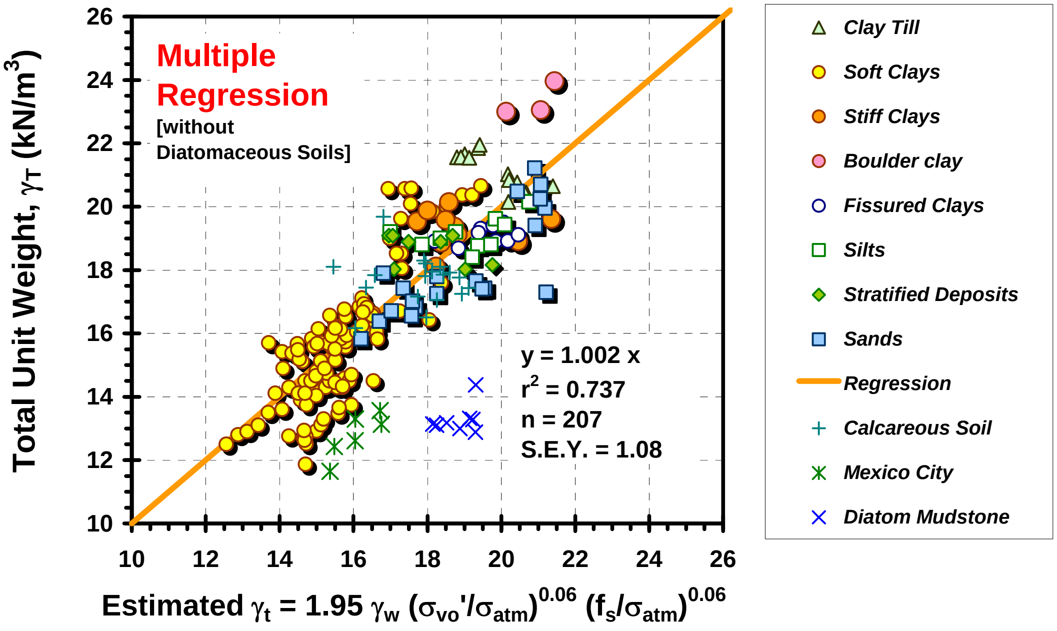

Figure 4. Total unit weight trend with sleeve friction and effective overburden stress

CONCLUSIONS

Soil unit weight can be approximately estimated from the measured CPT sleeve friction and effective overburden stress. The relationship appears valid for estimates in uncemented geomaterials including a variety of clays, silts, sands, tills, and mixed soil types, however, is apparently not valid for diatomaceous clays and perhaps of limited applicability in highly calcareous soils.

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