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New DMT method for evaluating soil unit weight in soft to firm clays

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ABSTRACT: A set of field measurements from flat dilatometer test (DMT) and laboratory data from undisturbed samples on 31 different clays have been explored to develop an empirical expression relating soil unit weight with DMT readings. For normally-consolidated (NC) to lightly-overconsolidated (LOC) soft to firm clays under investigation, a significant trend found that the total unit weight (γ_t) tracks with the contact pressure (p_0) and depth (z). A newly defined slope parameter (designated $m_{p0} = \Delta p_0/\Delta z$ with forced intercept = 0) was established for homogenous inorganic clay deposits and found related to the soil unit weight. Results showed a more reliable prediction with improved statistical measures, when compared with other available methods.

1 INTRODUCTION

The evaluation of soil properties plays a vital role in designing geotechnical structures. A necessary first step in a proper site investigation should be the assessment of the soil unit weight, as this is needed in the calculation of total and effective stresses. Unit weights are best determined by taking undisturbed tube samples and measuring the soil mass divided by the volume. However, with in-situ tests, the unit weight is estimated from direct measurements.

The flat dilatometer test (DMT) was developed in Italy by Marchetti (1980) and gained popular acceptance since its introduction due to its simplicity, repeatability, and quick application in geotechnical explorations. The DMT produces two pressure readings (A and B) by inflating a 60 mm diameter flexible steel membrane at each test depth using nitrogen gas. The corrected A reading or contact pressure, p_0, occurs when the membrane becomes flush with the flat blade face, and p_1 is the corrected B reading or expansion pressure to reach outward 1.1 mm. The DMT results are interpreted using three indices: (a) the material index: $I_D = (p_1-p_0)/(p_0-u_0)$, (b) dilatometer modulus: $E_D = 34.7(p_1-p_0)$, and (c) horizontal stress index: $K_D = (p_0-u_0)/\sigma_{vo}'$, where u_0 is the in-situ porewater pressure and σ_{vo}' is the effective overburden stress. Although no database was presented, Marchetti and Crapps (1981) suggested estimating the soil unit weight (γ_t) as a function of the I_D and E_D values, as shown in Figure 1.

Since then, various researchers have made attempts to verify the original relationships for estimating the soil unit weight from DMT readings in site specific geologic formations (e.g., Powell & Uglow 1988; Mayne & Martin 1998) or developed new trends between unit weight and DMT indices (Ozer et al 2012). While the aforementioned address applications in a range of different soil types, the focus herein will primarily be limited to soft to firm

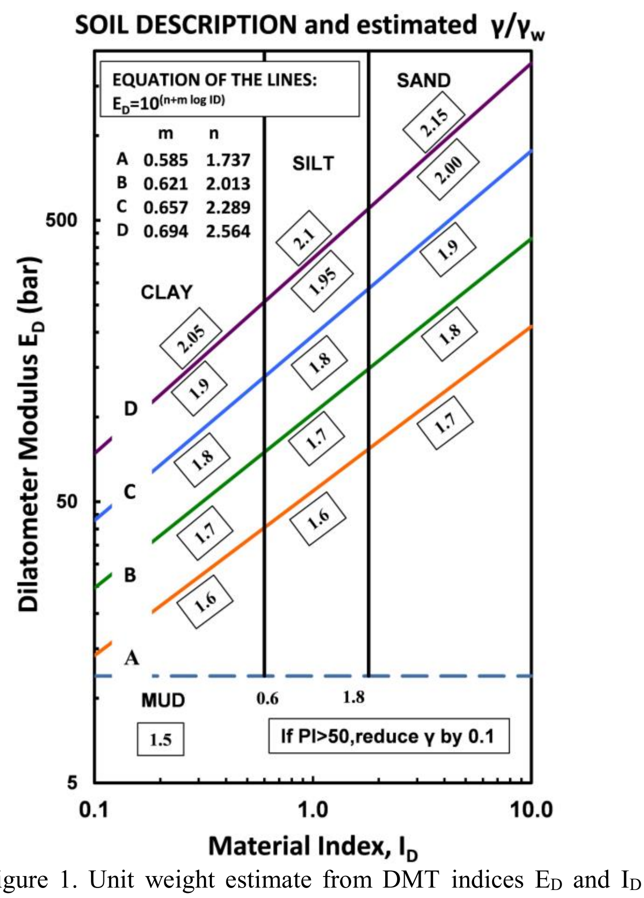

Figure 1. Unit weight estimate from DMT indices E_D and I_D (after Marchetti and Crapps, 1981)

natural clays that are relatively homogeneous and also commonly associated with a high groundwater table.

2 DATA COLLECTION

Table 1.1 Listing of soft to firm clay sites subjected to flat dilatometer tests (DMT) reviewed in this study

Site Name	Mean w_n (%)	Mean PI (%)	Mean unit weight, γ_t (kN/m^3)	Slope m_{p0} (kN/m^3)
Anacostia	65	32	15.9	29.1
Ariake	106	68	13.5	20.7
Backbol	84	56	16.0	28.5
Ballina*	107	66	14.1	31.5
Bothkennar	61	40	16.5	33.4
Colebrook Road	45	11	17.0	26.4
Drammen	52	28	16.6	29.8
Ford Design Ct	21	15	20.2	44.1
Foynes	37	23	18.6	30.5
Hamilton	95	45	13.7	18.7
Lilla Mellösa	70	54	15.7	28.6
Norrköping	76	36	15.7	29.3
NWU GSP	24	15	19.6	41.7
NWU-NGES	26	15	20.1	37.0
Onsøy	64	41	15.9	27.1
Porto Tolle	35	26	18.2	26.8
Recife	123	69	15.6	29.0
Saint Paul*	210	NA	11.4	23.6
Sarapui	139	78	14.0	21.5
Saro Rd 6/900*	160	103	12.1	26.6
Saro Rd 7/600*	150	101	13.2	28.7
Skå Edeby	74	37	15.7	28.5
South Gloucester	70	27	15.8	29.8
Strandbacken	45	13	17.2	34.3
Sundholmen	58	13	16.7	34.3
Torp	48	29	17.5	30.4
Valen	115	77	15.4	27.8
200th Street	58	27	16.2	30.0
Limerick Road	60	40	15.7	29.4
South Portland	24	44	17.2	35.8
High Prairie	38	37	17.6	33.9

* Clay site with organic content

For each site under investigation, information was compiled concerning the in-situ DMT readings, stress history, laboratory unit weight (γ_t), natural water content (w_n), and corresponding plasticity characteristics, such as the mean plasticity index (PI). The stress histories were measured from one-dimensional consolidation tests (either oedometers, automated consolidometers, and/or constant-rate-of-strain devices) and the overconsolidation ratios (OCR) generally ranged between 1 and 2 throughout much of the deposit depths. Groundwater tables are generally high in these soft clays, usually within 1 to 2 or 3 m depth.

The laboratory unit weights were measured from weighed samples of known volumes on tube samples. A variety of different samplers were used by the various researchers, including: Shelby, fixed Piston, free Piston, Laval, Sherbrooke, SGI, and Japanese type tubes. It was not possible to track all of the sample quality issues because of insufficient information, although sample disturbance may have some effects on the results.

In some cases, the unit weights were also obtained by calculation from natural water contents and specific gravity of solids (G_s). A comparison of measured γ_t and calculated unit weights from water contents, assuming fully saturated condition, is presented in Figure 2 for the Ballina site in eastern Australia (Pineda et al, 2014). The results show very good agreement.

Table 1.2 Listing of 30 soft to firm clay sites with locations and reference sources of information

Site Name & Location	Reference Source
Anacostia, DC	Mayne (1987)
Ariake, Japan	Watabe et al (2003)
Backbol, Sweden	Larsson & Mulabdic (1991)
Ballina*, Australia	Pineda et al (2014)
Bothkennar, UK	Nash et al (1992)
Colebrook Road, BC	Crawford & Campanella (1991)
Drammen, Norway	Lacasse &Lunne (1983)
Ford Center, Illinois	Mayne (2006)
Foynes, Ireland	Carroll and Long (2012)
Hamilton AFB, CA	Masood et al (1988)
Lilla Mellösa, Sweden	Larsson & Mulabdic (1991)
Norrköping, Sweden	Larsson & Mulabdic (1991)
NWU, Illinois	Finno (1989)
NWU-NGES, Illinois	Mayne (2006)
Onsøy, Norway	Lunne and Long (2003)
Porto Tolle, Italy	Marchetti (1980)
Recife, Brazil	Danziger (2007)
Saint Paul*, MN	Courtesy of MnDOT (2007)
Sarapui, Brazil	Almeida (2003), Danziger (2007)
Saro 6/900*, Sweden	Larsson & Mulabdic (1991)
Saro 7/600*, Sweden	Larsson & Mulabdic (1991)
Skå Edeby, Sweden	Larsson & Mulabdic (1991)
South Gloucester, ON	McRostie et al (2001)
Strandbacken, Sweden	Larsson and Åhnberg (2003)
Sundholmen, Sweden	Larsson and Åhnberg (2003)
Torp, Sweden	Larsson and Åhnberg (2003)
Valen, Sweden	Larsson & Mulabdic (1991)
200th Street, BC	Cruz (2009)
Limerick, Ireland	Bihs et al (2009)
South Portland, ME	Roche et al (2006)
High Prairie, AB	Cruz and Howie (2008)

* Clay site with organic content

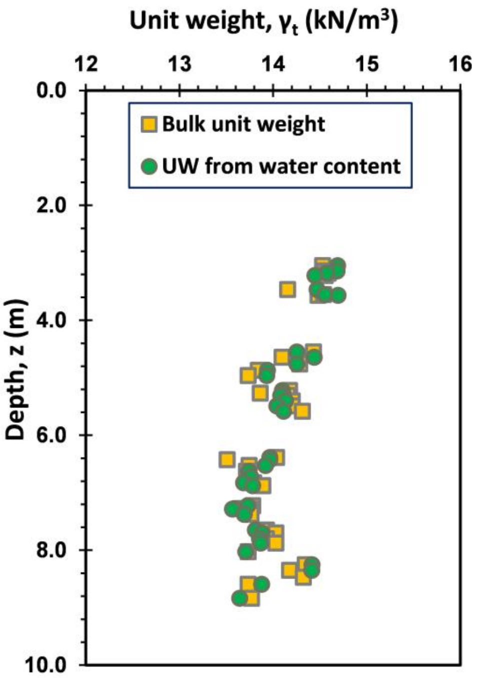

Figure 2. Unit weight profile of Ballina Clay site using mass-volume and water content data.

For the most part, all of the equipment and field procedures for DMT soundings are standardized and given by ASTM D 6635, as well as CEN and ISO standards (Marchetti et al. 2001).

During the DMT, the sharp stainless steel blade is inserted vertically at a rate of 20 mm/s and at the test depth, nitrogen gas is introduced to pressurize the inflatable circular membrane. The A-reading is captured within about 15 s after insertion and the B-reading taken about 30 s later. Thus, both A and B readings are obtained in about 1 minute. Generally, test depth intervals are every 200 mm in most of the world, excepting the USA where an approximate 300 mm interval is common (1 foot ≈ 305 mm).

3 SOIL PARAMETER TREND ANALYSIS

3.1 *Defining the DMT Parameter m_{po}*

For the series of soft to firm normally-consolidated (NC) to lightly-overconsolidate (LOC) clays under investigation, the DMT readings indicate certain trends of interest. One clear observation is that for soft clays with a high groundwater table, the corrected contact pressures (p_0) show a linear trend and increase with depth, as evidenced by four examples shown in Figure 3: (a) Anacostia Naval Air Station in Washington, DC, USA (Mayne 1987), (b) Sundholmen, Sweden (Larsson and Åhnberg 2003), (c) Ariake, Japan (Watabe et al, 2003), and (d) Onsøy, Norway (Lunne and Long 2003). The expansion pressures (p_1) in these materials also show a similar trend with depth, although not explored here.

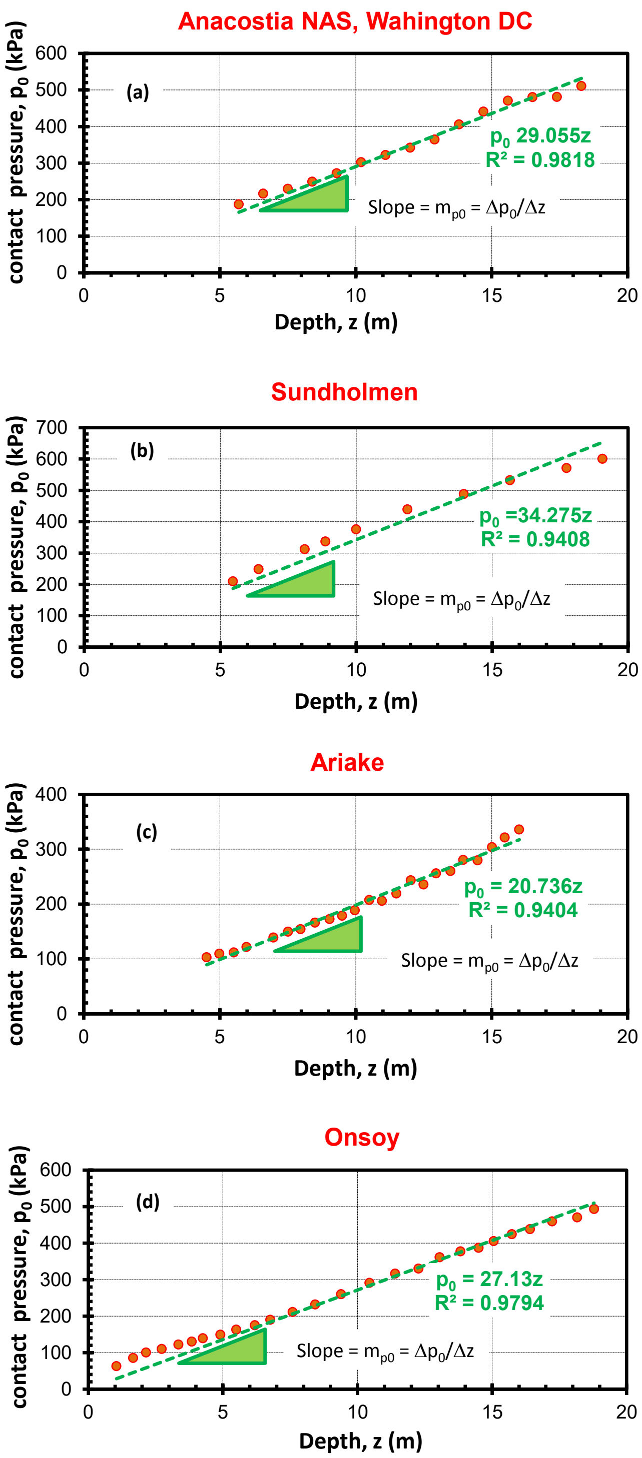

Figure 3. Example profiles showing linear trends for contact pressure with depth and slope parameter m_{p0} for four clays: (a) Anacostia, USA, (b) Sundholmen, Sweden (c) Ariake, Japan, and (d) Onsøy, Norway

A new parameter can be defined using regression analyses to obtain a best-fit line (intercept = 0):

$$m_{po} = \Delta p_0 / \Delta z \qquad (1)$$

For the normally-consolidated (NC) to lightly overconsolidated (LOC) inorganic clays under investigation, the slope parameter m_{p0} ranges from a low of 18 kN/m^3 (Hamilton Air Force Base) to a high value of 44 kN/m^3 (Ford Design Center and NGES at Northwestern University). For all these soils, the total unit weights ranged from 13.5 to 20.5 kN/m^3.

An examination of the data showed that the total unit weights track with the slope parameter m_{p0} for the majority of soft to firm inorganic clay soils under investigation, as evidenced by Figure 4. A few clays with organics showed variant trends and offset to the right. These are circled together as a group.

Of additional interest, the parameter m_{p0} has the same units as soil unit weight (i.e., kN/m^3).

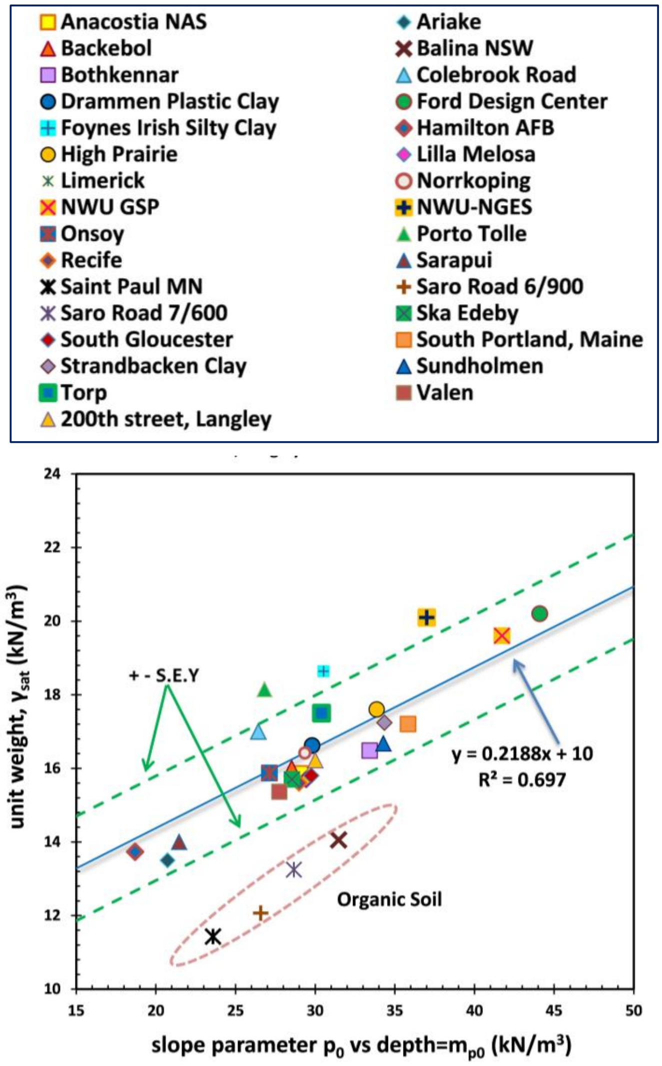

Figure 4. Total unit weight versus slope parameter m_{p0}

Based on the trend shown in Figure 4, one can establish an approximate expression between the total unit weight and slope parameter m_{p0} for soft to firm clays. Using a best fit line by forcing the trend line through intercept 10 (i.e., γ_w = unit weight of water), the relationship becomes:

$$\gamma_t = \gamma_w + 0.22 \cdot m_{po} \tag{2}$$

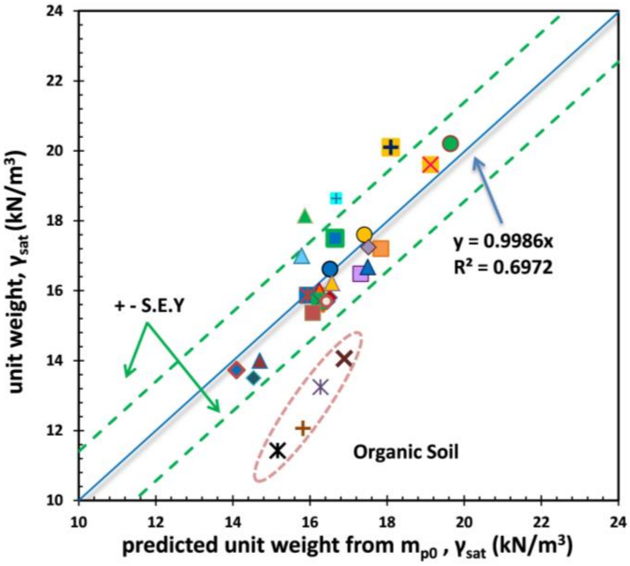

Figure 5. Lab soil unit weight versus predicted unit weight for all 31 clays

Consequently, one can apply this empirical relationship to predict the total unit weight of each of these soft clay soils. Figure 5 shows the comparison between the laboratory-measured unit weights and the predicted unit weights using the aforementioned empirical equation, and Figure 6 shows the lab unit weight profile compared to the predicted unit weight of the clay from m_{p0} of Anacostia. For stiff to hard clays with high OCRs and for fissured OC clays, an apparent value of m_{p0} is not applicable and future research is needed.

3.2 *Comparison between the Marchetti chart and this study*

Applying the DMT data from the collected sites, one can evaluate the validity of the three methods listed in the previous content. By plotting the lab unit weight against the predicted unit weight of each of the proposed approach, some statistical analyses are carried out and given in Table 2.1 for arithmetic ratio of measured-to-predicted values and Table 2.2 which considers regression fits in best fit lines between measured data and predicted results.

Table 2.1 Summary of the arithmetic statistics of Marchetti Chart and the slope parameter m_{p0} in predicting soil unit weight

Prediction Method	Number of data, n	Mean Value (Range)	Mean of Meas/Pred (Range)	COV* Meas/Pred
Marchetti-Crapps 1981 Chart	31	15.5 (14.7-16.6)	1.05 (0.82-1.28)	0.11
This study (2016)	31	16.2 (13.1-20.1)	1.01 (0.96-1.14)	0.08

Note: * COV = covariance = standard deviation/mean

Table 2.2 Summary of the regression statistics of Marchetti Chart and the slope parameter m_{p0} in predicting soil unit weight

Prediction Method	Number of data, n	Regression Slope	R^2 Meas/Pred	S.E.Y**
Marchetti-Crapps 1981 Chart	31	1.04	0.026	1.77
This study (2016)	31	1.01	0.698	1.42

Note: ** S.E.Y. = standard estimate of the Y-estimator

From Tables 2.1 and 2.2, it is observed that for the soils reviewed, the unit weights range from about 13 kN/m^3 to 20 kN/m^3 (mean γ_{sat}=16.2 kN/m^3). For the ratio of measured to predicted unit weight value, the corresponding covariance (also, called coefficient of variation, or COV=standard deviation/mean) for the two methods are 0.11 and 0.08. Thus, a better prediction is obtained for these soft clays.

The coefficient of determination (R^2) from the slope parameter regression is much larger (R^2 = 0.698) for the m_{p0} approach than that from the Marchetti chart (R^2 = 0.026). Moreover, the improvements are also drawn in terms of the standard error of the Y-estimate analysis (S.E.Y). A reduced value from 1.77 (1981) to 1.42 (2016) is obtained, indicating less variability.

4 CONCLUSIONS

This study involved a re-interpretation of in-situ DMT results from 31 soft to firm normally-consolidated to lightly overconsolidated clays worldwide where OCRs < 2. Most of these deposits were homogeneous and had a high groundwater table, generally less than 2 m. A new slope parameter (designated $m_{p0} = \Delta p_0/\Delta z$ with forced intercept = 0) was defined and found to relate to the total soil unit weight. Both m_{p0} and γ_t have units of kN/m^3.

Statistical measures are used to quantify the trends and the unit weight predicted by m_{p0} is provided and compared with the earlier Marchetti-Crapps (1981) relationship, showing an improved estimate by this new approach. However, the m_{p0} approach is not applicable to stiff and hard clays, nor silts and sands, thus specific to only to soft and firm inorganic clays. Data from a few organic clays were found to show a displaced trend.

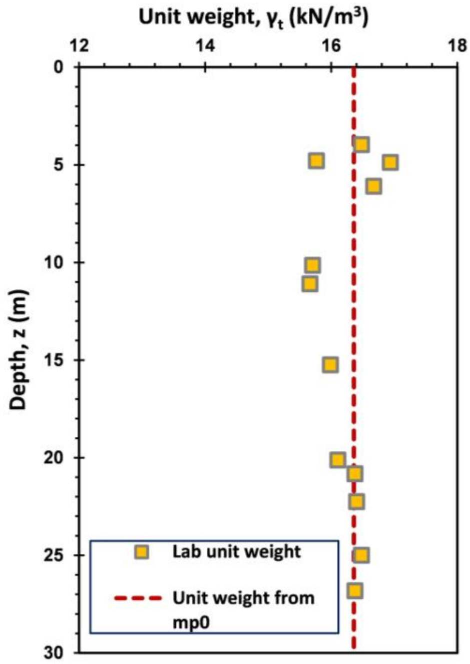

Figure 6. Profile of lab-measured unit weight and DMT-predicted unit weight from m_{p0} for Anacostia soft clay site in Washington, DC.

5 ACKNOWLEDGMENTS

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