Comparison of Pore Pressure Parameters from Piezocone and Dilatometer

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ABSTRACT

The Piezocone (CPTU) and the Marchetti Flat Plate Dilatometer (DMT) provide a number of empirical correlations for the purpose of soil identification. Each tool has defined a pore pressure parameter. For the piezocone, the parameter B_q 'is based on the penetration pore pressures, the corrected tip resistance, the total overburden stress, and the existing hydrostatic pore pressure. This index has been used to characterize soil behavior rather than the actual soil type. For the dilatometer, the parameter U_d is based on the corrected pressures p_0 and p_2, calculated using the A and C readings and the existing hydrostatic pore pressure. This index can be combined with the material index I_D to help with soil identification. Results from several test sites provide a promising direct correlation between B_q and $U_{D,}$ which can be used to enhance the identification of soil types by simply using the C-reading when performing DMT tests. Although the C-reading has been grossly ignored by users of the DMT, this new development will encourage measurement of this reading which provides similar trends to the pore pressures measured by the CPTU. The latest DMT equipment allows for the automatic measurement of the C-reading, which will assist in developing and enhancing existing correlations. This paper will present results at test sites located on opposite coasts of the USA. The trends of the B_q and U_D indices are shown to be remarkably similar in all types of soils.

Keywords: C-reading; pore pressure parameter; pore pressure ratio.

1. Introduction

When Marchetti introduced the flat dilatometer in his 1980 ASCE paper (Marchetti, 1980), he described the test as requiring only two pressure readings: the A-reading, corresponding to the pressure required for lifting off the membrane from the body of the probe, and the B-reading, corresponding to the pressure to move the membrane 1 mm into the soil. Once corrected for membrane stiffness, the corrected pressure readings p_0 and p_1 form the basis for the DMT indices I_D, K_D, and E_D.

In an effort to understand the mechanics of the DMT test, Campanella et al. (1985) devised a research dilatometer that fully recorded the expansion curve from A to B as well as the full deflation. Their probe was also equipped with a pore pressure sensor at the center of the expanding membrane. They observed that the closing pressure following deflation reflected the in situ hydrostatic ambient conditions in sands. In clays, the closing pressure also reflected the measured total pore pressure by the sensor on the membrane. This total pore pressure was significantly higher than the ambient pore pressure, suggesting that the closing pressure could measure excess pore pressures from cavity expansion in soft to medium clays. Schmertmann (1986) discussed this closing pressure and suggested that this C-reading could be used to help determine the position of the water table and interpret I_D for stratigraphy and dilative behavior of silts and clays.

This closing pressure or C-reading is obtained by controlled deflation (15-30 sec) of the membrane immediately after the B-reading using the flow control valve. This pressure is referred to as p_2. As shown in Eq. 1, p_2 is corrected for membrane stiffness (ΔA) and gauge offset (Z_m) (Schmertmann, 1985, 1986 – DMT Digest no. 5 and 8).

$$p_2 = C - Z_M + \Delta A \tag{1}$$

This equation was first shown in the DMT digest no. 5 but was later published by Lutenegger (1988) using a correction of $-\Delta A$. It was later appropriately corrected in the ASTM Standard D-6635.

The DMT Digest no. 9 (Schmertmann, 1987) suggested making the C-reading part of the standard procedure and creating a pore pressure index using the p_2 pressure, as shown in Eq. 2.

$$U_D = \frac{(p_2 - u_0)}{p_0 - u_0} \tag{2}$$

where U_D = pore pressure index
p_2 = corrected C-reading
p_0 = corrected A-reading
u_0 = in situ hydrostatic water pressure

This paper presents profiles of U_D values at three different test sites in soft to medium clays. Comparison with pore pressures measured by the piezocone (CPTU) using the pore pressure parameter B_q shows striking similarities between the two indices.

2. Testing Program

DMT and CPTU testing were carried out as part of three comprehensive site characterization efforts. The first study presented in this paper was carried out at Treasure Island in San Francisco, California. The primary objective of this project was to characterize the site for future installation of a deep accelerometer array for monitoring earthquakes. Results from this study are presented in Pass (1994). The second project evaluated the horizontal stress near a highway embankment on soft sensitive clay using the self-boring pressuremeter. This site, known as Pease Air Force Base (Pease AFB) in Portsmouth/NH, was located near a well-documented test embankment previously constructed and loaded to failure (Ladd, 1972). Results from this project can be found in NeJame (1991), Findlay (1991), and Murray (1995).

A few kilometers north of the Pease AFB site is the Newington-Dover test site, where a test embankment on the soft sensitive clay was constructed in stages to evaluate the optimal spacing of prefabricated drains to be used for the reconstruction of several highway embankments and roadways on this soft sensitive marine clay. The results of this study can be found in Getchell (2013), Santamaria (2015) and Coen (2016). The clays at both Pease AFB and Newington-Dover are part of the Presumpscot Formation, which runs up the coast from Massachusetts to Maine on the eastern seaboard.

Table 1 summarizes some index properties for all three test sites, including the clay sensitivity measured using a Geonor Vane Borer. These results were obtained from samples collected at each site and tested in our laboratory. The Atterberg limits represent the range encountered for all specimens within the clay deposits. The void ratios and unit weights were measured from consolidation testing of undisturbed samples.

Table 1. Index properties at Treasure Island, Pease AFB and Newington-Dover test sites.

Test site	**γ_t (kN/m³)**	**e_o**	**w_n**	**LL**	**PI**	**S_t**
Treasure Island, CA Pass (1991)	17.4	1.1 – 1.4	42 – 49	42 – 51	19 – 27	4.2
Pease Air Force Base, Portsmouth, NH Findlay (1991)	17.3 ± 3	1.1 ± 0.4	42 ± 7	34 ± 3	13 ± 1	10 – 15
Dover test embankment, Dover, NH Getchell (2013)	17.3	1.2	31 – 49	30 – 42	9 – 17	25

Several in situ testing tools and laboratory tests were conducted as part of these site investigations. This paper focuses primarily on the DMT and the CPTU pore pressure measurements. Testing with the flat plate dilatometer was performed according to the ASTM standard D 6635.

Testing with the CPTU was performed per ASTM D3550 using two different piezocone types. At Pease AFB and Treasure Island a Wissa cone Type 1 (pore pressure filter element located at the tip of the cone) was used to profile the soft sensitive clays in Portsmouth and the soft to medium clay at Treasure Island. The other site at Newington-Dover used a standard piezocone Type 2 (pore pressure filter element at the shoulder). The tip resistance measurements were corrected for end area ratio and offset in the Wissa cone case so that the penetration pore pressures are all relative to the more conventional Type 2 pore pressure filter element location.

3. DMT-CPTU Comparisons

The DMT-CPTU comparisons were based on the DMT material index I_D, the DMT pore pressure parameter U_D, and the CPTU pore pressure parameter B_q. The material index was calculated using the expression developed by Marchetti (1980) as in Eq. 3:

$$I_D = \frac{(p_1 - p_0)}{p_0 - u_0} \quad (3)$$

For comparison with the DMT, the pore pressure index B_q was calculated for each CPTU sounding using the expression developed by Robertson and Campanella (1989) and given in equation 4:

$$B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}} \quad (4)$$

where B_q = pore pressure parameter
q_t = corrected penetration tip resistance
u_2 = penetration pore pressure at shoulder location Type 2

3.1. Treasure Island Naval Station

Treasure Island is an artificial island originally constructed for the 1939 Golden Gate International Exposition. More than 12 to 14 m of sand was pumped from the bay to create the 162-ha island. As seen in Fig. 1, the sand fill was hydraulically deposited over the soft San Francisco Bay Mud deposit. Profiles of DMT and CPTU were advanced using a conventional drill rig down to about 30 m. Fig. 1 shows a CPTU profile, which delineates the position of the Young Bay Mud from the hydraulic sand fill. Fig. 2 presents a sounding of DMT corrected pressures for an adjacent profile.

A comparison between the DMT U_D and the CPTU B_q was shared with Professor Marchetti which he found promising. In his state-of-the-art paper (Marchetti, 1997) he states that "*the example in (Benoit, 1989) illustrates how UD can discern "permeable" layers (UD =0), "impermeable" layers (UD =0.7) and intermediate permeability layers (UD between 0 and 0.7), in agreement with Bq from CPTU*". This example is presented in Fig. 3 from Pass (1994).

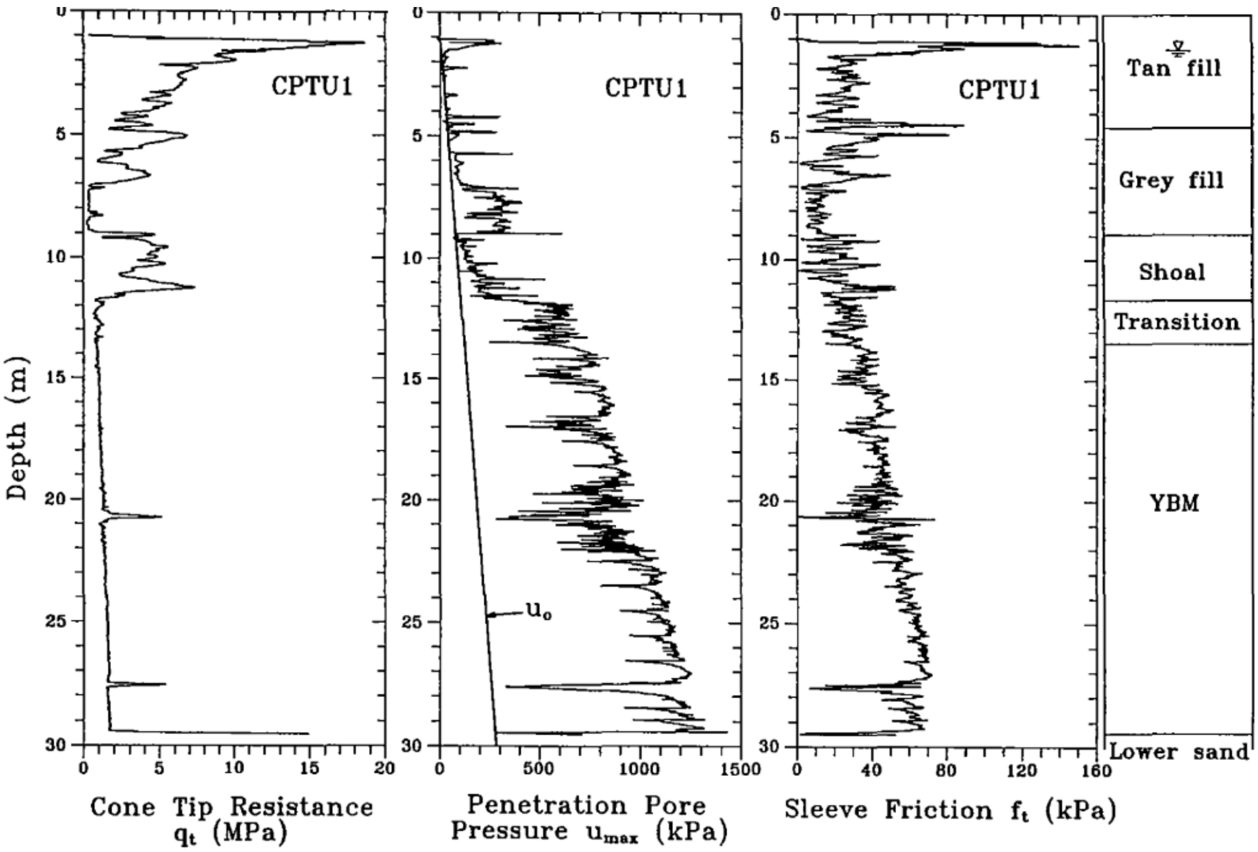

Figure 1. CPTU profile at Treasure Island (after Pass, 1994).

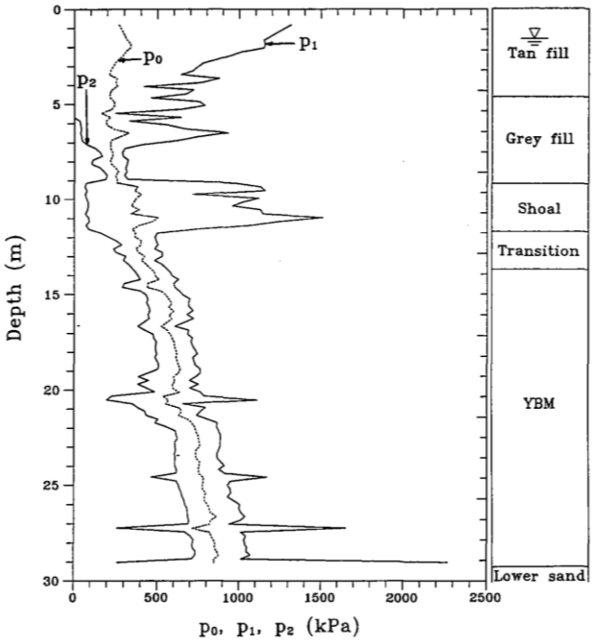

Figure 2. Corrected DMT readings at Treasure Island (after Pass, 1994).

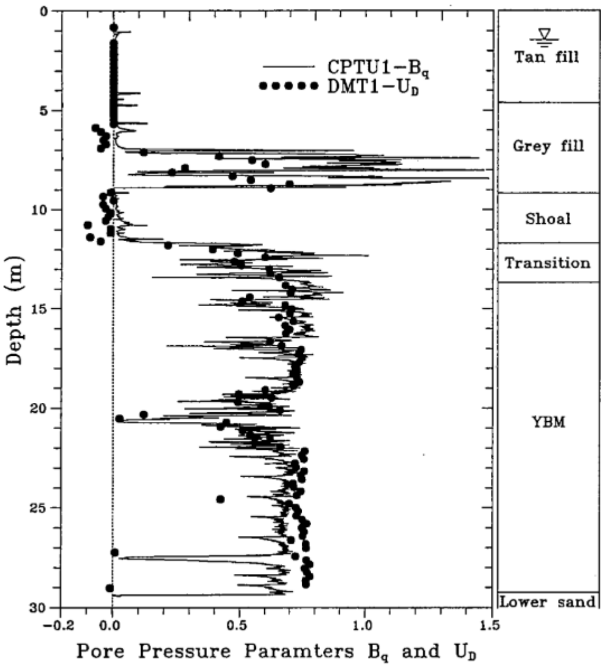

Figure 3. Comparison of pore pressure parameter and ratio from DMT and CPTU, respectively, at Treasure Island, California (after Pass, 1991).

3.2. Pease Air Force Base

Fig 4 shows a profile of DMT corrected readings in terms of p_0, p_1, and p_2 for sounding PD6 at Pease AFB, while Fig. 5 shows the conventional DMT indices I_D, K_D, and E_D. Below the highly overconsolidated crust is the layer of normally consolidated soft sensitive clay from about 4.3 to 7.3 m, where it transitions to a stiffer layer before reaching the glacial till. NeJame (1991) observed that the DMT pressures were very consistent within the soft clay and typical for this type of deposit. It was also noted that the p_2 readings in the sand or silt layers are in good agreement with the measured hydrostatic pore water pressure u_0.

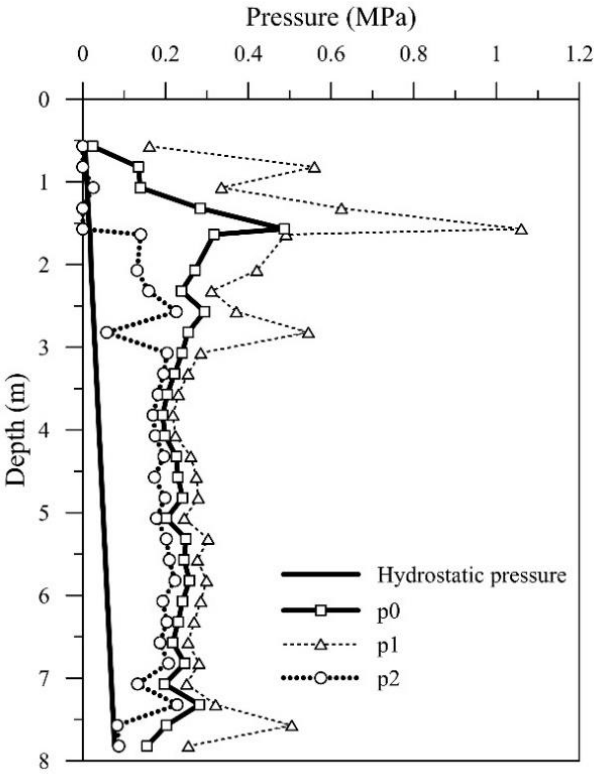

Figure 4. Corrected DMT readings at Pease AFB (adapted from NeJame, 1991).

NeJame (1991) compared the pore pressure parameter U_D to the material index I_d to determine the viability of using the C-reading for soil identification. As shown in Fig. 2, the two profiles are mirror images. As expected, the zone classified as clay from I_d has the largest values of U_D, while the zone identified as sand has the lowest values of U_D. The pore pressure parameter is a good predictor of soil types as it relates to the excess pore pressures surrounding the probe after insertion and testing.

A subsequent study by Murray (1995) investigated the use of the Wissa cone in this very soft sensitive clay. Murray conducted a series of soundings at Pease AFB adjacent to the DMT profiles using the Wissa CPTU. Fig. 6 shows sounding CPTU_M3 with a desiccated crust down to about 1.5 m below which is the normally consolidated soft silty clay to approximately 6.8 m before reaching the lower sand layer and the glacial till. Within the clay layer are several coarse sand lenses reflected by the higher tip penetration resistance values.

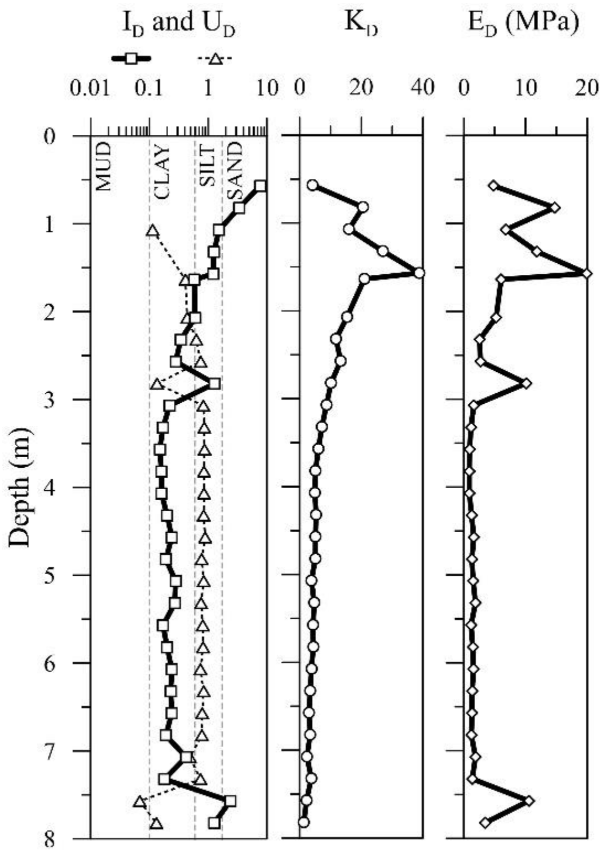

Figure 5. Comparison of pore pressure parameter U_D and material index I_d at Pease AFB (adapted from NeJame, 1991).

Fig. 7 compares the CPTU pore pressure parameter Bq from the sounding CPTU_M3 to the DMT pore pressure ratio UD from profile PD6 and found a striking similarity between both pore pressure expressions. Murray and Benoît (1995) discussed using the Bq parameter to classify soft soils. They found that the method of Larsson and Mulabdić (1991) was more reliable at identifying the very soft sensitive clay at Pease AFB than that of Robertson (1990).

3.3. Newington-Dover

Fig. 8 shows two CPTU soundings with a Type 2 piezocone pre-embankment construction. The profiles are very repeatable and clearly delineate the very soft clay portion of the deposit. Adjacent testing with the DMT is shown in Fig. 9. The DMT pressure profile shows very close p_0, p_1 and p_2 values corresponding to the I_D values within the soft clay. These measurements were used to calculate B_q and U_D for two CPTU and DMT profiles, as shown in Fig. 10. The results indicate that the correlation between the CPTU B_q and the DMT U_D is in better agreement when using a Type 1 piezocone, as shown in the previous two cases at Pease AFB and Newington-Dover. The profile of U_D is consistent with prior cases and shows an average of about 0.8.

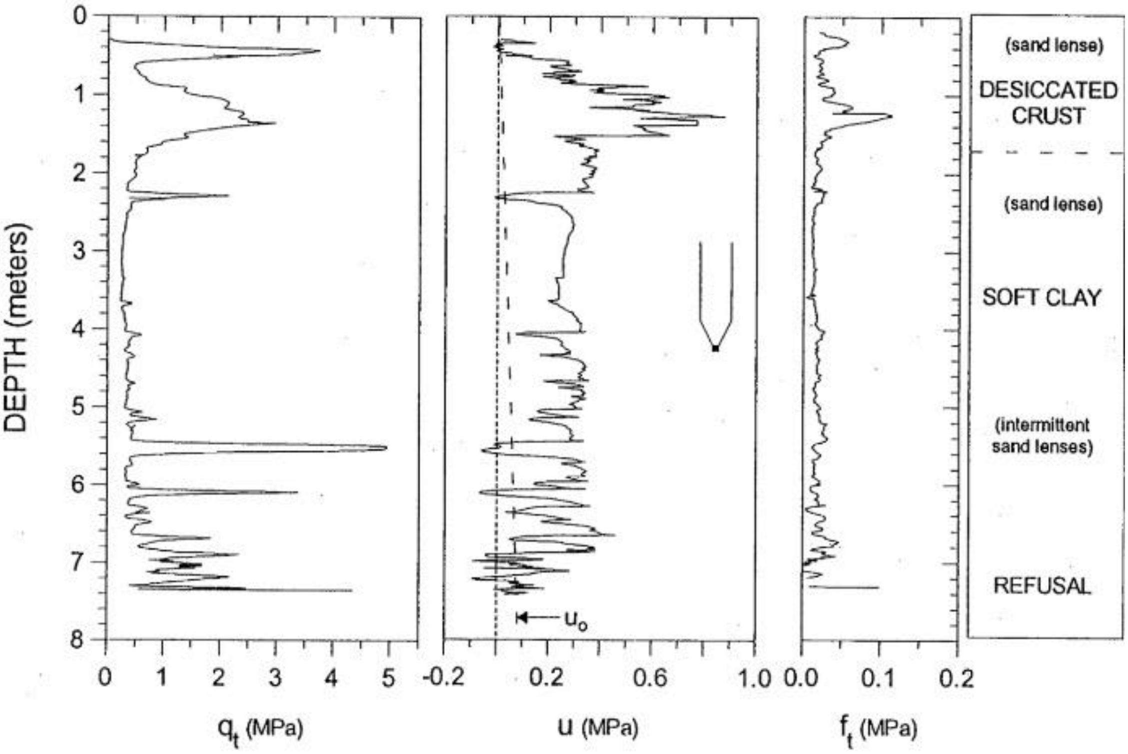

Figure 6. CPTU sounding Pease AFB (after Murray, 1995).

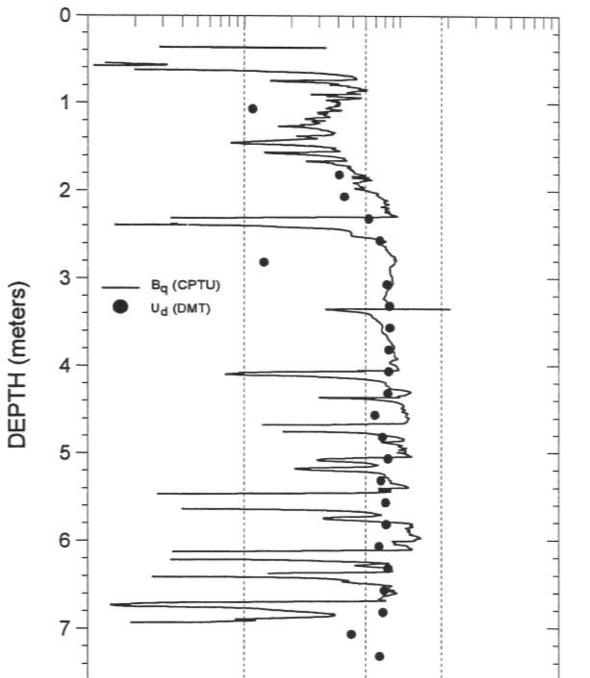

Figure 7. Comparison of pore pressure parameter and ratio from DMT and CPTU, respectively at Pease AFB (after Murray, 1995).

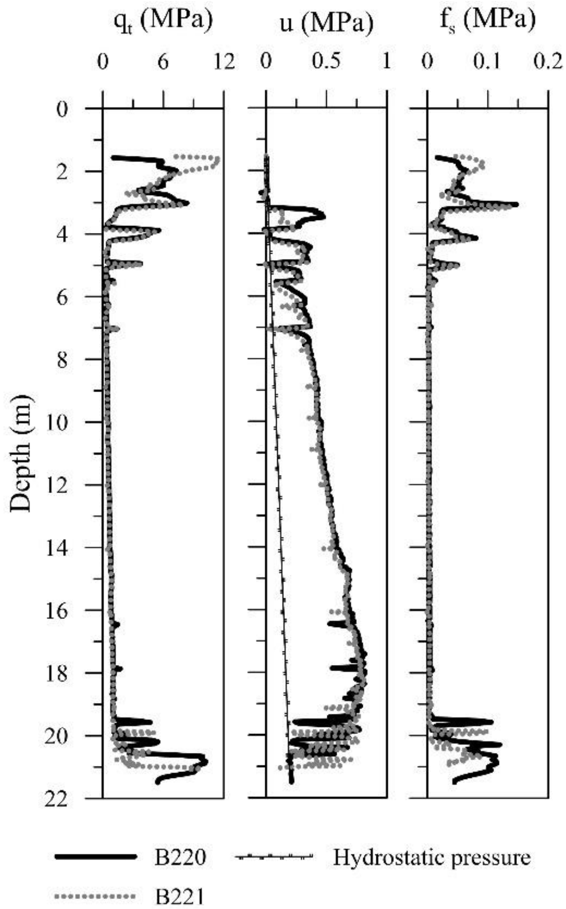

Figure 8. CPTU soundings at Newington-Dover test embankment (after Getchell, 2013).

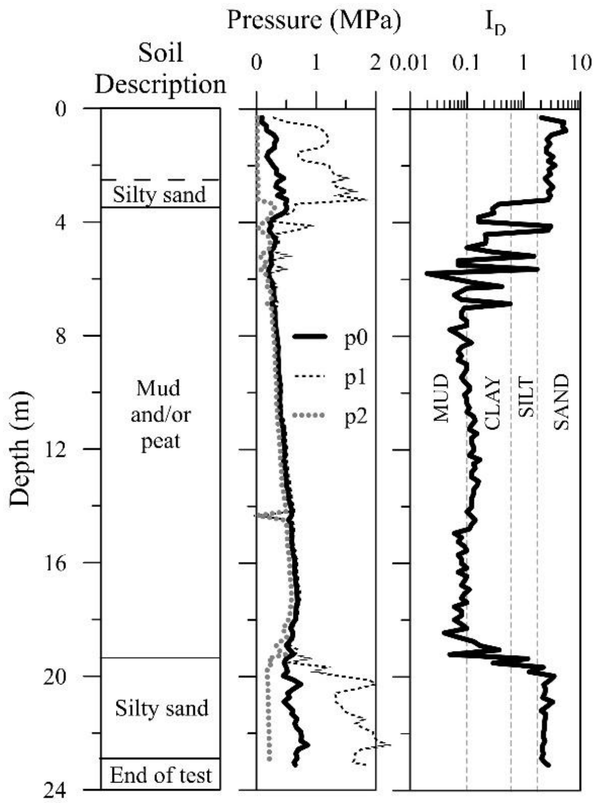

Figure 9. Corrected DMT readings and material index I_D at the Newington-Dover test embankment (adapted from Getchell, 2013).

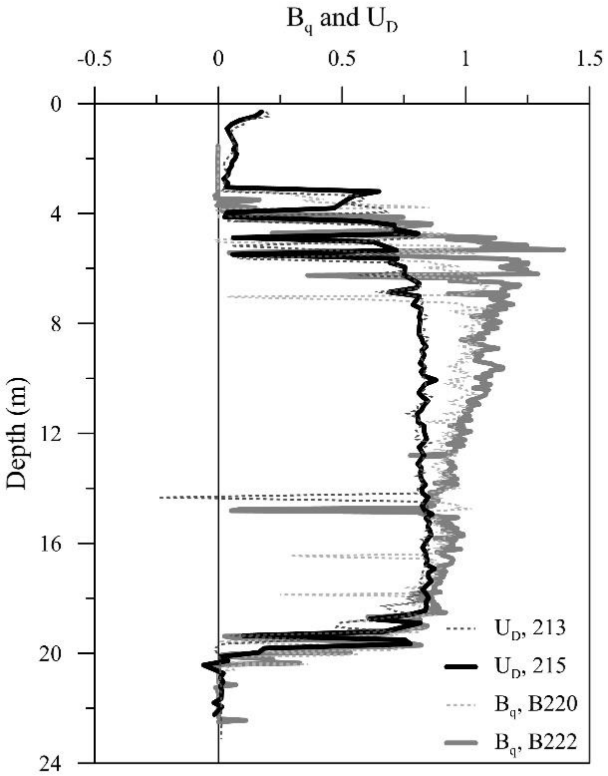

Figure 10. Comparison of pore pressure parameter and ratio from DMT and CPTU, respectively, at Newington-Dover test embankment, New Hampshire (adapted from Getchell, 2013).

Table 2 summarizes the pore pressure parameters U_D and Bq for the dilatometer and CPTU, respectively, at sites in New Hampshire and California, USA.

Table 2. Summary of average results for pore pressure parameters at all sites.

Site	Material	U_D	B_q
Treasure Island (Pass, 1991)	Fill	0	0
	Clay	0.7	0.6
Pease AFB (NeJame, 1991; Murray, 1995)	Clay	0.7	0.9
Newington-Dover (Getchell, 2013)	Silty sand	0	0
	Mud/Peat	0.8	0.8 – 1.1*

* B_q averages 0.98 from 8 to 14 m and 0.87 from 15 to 18 m

The correlation between U_D and B_q for the Newington-Dover site is not as close as the results shown for the other two sites. One major difference maybe the type piezocone used in Newington-Dover (Type 2) versus a Type 1 at the other sites even though the Type 1 pore pressures were adjusted for the position of the filter element. Another possibility is the geological history of the Presumpscot clay formation at both Newington-Dover and Pease AFB. Results from previous research performed on the Presumpscot clay suggest that the disparity between U_D and Bq seen in Fig. 10 may possibly be attributed to a natural anomaly rather than the location of the pore pressure sensor on the piezocone. A study by Santamaria et al. (2015) investigated an undrained strength reduction observed at various sites where the Presumpscot clay was tested using a Geonor field vane. This shift was previously shown in Ladd (1972), although it was never discussed in his paper (Fig. 11). At the Newington-Dover site, a strength reduction of nearly 25% occurs at a depth of about 15 m. Santamaria et al. (2015) were unable to determine with certainty the origin of this shift based solely on variations of grain sizes but hypothesized that a seismic event or a low-level lowstand exposing the Presumpscot Formation might be responsible for this anomaly. Nevertheless, U_D and B_q are in close agreement in the zone below the anomaly.

4. Conclusions

Using the results from our investigations, the use of the C-reading in DMT testing shows good potential to improve soil identification and as observed by Marchetti (1997) it can help discern between permeable and impermeable soils. Field experiments on different materials suggest that U_D and Bq approach zero for non-cohesive soils and range between 0.6 and 1.1 for cohesive soils (clay and mud/peat). In most cases, the profiles of U_D and Bq are nearly identical when using a Type 1 piezocone, but as shown for the Newington-Dover site, the Type 2 piezocone gave values of Bq approximately 20% greater than the U_D values. Testing at other clay sites will likely improve this correlation and assist in soil identification.

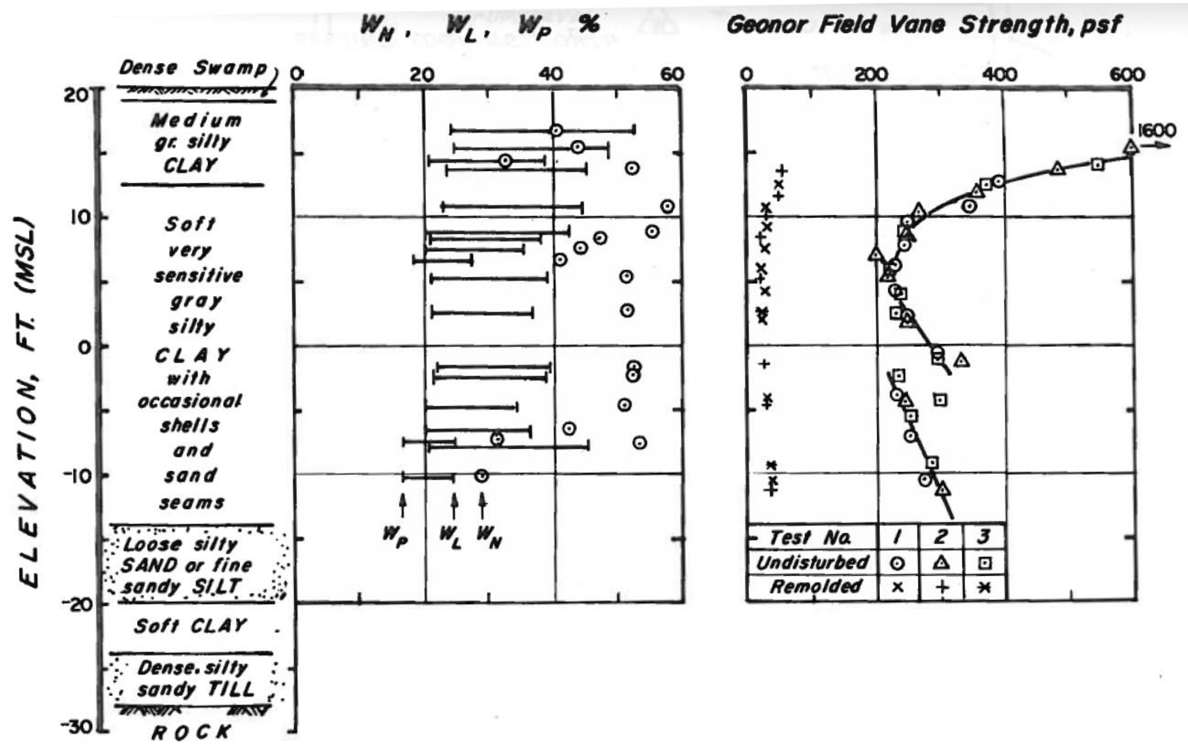

Figure 11. Soil profile, index properties and field vane strengths at experimental test section (Ladd, 1972).
Note: 1 ft = 0.3048 m and 1 psf = 0.048 kPa.

5. Acknowledgements

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