Settlement Analysis using the Dilatometer: Embankment over Soft Marine Clay Deposit in Dover, New Hampshire, USA.

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Keywords: dilatometer, settlement, dissipation

ABSTRACT: Flat plate dilatometer testing was performed before construction of a roadway embankment test section, Dover Test Embankment (DTE), for prediction of settlement rate and magnitude. The underlying, compressible soils are marine clays commonly found in the New Hampshire Seacoast area. The embankment fill was constructed after prefabricated vertical drains (PV-Drains) were installed with a triangular spacing of 1.8 m. Multiple dilatometer profiles and dilatometer dissipation tests were performed before the PV-Drains were installed. Data reduction for the dilatometer was completed using Marchetti's SDMT Elab software and DMT Dissip software. The dilatometer testing results were compared to the results of other in situ tests, in addition to research findings of others at nearby sites with similar soils. The constrained modulus (M_{DMT}) was used to estimate total settlement and is compared to the total settlement estimated with the Boussinesq method for embankments. This paper also presents the geotechnical instrumentation data collected during embankment construction and for a two year period of time that followed. The instrumentation data is used to evaluate the effectiveness of settlement prediction by traditional methods as well as those based on dilatometer testing.

1 INTRODUCTION

The New Hampshire Department of Transportation (NHDOT) constructed a road embankment test section, Dover Test Embankment (DTE), on top of a compressible marine deposit during the fall of 2012 to determine the effective treatment for long-term settlement of these clays in the New Hampshire Seacoast. Prior to construction, prefabricated vertical drains (PV-Drains) were installed in a triangular arrangement spacing of 1.8 m. The DTE has multiple segments and each has its own consistent embankment geometry. Segment 1 of the DTE is the focus of this paper and was 3.7 m tall and 60 m long with an inclination of 2H:1V along the side slopes.

Prior to construction of the DTE, the University of New Hampshire (UNH) performed laboratory consolidation testing on undisturbed samples in addition to piezocone (CPTu), field vane (FVT) and dilatometer (DMT) testing. The data collected was compared with previous research findings made at sites nearby with similar soil conditions, including Ladd (1972), Ladd et al. (1972), NeJame (1991) and Murray (1995), and the other in situ tests performed by the NHDOT in the area. After construction of the DTE and PV-Drains installation, additional CPTu and DMT tests were performed through the embankment fill.

2 BACKGROUND

2.1 *Site Characterization*

The DTE was constructed at the intersection of Route 4 and the Spaulding Turnpike in Dover, NH, west of the Little Bay and east of the Piscataqua River. This site is influenced by the tide and is a designated wetland resulting in poor drainage. The groundwater table level was monitored prior to, during, and after construction and was found to vary by as much as 1.5 m (Getchell et al., 2013). In Segment 1, the groundwater table depth, below original ground surface, during Phases 1 and 2 was reported at approximately 2 m and 0.5 m, respectively. Prior to construction, Standard Penetration Testing (SPT) was performed by the NHDOT to define the stratigraphy of the site. At the top is a fill consisting of a mixture of loamy topsoil, medium to fine sand and sandy silt and varied in thickness between 0.6 and 3.1 m. The fill overlies an alluvium layer with thickness between 1.4 and 3.1 m, comprised of fine sand and variable amounts of silt. The alluvium layer is underlain by a compressible marine clay deposit. Below the marine deposit lays a glacial outwash layer, followed by a glacial till layer and then bedrock. The marine deposit is part of what is known as the Presumpscot Formation and consists of an upper stiff layer, approximately 3 m thick, followed by 15 m of a very soft layer with variable amounts of silt and clay in addition to scattered fine sand layers. The NHDOT performed Atterberg Limit tests (plastic limit and liquid limit) on the marine clay deposit at various depths which resulted in values similar to that of a marine illitic clay. The Atterberg Limits and natural water contents (w) collected are plotted with depth and elevation in Fig. 1, along with the corresponding total unit weight and undrained shear strength that were determined from the in situ vane shear testing performed by UNH.

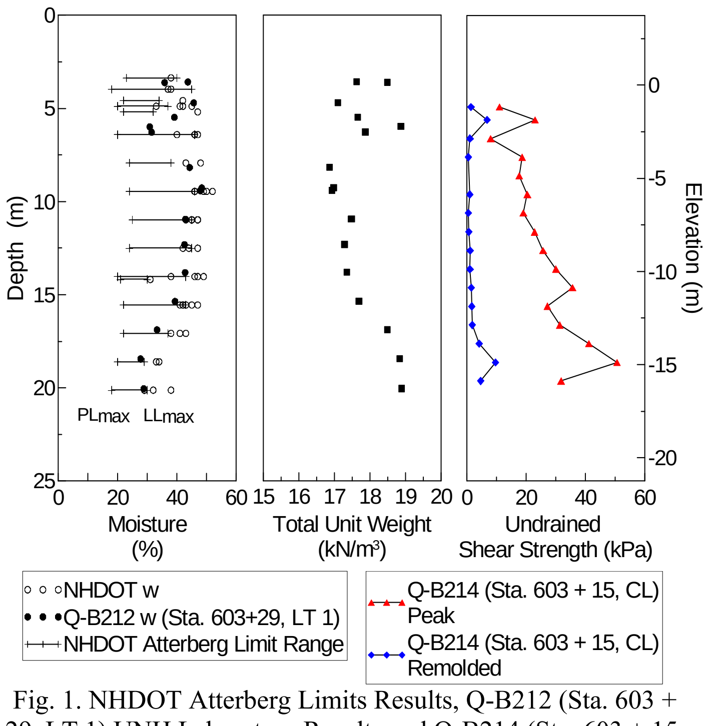

Fig. 1. NHDOT Atterberg Limits Results, Q-B212 (Sta. 603 + 29, LT 1) UNH Laboratory Results and Q-B214 (Sta. 603 + 15, CL) FVT Results (Getchell, 2013). *Note that the station information is given in feet.*

The average properties within the soft to very soft clay layer consist of an initial void ratio of 1.2, a liquid limit of about 38%, a plastic limit of 24% and, a natural water content of 41% which along with the field vane results is indicative of its sensitivity and potential for significant settlement. This marine clay classifies mostly as a low plasticity clay (CL) on the Unified Soil Classification System (USCS) with some specimens falling into the silty clay of low plasticity (ML).

2.2 *Testing Phases*

Phase 1 testing was performed during the summer of 2012. Undisturbed sampling for laboratory consolidation testing, FVT, DMT and CPTu testing were performed within the wooded area adjacent to the proposed embankment alignment.

Prior to construction, the footprint of the embankment was cleared of all vegetation and a sand drainage blanket was installed. Next, the PV-drains were driven through the blanket and the various NHDOT instrumentation was installed at each test section. The instrumentation included: settlement platforms, inclinometers, vibrating wire piezometers and benchmarks. Four months after construction of the DTE, additional DMT and CPTu testing were performed (Phase 2).

2.3 *Previous Research Findings*

As mentioned previously, other research performed within the Seacoast region was used for comparison with the data collected at the DTE site. NeJame (1991) performed dilatometer testing at the Pease Air Force Base (PAFB) in Portsmouth, NH, a short distance from the DTE site. Based on his investigation, the marine deposit was not as thick as that found at the DTE site, however, it did exhibit similar trends in the DMT index properties and derived geotechnical parameters. The overall stratigraphic sequence of the site was also similar. Additionally, Murray (1995) performed piezocone testing at the PAFB using a Wissa cone. He also found similar values in geotechnical properties to that of the marine deposit observed in Dover.

In 1967, the New Hampshire Department of Public Works and Highways (NHDPWH) began a program of improvements along Interstate 95 in Portsmouth, NH. A test embankment was constructed and loaded to failure. The test embankment was used by Ladd (1972) and Ladd et al. (1972) to evaluate the ultimate capacity of the underlying soft sensitive marine clay. The geotechnical parameters determined by those studies were used by the NHDOT for preliminary calculations and design of the current test embankment.

3 DILATOMETER TESTING

3.1 *Testing Program*

A flat dilatometer blade was used to perform the DMT profiling in accordance with ASTM D6635 (2001) Standard Test Method for Performing the Flat Plate Dilatometer. In addition, A-method dissipation tests were performed by taking a series of "A" readings for an extended period of time (approximately 24 hours), immediately after being pushed to the desired depth. Two phases of DMT testing were completed. Phase 1 was conducted prior to installation of PV-Drains and embankment construction. Phase 2 was conducted 4 months after completion of embankment construction.

During Phase 1 of testing, one continuous profile was performed with tests every 15 cm at station 603+28 LT 14. Additionally, fifteen dissipation tests were performed every meter at nearby station 603+40 LT 4 and four dissipation tests were performed every 3 m at station 603+35 LT 25. In between the dissipation testing locations, DMT tests were performed every 15 cm to use in comparison with the continuous profile.

During Phase 2, four continuous profiles were performed with tests every 15 cm. Ten dissipation tests were performed every 1.5 m at station 603+40 RT 5.

3.2 *Data Reduction*

Marchetti's SDMT Elab software was used to correct the A, B and C readings for membrane stiffness and gauge zero offset. The corrected readings correspond to p_0, p_1 and p_2 which were used to evaluate the DMT indices: material index (I_D), horizontal stress index (K_D), and constrained modulus (M_D). Plots similar to Fig. 2 were constructed for each profile showing various indices

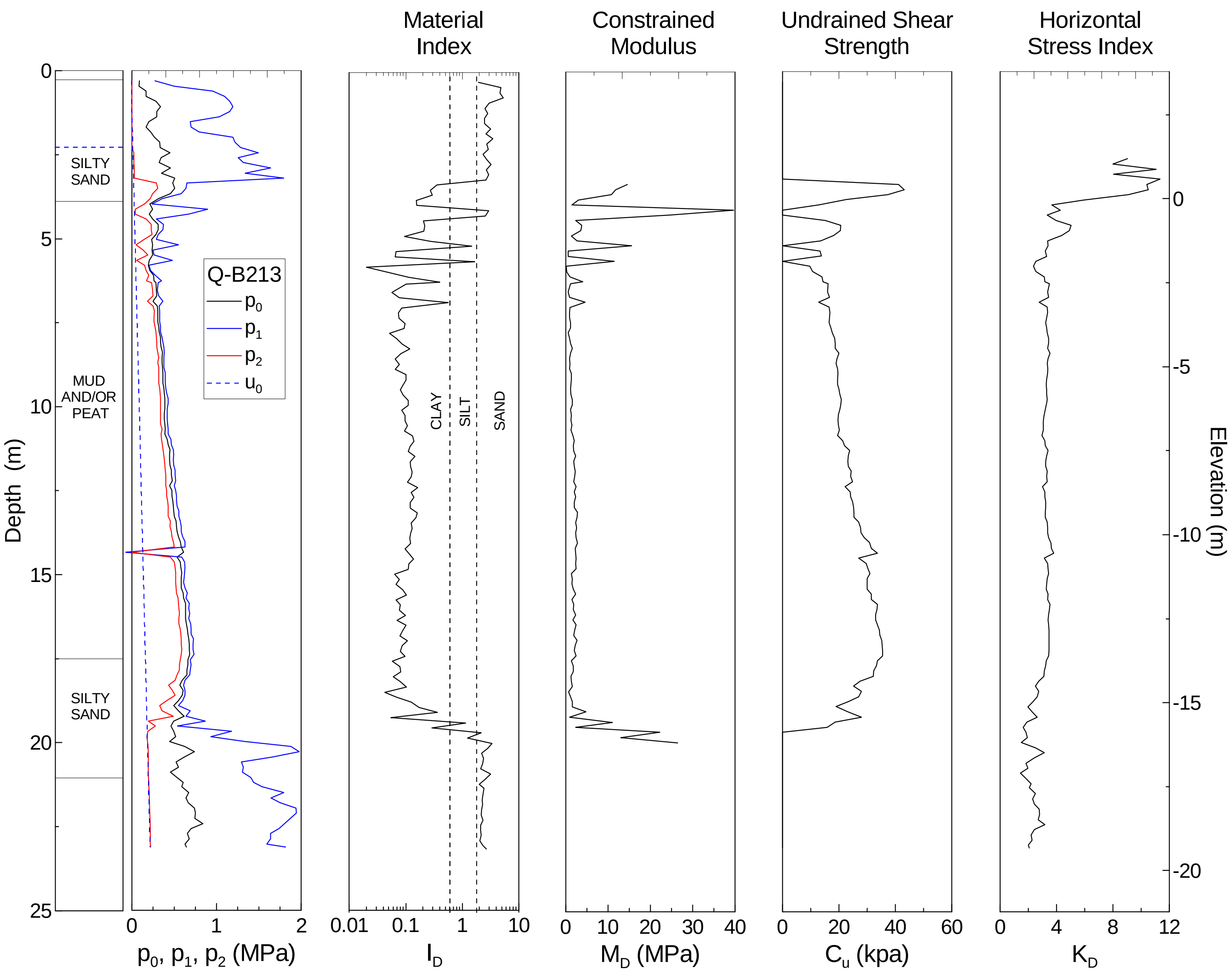

Fig. 2. Segment 1 Q-B213 (Sta. 603 + 28, LT 14) DMT Phase 1 Readings, Material Index Classification (I_D), Horizontal Stress Index (K_D) and Dilatometer Modulus (E_D) (Getchell, 2013).

with respect to depth and elevation. Total unit weight (γ_T), undrained shear strength (C_u), overconsolidation ratio (OCR), coefficient of consolidation (c_v), coefficient of lateral earth pressure (K_0) and permeability (k) were also estimated using various empirical relationships.

The DMT dissipation tests were analyzed using the Marchetti DMT Dissip software which plots the corrected A reading against the logarithm of time as shown in Fig. 3. The software plots the "S"-shape curve and selects the contraflexure point which corresponds to a time (T_{flex}) for estimate of the horizontal coefficient of consolidation ($c_{h,OC}$).

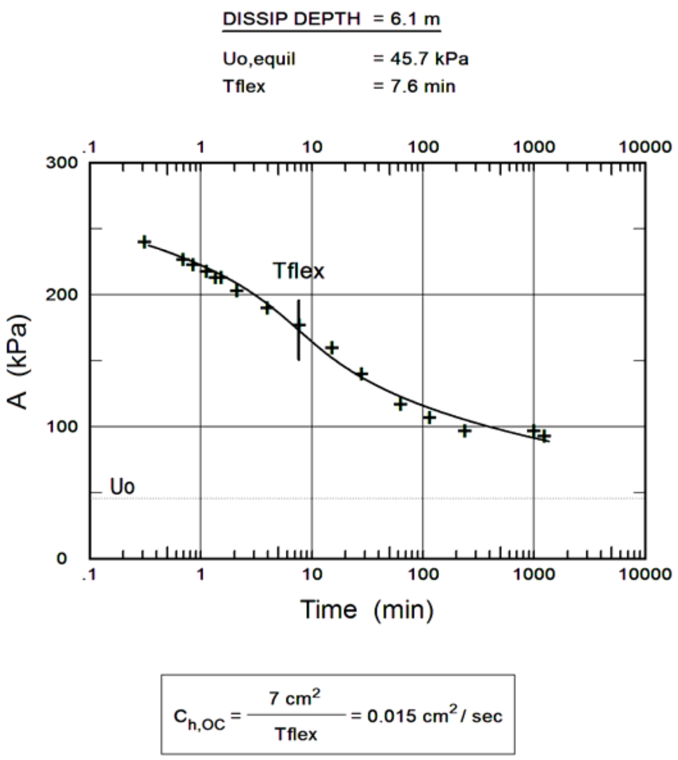

Fig. 3. Segment 1 Q-B215 (Sta. 603 + 40, LT 4) DMT Dissipation Test at Elevation 0 ft (Getchell, 2013).

From the consolidation testing the c_v values corresponding to the virgin compression for the Dover site, in the normally consolidated zone, range between 11 and 42 x 10^{-4} cm^2/sec. Findlay (1991) found a range for c_v of 16 to 95 x 10^{-4} cm^2/sec with an average value of 41 x 10^{-4} cm^2/sec. Test results by Findlay (1991), using horizontally trimmed specimens, gave an average horizontal coefficient of consolidation c_h of 29 x 10^{-4} with a range of 20 to 53 x 10^{-4} cm^2/sec. The in situ horizontal coefficient of consolidation for Dover in the normally consolidated zone ranges between 7.5 and 530 x 10^{-4} cm^2/sec. Fig. 4 shows Dover consolidation and DMT test results compared to results reported by Findlay (1991).

For the DTE site, the average vertical coefficient of consolidation was estimated at 13 x 10^{-4} cm^2/sec while the horizontal coefficient of consolidation obtained from DMT dissipation tests gave an average value of 11 x 10^{-4} cm^2/sec.

The average compression and recompression indices for the DTE from consolidation testing were found to be 0.31 and 0.05, respectively.

3.3 *Phase 1 Results*

After compiling the data from the DMT tests and other testing methods performed in Phase 1, the marine deposit can be summarized as shown in Table 1. The layer can be characterized as soft to very soft normally to near normally consolidated.

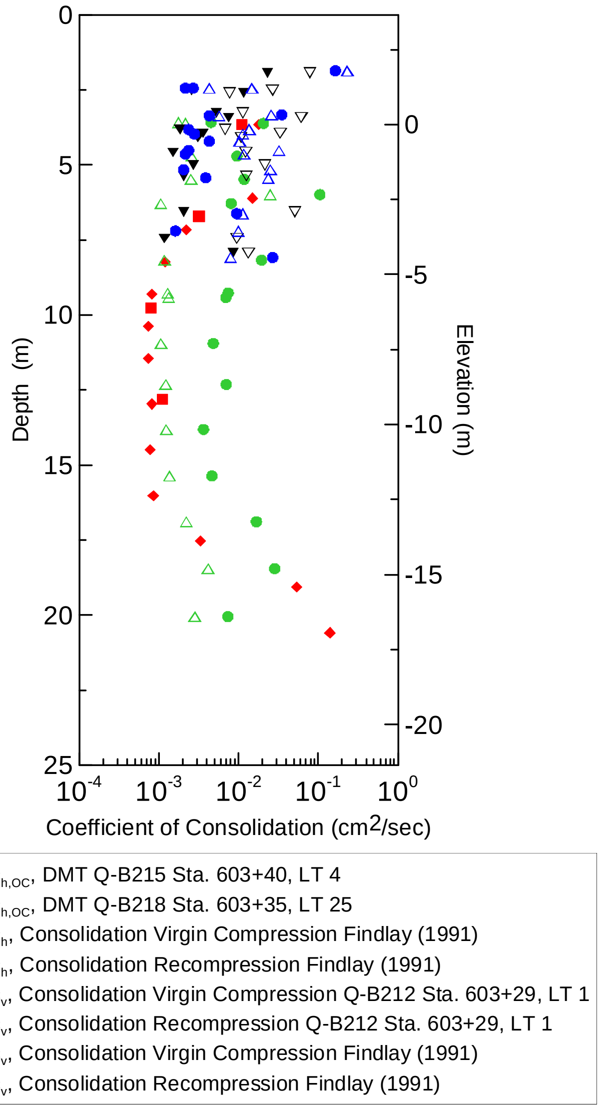

Fig. 4. Horizontal and Vertical Coefficients of Consolidation Found in Segment 1 and by Findlay (1991).

Table 1. Summary of Engineering Properties for the Dover Test Embankment, NH (Getchell, 2013).

Depth Below Surface (m)	γ_T (kN/m^3)	C_u (kPa)	OCR	K_0	k (cm/sec)
6 - 18	17.3	22	1.3	1.00	7.1 x10^{-8}

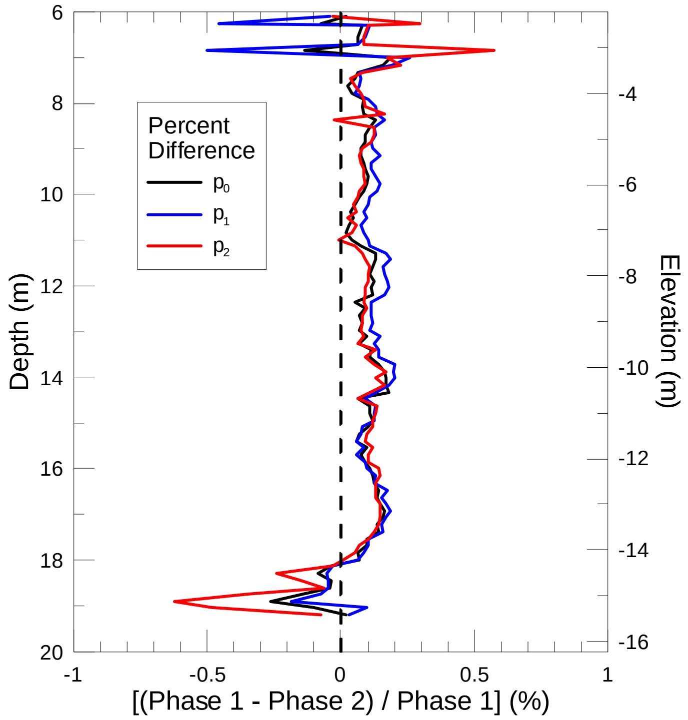

Fig. 5. Phase 1 and 2 Segment 1 DMT Readings (Getchell, 2013).

The values presented in Table 1 are in good agreement with those found in Portsmouth, NH.

3.4 *Phase 2 Results*

The DMT testing performed during Phase 2, 4 months after embankment construction, appeared to exhibit the same trends found during Phase 1, however, slightly lower values of p_0, p_1 and p_2 were observed suggesting a decrease in undrained strength. Fig. 5 shows the percent difference between Phase 1 and Phase 2 for the zone of interest from approximately 6 to 18 m within the soft clay layer.

Although small, an increase in strength should result as the marine clay is consolidating under the embankment. The DMT results suggest a decrease in strength after four months of dissipation although those differences are small. It is likely that this particular profile was performed near or within the remolded zone from the installation of the PV-drain. During installation, total remolding of the clay could be observed as the mandrel was retracted to the ground surface. Unfortunately the exact positions of the drains could not be determined once the embankment was constructed and the verticality of the drains is not always ensured during installation. Other profiles were carried out to verify these results and showed similar behavior suggesting a strong influence of drain installation remolding on the DMT measurements. Additional DMT profiles are planned to assess the property changes over time.

4 SETTLEMENT ANALYSIS

Prior to both phases of testing, the NHDOT had predicted a total settlement of up to 0.75 m based on the work performed by Ladd (1972) and Ladd et al. (1972). Using the data collected in the field and laboratory, settlement calculations were performed using hand calculations. Current studies are using finite element analysis with PLAXIS 2D and the Rocscience software Settle 3D. The hand calculations presented here provided a total settlement, whereas, the finite element analysis and Settle 3D will help estimate the time rate settlement of the marine deposit.

4.1 *DMT Hand Calculations*

The Boussinesq method for embankments was used to calculate the stress distribution below the center of the embankment. Various load types have been derived from Boussinesq's original equations for the state of stress within a homogenous, isotropic, linearly elastic material for a load acting perpendicular to the surface, including embankment loading (Holtz et al., 2011).

The NHDOT recommended a unit weight of 18.9 kN/m^3 be used to represent the embankment fill. From there, Equation 1 was used to estimate the stress at each depth below the embankment based on the embankment dimensions described in Fig. 6.

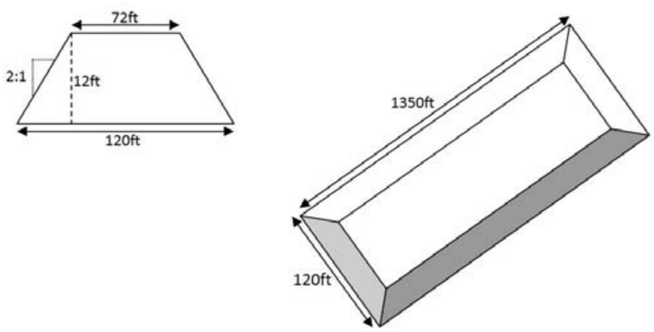

Fig. 6. Settlement Prediction Embankment Dimensions (Getchell, 2013).

Note: 1 ft = 0.3048 m

$$\sigma_z = 2 \times \frac{q_0}{\pi}\left[\beta + \frac{x\alpha}{a} - \frac{z}{R_2^{\,2}}(x-b)\right] \tag{1}$$

$$\alpha = \tan^{-1}\left(\frac{b}{R_2}\right) - \tan^{-1}\left(\frac{b-a}{R_2}\right) \tag{2}$$

$$\beta = \tan^{-1}(\frac{b-a}{R_2}) \quad (3)$$

where, q_o = the load of the embankment; a = 7.9 m; b = 18.3 m; and R_2 = the depth below the embankment.

After the Boussinesq method was performed, the total settlement was calculated based on the DMT constrained modulus using Equation 4.

$$S_{DMT} = \sum \frac{\Delta\sigma_z}{M_{DMT}} \Delta z \quad (4)$$

where, $\Delta\sigma_z$ = change in stress due to the weight of the embankment; and Δz = height of compressible layer (Marchetti et al., 2001).

The constrained modulus is believed to be one of the most reliable parameters obtained by the DMT and is calculated as follows:

$$M_{DMT} = R_M E_D \quad (5)$$

where, R_M is depended on the material index (I_D); and E_D = dilatometer modulus.

The hand calculations provided a total settlement of 0.5 m. As of December 2014 (about 2 years after construction), the DTE had experienced 0.45 m of settlement, as shown in Fig. 7 using data from a settlement plate beneath the centerline of the test embankment.

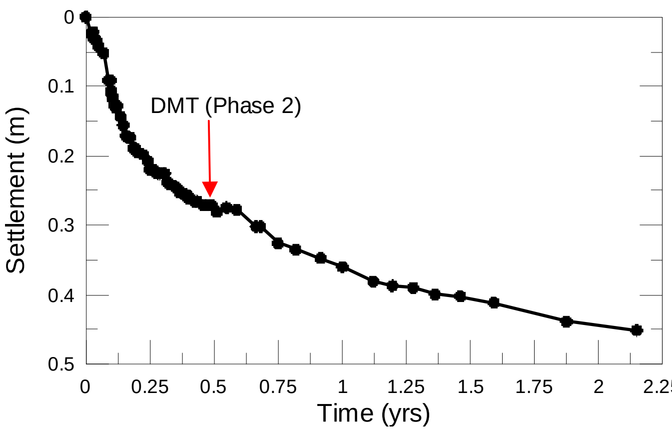

Fig. 7. Settlement Measurements for Settlement Platform 1 in Segment 1 with 1.8 m PV Spacing, Beginning 8 October, 2012.

5 CONCLUSIONS

Laboratory consolidation, FVT, CPTu and DMT testing was performed in Dover, NH to characterize the soft marine sensitive clay deposit found throughout the Seacoast area and to assist in the prediction of the long-term settlement under the Dover Test Embankment. Based on the collected data, the marine deposit was characterized as previously summarized in Table 1. Based on the hand calculations for settlement, the DTE settled about 90% of the total estimated settlement after 2.15 years. These estimates will be refined and revised following further analytical studies using coefficients of consolidation obtained from the DMT. In this study, the dilatometer was found to be very useful and reliable in providing the necessary parameters for embankment design and of settlement estimates compared to conventional approaches which have historically consisted of SPT, Atterberg Limits and laboratory consolidation testing.

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