Driven Pile Setup Testing and the Dilatometer

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ABSTRACT: The flat dilatometer test (DMT) provided essential insitu stress measurements used to investigate the increase of driven pile capacity with time, or “pile setup”. Five, square, prestressed concrete piles driven in both cohesive and cohesionless soils in Florida and repetitively tested for up to five years included DMT cells that measured the total lateral stress against the pile. The calculated effective stress correlated to the pile side-shear increase over the five-year test period. DMT soundings also measured insitu lateral stresses that matched the lateral stress on the piles immediately after driving, and C-readings that agreed with the tidal hydrostatic pore pressures. The coefficient of consolidation from DMT A-reading dissipation tests correlated with that from cone penetrometer pore-pressure dissipation tests, as did the penetration thrust measured at the top of the rods versus thrust measured just above the DMT blade.

1 INTRODUCTION

Driven piles often exhibit a significant increase in capacity versus time, which many engineers refer to as "setup" and which results primarily from increasing side shear capacity (Bullock, 2008). Skov & Denver (1988) observed that the rate of increase gradually diminishes, with capacity following a linear trend versus the logarithm of elapsed time. The setup process initially increases the shear resistance along the pile sides because of consolidation and an increase in the lateral effective stress within soil displaced during pile installation (Bullock et al. 2005, Chow et al. 1998, and Axelsson 1998). Additional setup, after about 30 days, occurs because of mechanical aging that increases the friction angle, a process that Schmertmann (1991) identified as affecting any soil under constant stress.

To investigate long-term pile setup, researchers at the University of Florida (UF) drove five, 457-mm, square, prestressed concrete piles into a variety of coastal plain soils, and then performed multiple load tests to measure changes in side shear capacity (Bullock 1999). The UF test program also evaluated the effects of the initial lateral effective stress against the piles, pore-pressure dissipation, effective stress change, and soil type, as well as the potential use of insitu tests for predicting side shear. The flat dilatometer test (DMT) provided important site characterization and lateral stress measurements for this research.

2 LATERAL STRESS ON PILES

2.1 *Florida test piles*

As shown in Fig. 1, the UF test piles included an Osterberg Cell (O-cell) cast into the bottom of each pile to perform repeated static load tests using minimal equipment. UF chose test sites adjacent to active bridge projects in Florida, where contractors installed the test piles using a variety of hammers, including a Delmag D46-32, a Delmag D62-22, and Fairchild 32. Dynamic tests provided an estimate of the static capacity for the end of initial driving and restrikes 15 min and 1 hr later using the CAPWAP program (Bullock et al. 2005). After driving the test piles into a strong bearing layer, pressure applied to the O-cell from the surface pushed the pile upward to mobilize the available side shear. Static testing began within 24 hrs of initial driving and continuing for as many as 4.7 yrs.

Fig. 2 shows an approximately log-linear trend of the whole-pile side shear for the five UF piles. The test piles also included strain gages to determine the distribution of side shear down the pile, dividing the five piles into 28 segments by soil type for more detailed analysis of the setup. Segment side shear ranged from near zero to 269 kPa. Pile instrumentation also included Dilatometer total stress cells and piezometers to determine the lateral total stress, pore pressure, and lateral effective stress at the center of 20 of the pile segments, or about 3 to 5 locations per pile. Bullock (1999) presents comprehensive test details and results for each of the five test piles.

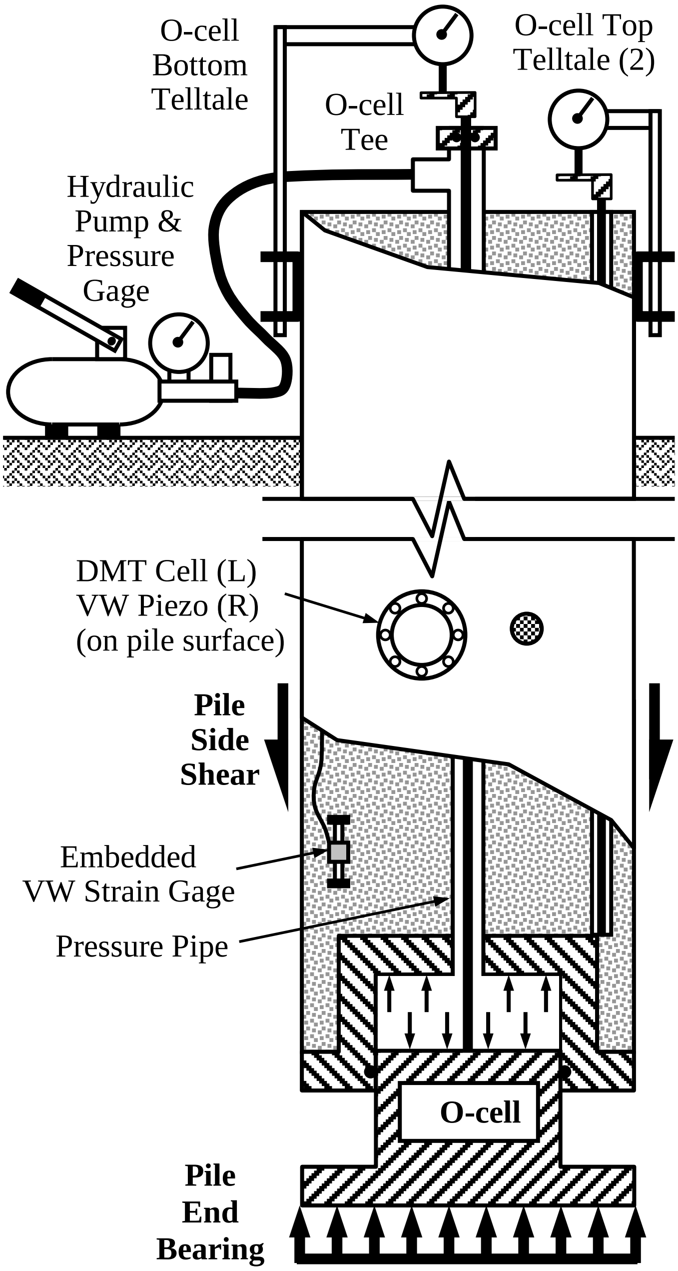

Fig. 1. Florida test pile instrumentation

2.2 *Dilatometer cells and piezometers*

DMT cells mounted flush with the pile face measured the total lateral stress in the soil on one side of the pile (Fig. 3). Essentially a cutout from a Marchetti flat plate Dilatometer blade, these stainless steel cells had the same basic design and dimensions with a 60-mm diameter, 0.2-mm thick, stainless steel membrane. Manual “A-readings” of the membrane lift-off pressure were obtained using a standard DMT control unit with a resolution of about 1 kPa and an accuracy of 1 to 4 kPa depending on the pressure gage used. The pressure was vented immediately following the A-reading to avoid disturbing the insitu lateral stress.

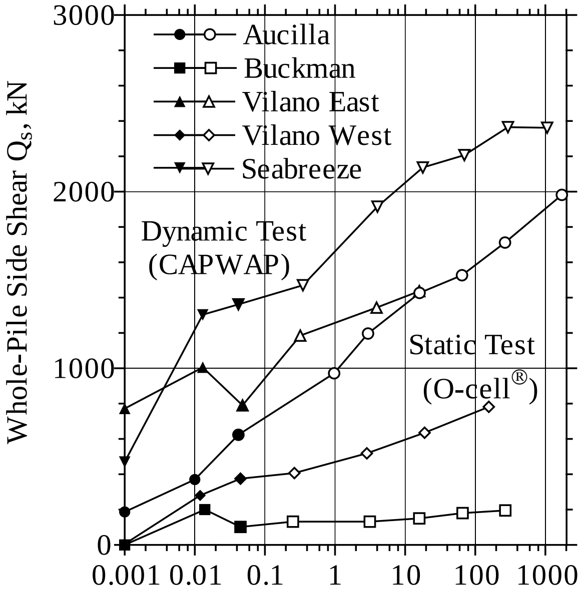

Fig. 2. Side shear setup for UF research piles

Pore pressure in the soil was measured adjacent to each DMT cell (spaced 150 mm center to center) using a vibrating wire (VW) piezometer (Geokon model 4500S), also mounted flush with the pile face. It included a 50-micron, 16-mm diameter, stainless steel filter, saturated with a solution of 50% glycerin and 50% water. This piezometer provided an accuracy of 5 KPa with a 1 MPa range. Readings were taken manually using a GK401 VW Readout Box or digitally using a datalogger. Both the piezometers and DMT cells were covered and sealed during pile construction, and then uncovered just prior to penetration into the soil. Readings began at the end of initial driving.

The DMT cells and piezometers included anchors into the pile concrete and were bolted to a steel angle clamped to the casting bed rails to maintain their position during pile construction. Figs. 3 and 4 show the DMT cells and piezometers in place ready for concreting and on the Seabreeze (SBZ) test pile.

One VW piezometer worked inconsistently and one DMT cell leaked (on different pile segments) prior to pile installation, but the remaining 18 instrument pairs provided reasonable and consistent measurements throughout the tests. The DMT cells were installed in saturated soil, and eventually all of them leaked, likely around the membrane seal. However, by using a voltmeter to monitor the cell circuit, the tester could detect the abrupt increase in resistance that occurred at the membrane lift-off pressure when the steel-steel contact to the membrane is broken and the electrical circuit then shorts through the water inside the cell.

Fig. 3. DMT cell and piezometer in pile form

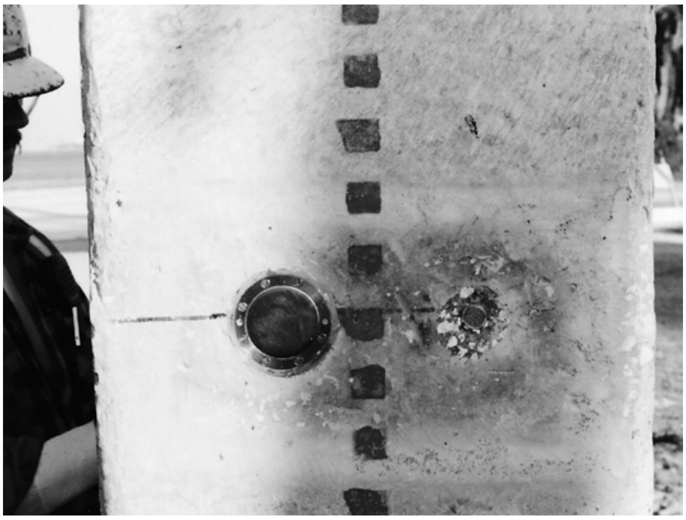

Fig. 4. DMT cell (L) and piezometer (R) on SBZ pile

2.3 *Measured stresses*

Used together, the piezometers and Marchetti Dilatometer (DMT) total stress cells measured the effective lateral stress at 20 test pile locations, with 3 to 5 locations on each test pile. Fig. 5 shows a log time plot of the measured total stress, pore pressure, and effective lateral stress for one of the test piles. Bullock (1999) used these plots to separate the portion of the measured setup due to consolidation and lateral stress change from that which occurred during long-term aging. In most cases, the effective stress tended to stabilize along with the pore pressure, which generally occurred within two weeks but as long as 157 days.

2.4 *DMT cell advantages*

The DMT cells proved robust during pile handling and installation. The stainless steel cells use a mechanical system that provided reliable and reasonable results. A different design for the membrane seal, or silicone adhesive, might prevent the long-term leakage.

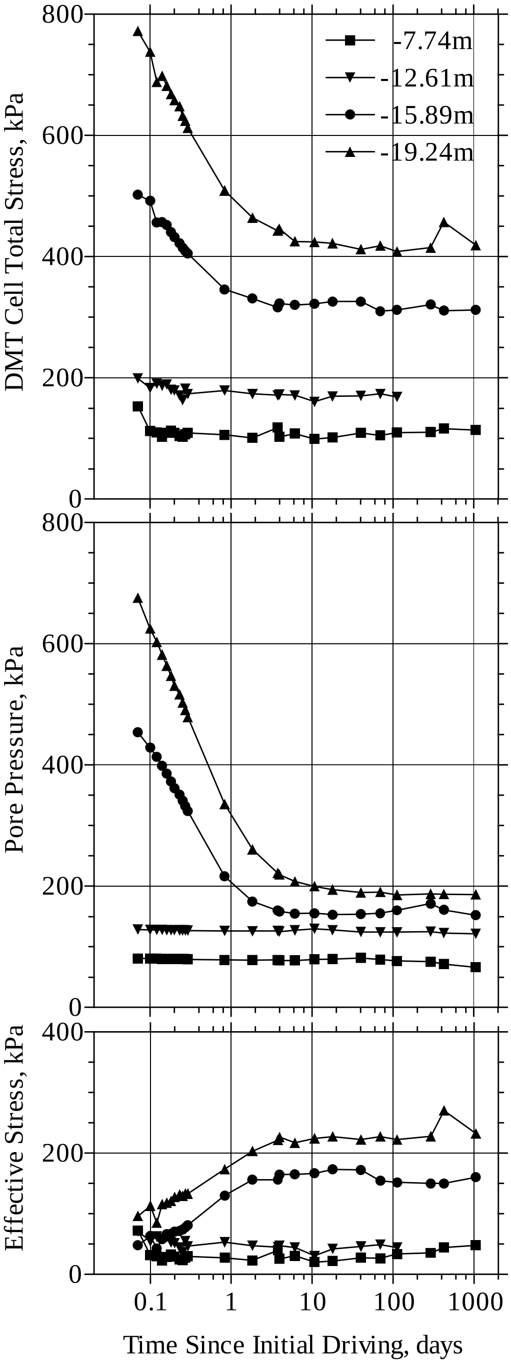

Fig. 5. Lateral stresses measured at Seabreeze

3 ADDITIONAL SITE INVESTIGATION

3.1 *Predicting setup*

At two of the of the test sites, Vilano East (VLE) and Vilano West (VLW), UF performed additional site investigation tests (Bullock 1999) to develop a method of predicting the observed pile setup factors using the Cone Penetrometer Test (CPT), the DMT, and the Standard Penetration Test (SPT). Tests at representative depths near the test piles (< 4 m away) included staged measurements of the Cone Penetrometer sleeve side shear, Dilatometer thrust measurements using a load cell placed immediately above the blade, and torque measurements on the SPT sampler. Begun about 4 yrs after test pile installation, the CPT and DMT tests recorded the

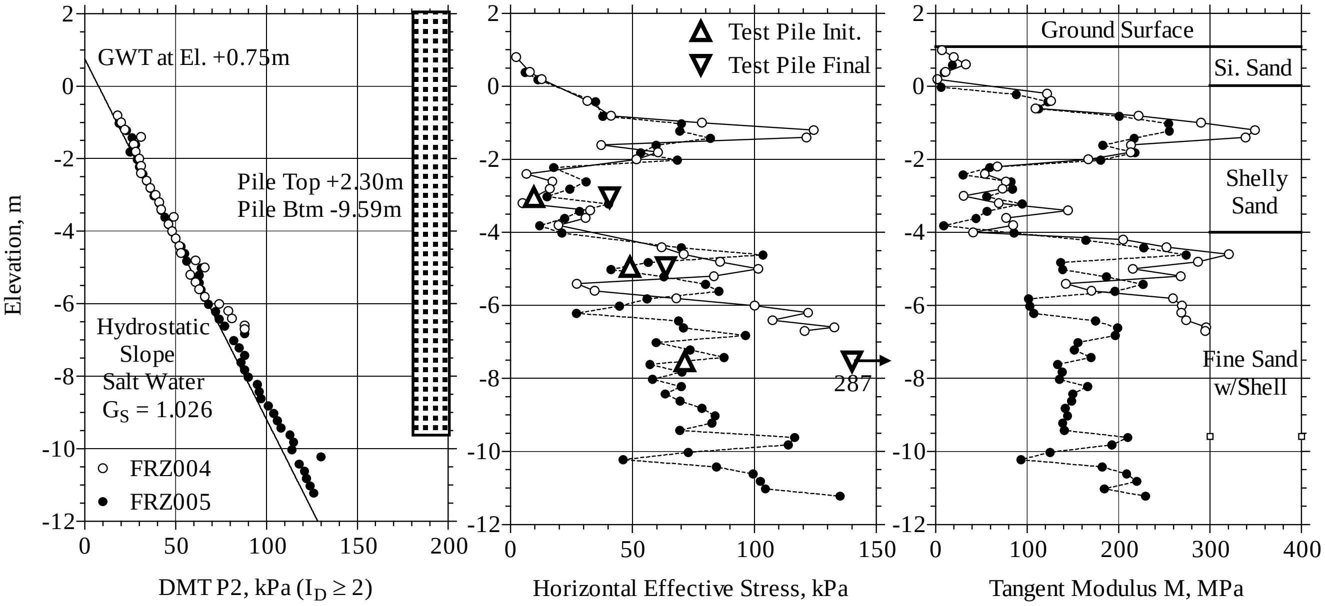

Fig. 6. DMT results from VLE

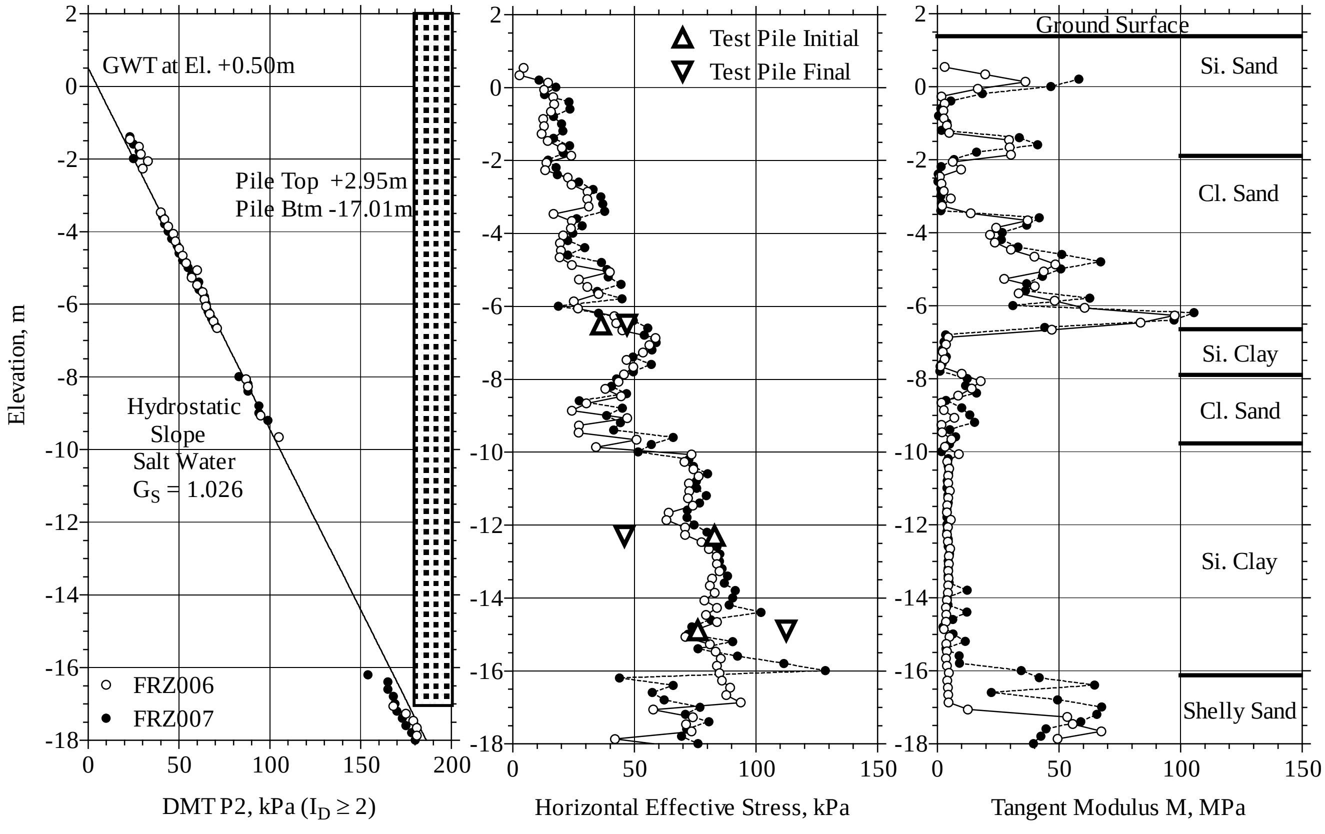

Fig. 7. DMT results from VLW

initial penetration resistance and then the final resistance several hours later, after the excess pore pressure had fully dissipated.

Although the CPT friction sleeve did model pile setup behaviour, the CPT electronic requirements made the test protocol impractical. For the DMT, a new 10-ton load cell was developed to measure the rod thrust just above the blade. However, end bearing on the blade, which should not change significantly, appeared to dominate the penetration resistance and obscured the increase in side resistance. The test results compared poorly with the pile setup and did not prove useful.

In sand, all of these tests produced unsuitable, negative setup factors during the necessarily short test duration (< 24 hrs), similar to short-term static test results from the piles. For cohesive soils, the Standard Penetration Test with Torque measurement (SPT-T) proved the most practical. While the DMT soundings did not directly predict pile setup, they did provide other useful results as discussed below. Figs. 6 and 7 show the results from the four DMT soundings at VLE and VLW.

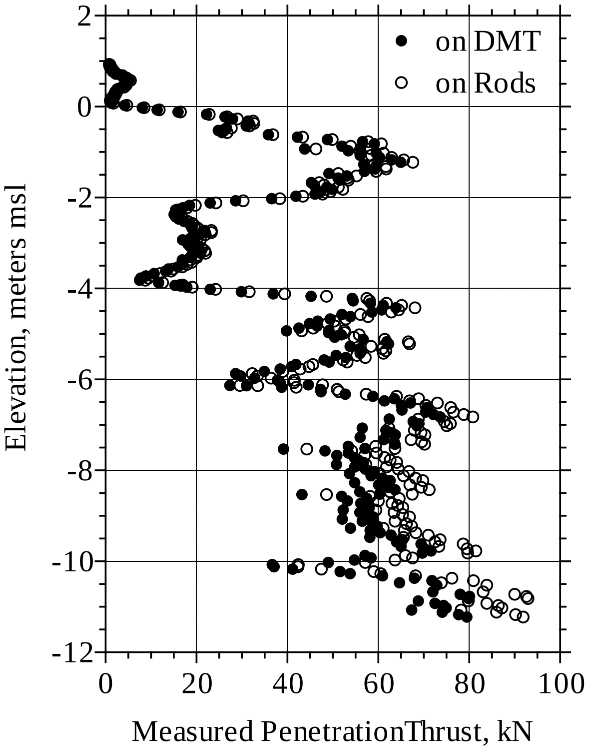

Fig. 8. VLE penetration thrust - DMT FRZ005

3.2 *DMT thrust*

Schmertmann (1988) developed a back-calculation for the friction angle in sands based on the DMT data and the penetration resistance on the blade. Ideally, an oversized ring on the rod adapter to the blade removes most of the friction on the penetration rods so that thrust measurements made at the surface represent the penetration resistance at the blade. The rod thrust measurements for the VLE and VLW soundings provided an opportunity to verify the effectiveness of the friction reducer in typical use. The blade load cell included a 48-mm diameter friction ring for the 36-mm diameter CPT rods. Additional bearing was expected on the friction ring, which the surface thrust measurement included but the blade load cell would not.

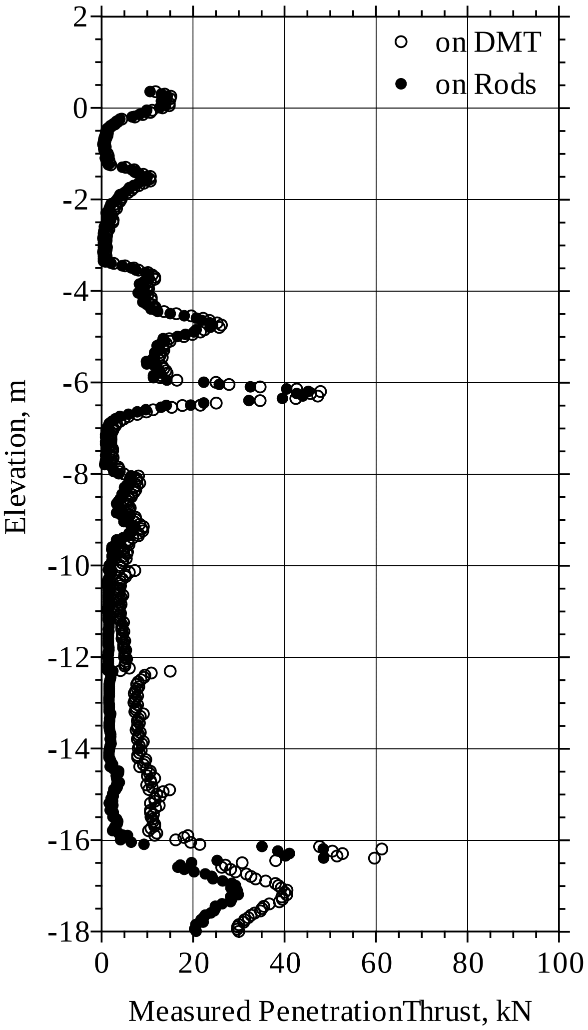

Fig. 9. VLW penetration thrust - DMT FRZ007

Figs. 8 and 9 show simultaneous thrust readings at the top of the rods and at the load cell above the blade for two of the four DMT soundings. Fig.10 compares the thrust values directly from all four soundings. In the weaker soils, the thrust on top of the rods and at the blade appear very similar. In the dense sands, significant bearing developed on the friction ring, but this bearing is included in the calculations for friction angle. Separate analyses for friction angle prepared using each thrust measurement provided almost the same values, indicating that the rod friction was not significant for these soundings. Direct thrust measurement at the blade should provide a more accurate analysis for critical applications such as research testing.

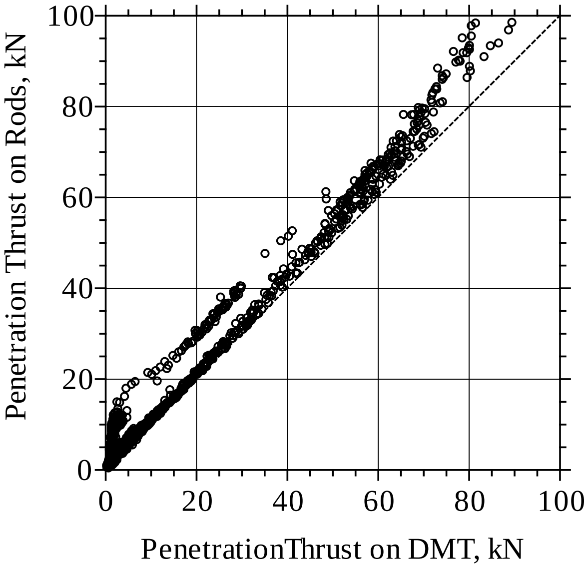

Fig. 10. Comparison of thrust measurements

3.3 *C-readings*

Schmertmann (1988) also proposed using C-readings to obtain the insitu pore pressure, measuring the pressure on the blade membrane after controlled depressurization from the DMT B-reading back to the A-reading position, as subsequently described in ASTM (2014). The VLE and VLW test sites are located immediately adjacent to the Atlantic Ocean with the tidal phreatic surface near the ground surface at the time of testing and just above mean seal level. Figs. 6 and 7 correctly indicate the elevation of the groundwater surface using the C-reading corrected to P_2 by subtracting the gage zero and adding the delta-A membrane calibration.

3.4 *Lateral stress from DMT*

Figs. 6 and 7 include depth profiles of the insitu lateral effective stress estimated by the DMT (from k_o). These figures also include the initial and final lateral effective stresses measured by the pile DMT cells. The initial lateral effective stress against the piles matches well with the lateral effective insitu stress from the DMT and could be used in calculations for the end-of-drive pile capacity before setup. Marchetti et al. (1986) postulated similar results for the setup pile capacity based on fully dissipated measurements of the DMT A-reading.

3.5 *Dissipation testing*

The thrust testing performed for setup prediction using the CPT and DMT at VLE and VLW also provided dissipation test results for pore pressure and A-readings respectively (Bullock 1999). While the A-reading does not directly measure pore pressure, its dissipation with time has been shown by Campanella et al. (1985) to closely track the dissipation of pore pressure in the soil in front of the DMT membrane. The CPT soundings included 20 pore-pressure dissipation tests. The DMT soundings included 26 A-reading dissipation tests, with 20 of these tests performed at depths comparable with the CPT dissipation tests. The A-reading tests followed ASMT (2014), pressurizing the DMT membrane just enough to repeatedly measure only the A-reading before venting the pressure and obtaining curves similar to Fig. 11. Schmertmann (1988) observed that the time observed for 50% A-dissipation, t_{50}, was about 2.5 times that required for CPT pore-pressure dissipation, probably due to the nearly plane-strain condition around the DMT blade versus the axisymmetric conditions around the cone. Fig.12 shows the comparison between t_{50} from the CPT and the DMT. While this plot contains some scatter, probably some of which is due to spatial variability, it shows the ratio of DMT to CPT for t_{50} as 3.8.

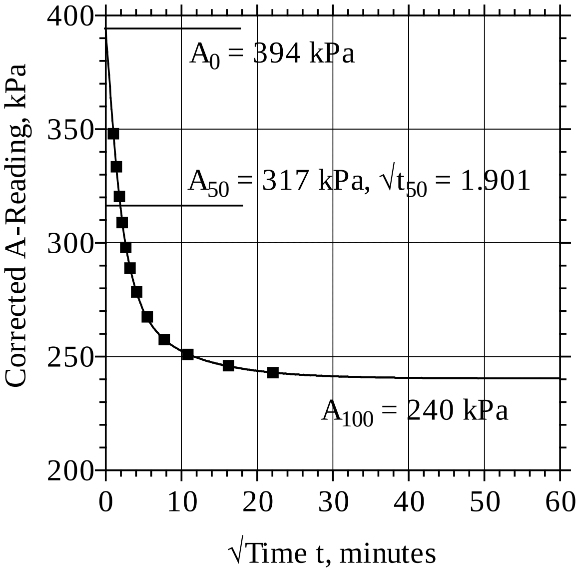

Fig. 11. DMT A-dissipation: FRZ007, El. -10.09m

Schmertmann (1988) also provides a recommended method for calculating the horizontal coefficient of consolidation, c_h, from the A-dissipation. Robertson et al. (1992) provides a similar method for calculating c_h from the CPT dissipation. Fig. 13 shows a comparison of c_h using these two methods the DMT and CPT. Given that both methods likely provide results with accuracy of an order of magnitude, the comparison shows that the DMT provided results comparable to the CPT.

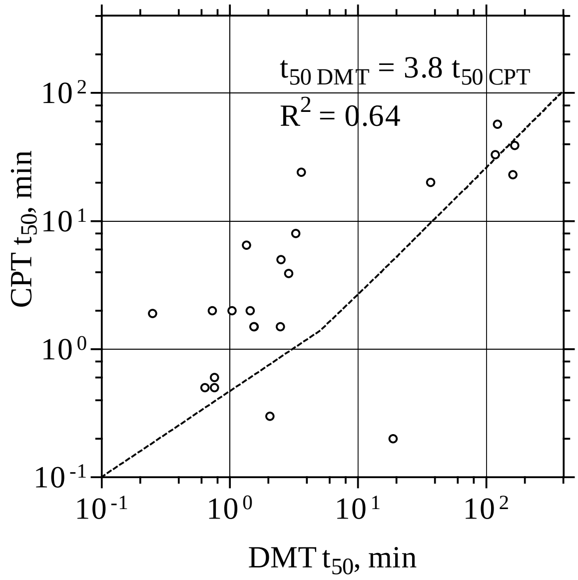

Fig. 12. Comparison of $t_{50\ DMT}$ vs. $t_{50\ CPT}$

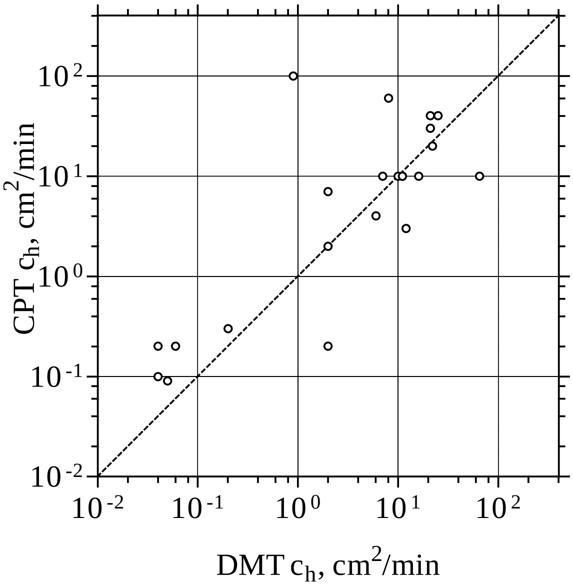

Fig. 13. Comparison of $c_{h\ DMT}$ vs. $c_{h\ CPT}$

4 CONCLUSIONS

DMT measurements provided key information for the UF pile setup research.

- DMT cells measured the lateral stress against the test piles to separate pile side shear increase that occurred during consolidation and effective stress change versus long-term steady state.
- DMT cells proved reliable and usable even after flooding occurred long-term.
- Changes in penetration resistance intended to model pile setup during a dissipation test did not prove useful, likely because of including point bearing on the bottom of the blade.
- A 10-ton load cell just above the DMT blade provided a direct measure of penetration resistance for more accurate friction angle calculations.
- A friction reducer eliminates most of the rod friction to allow using thrust measurements at the top of the rods for friction angle calculations based on bearing formula and DMT results.
- C-readings accurately predicted the groundwater phreatic surface.
- The insitu lateral effective stress from the DMT matched the initial lateral effective stress against the test piles.
- DMT A-dissipation tests provided t_{50} values approximately 3.8 times greater than CPT t_{50}.
- DMT A-dissipation tests c_h values compared well c_h from CPT pore-pressure dissipation.

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