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GROUND IMPROVEMENT RESULTING FROM INSTALLATION OF DRILLED DISPLACEMENT PILES

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Drilled displacement piles (also known as augered cast-in-place displacement piles or augured, pressure grouted displacement piles) are installed by the displacement of soil and subsequent placement of fluid cement grout within the evacuated volume. Depending on the soil grain-size characteristics, soil behavior, *in situ* soil density, pile spacing, and pile diameter, the installation process can result in measurable densification and an increase in lateral stress. This paper examines the conditions prior to and following the installation of drilled displacement piles at sandy sites using the cone penetration test. The data support that the installation of drilled displacement piles results in a substantial increase in tip resistance.

Introduction

As described by NeSmith (2002a; 2002b), drilled displacement piles are installed by the displacement of the soil within the pile volume and subsequent placement of fluid cement grout in the evacuated volume. The drilling tool (shown in Figure 1) used to install displacement piles consists of a bottom auger section with a length of 0.9 m (3 ft), a displacement section that is equal to the nominal diameter of the pile, and a few flights of reverse auger above the displacement section. As this tool is advanced, the soil in the pile volume is displaced horizontally. Depending on the soil grain-size characteristics, *in situ* soil density, pile spacing, and pile diameter, the installation process can result in measurable densification and an increase in lateral stress.

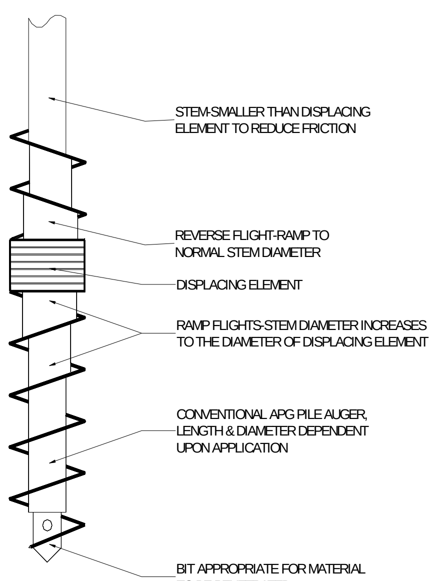

Figure 1. Berkel Displacement Tool

Characterization of Improved Ground

Siegel *et al.* (2007) used the cone penetration test (CPT) to characterize the improved ground conditions immediately after installation of 406 mm (16 in) diameter drilled displacement piles at a site in North Myrtle Beach, South Carolina. The testing in North Myrtle Beach was limited to the upper 8.5m (28 feet) of beach sand and shell hash of Pleistocene age. These upper soils classify as silty sand (SBT=7) and sand (SBT=8 or 9) according to the sleeve friction based system proposed by Robertson *et al.* (1986).

As an illustration of the effectiveness of drilled displacement piles, Figure 2 graphically compares the pre-installation and post-installation profiles of corrected cone tip resistance (q_t) collected adjacent to a single pile at the North Myrtle Beach site. It is of some significance that the increase in tip resistance begins at a depth of approximately 1.5 m (5 ft) below the working ground surface. It is the authors' opinion that a lack of confining pressure at shallow depths resulted in the soil being pushed upward rather than laterally displaced. Otherwise, there is a significant increase in tip resistance for the post-installation conditions.

The influence of the displacement pile installation can be represented by the ratio of the post-installation tip resistance to the pre-installation tip resistance. The term *tip resistance ratio* (R_q) is defined as:

$$R_q := \frac{q_{t\_post\_installation}}{q_{t\_pre\_installation}} \qquad \text{Eq. 1}$$

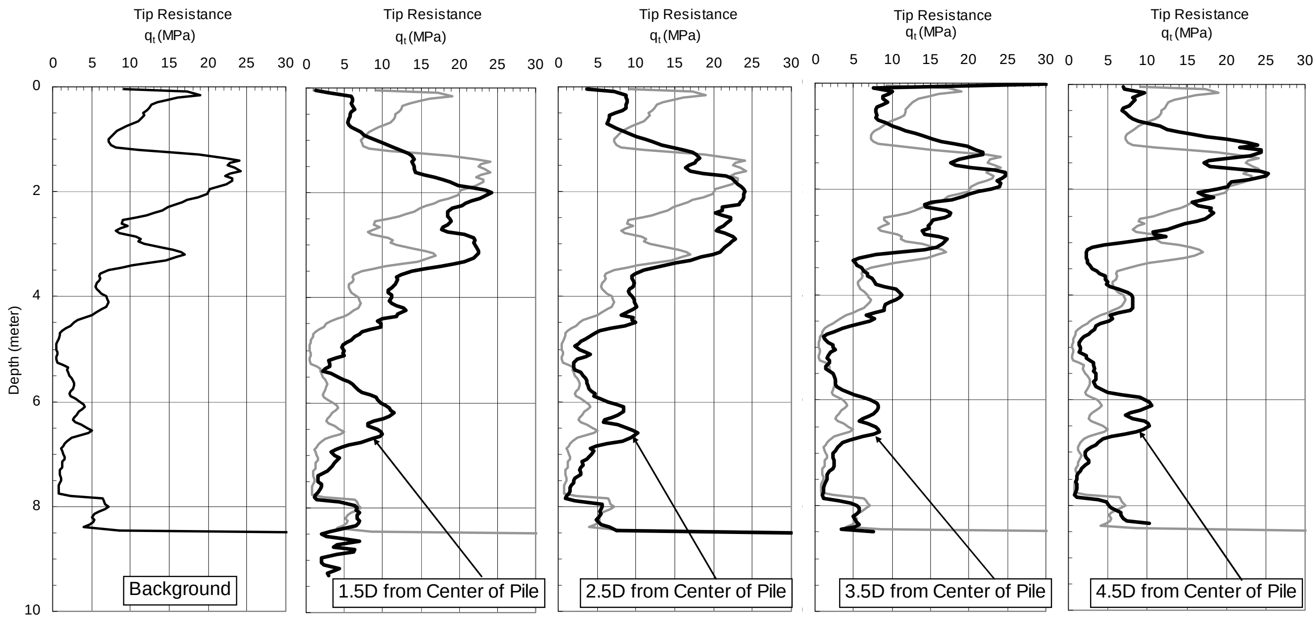

Figure 2. Tip Resistance Versus Depth Near A Single Displacement Pile

It is possible to make use of the tip resistance ratio (R_q) in evaluating the data shown in Figure 2. That is, an R_q value was computed for each test increment of 50 mm (2 in) and then plotted versus the normalized (corrected) tip resistance q_{t1} which is defined as:

$$q_{t1} := \left(\frac{q_t}{p_a}\right)\left(\frac{p_a}{\sigma'_{vo}}\right)^{0.5} \qquad \text{Eq.2}$$

where σ'_{vo} is the vertical effective stress and p_a is atmospheric pressure.

The resulting plots of R_q versus q_{t1} for the data collected near a single drilled displacement pile at the North Myrtle Beach site are presented in Figure 3. These plots illustrate several significant points regarding the soil improvement experienced adjacent to drilled displacement piles in stratified soils. The highest R_q values represent soils with a q_{t1} of less than 50. In other words, looser soils experience greater relative improvement (in terms of increased tip resistance) in comparison to denser soils. As may be expected, R_q tends to decrease as the distance away from the pile increases. For these specific conditions, it is clear that the beneficial effect of the drilled pile installation extended a distance of at least 4.5D away from the center of the pile. It is postulated that the improvement will depend on the pre-installation soil conditions.

This same methodology may be applied to the characterization of the improvement of the ground within groups of drilled displacement piles. Siegel *et al.* (2007) performed cone penetration testing within groups of piles at the aforementioned North Myrtle Beach site. The relationship between the pile cross-sectional area and the pile spacing were represented in a single value known as the *area replacement ratio* (a_s) that is defined as the cross-sectional area of the pile divided by the tributary area for each pile in the pile group. Of course, the perimeter piles by definition have an open boundary which leads to a practical difficulty when defining the tributary area for actual design. This issue can be circumvented by installing non-structural displacement elements at the perimeter of the actual pile groups to achieve the beneficial effect of the displacement process. In this manner, even perimeter piles in a pile group may take full advantage of the ground improvement.

Test Sites

The ground improvement within groups of piles was evaluated using the CPT for five sites (including the North Myrtle Beach site) in the United States. The portions of the soil profiles containing zones of clay and/or silt were excluded from the evaluation. Considering that the North Myrtle Beach site (Figure 4) is documented elsewhere (Siegel *et al.*, 2007), the following sections focus on the other four sites.

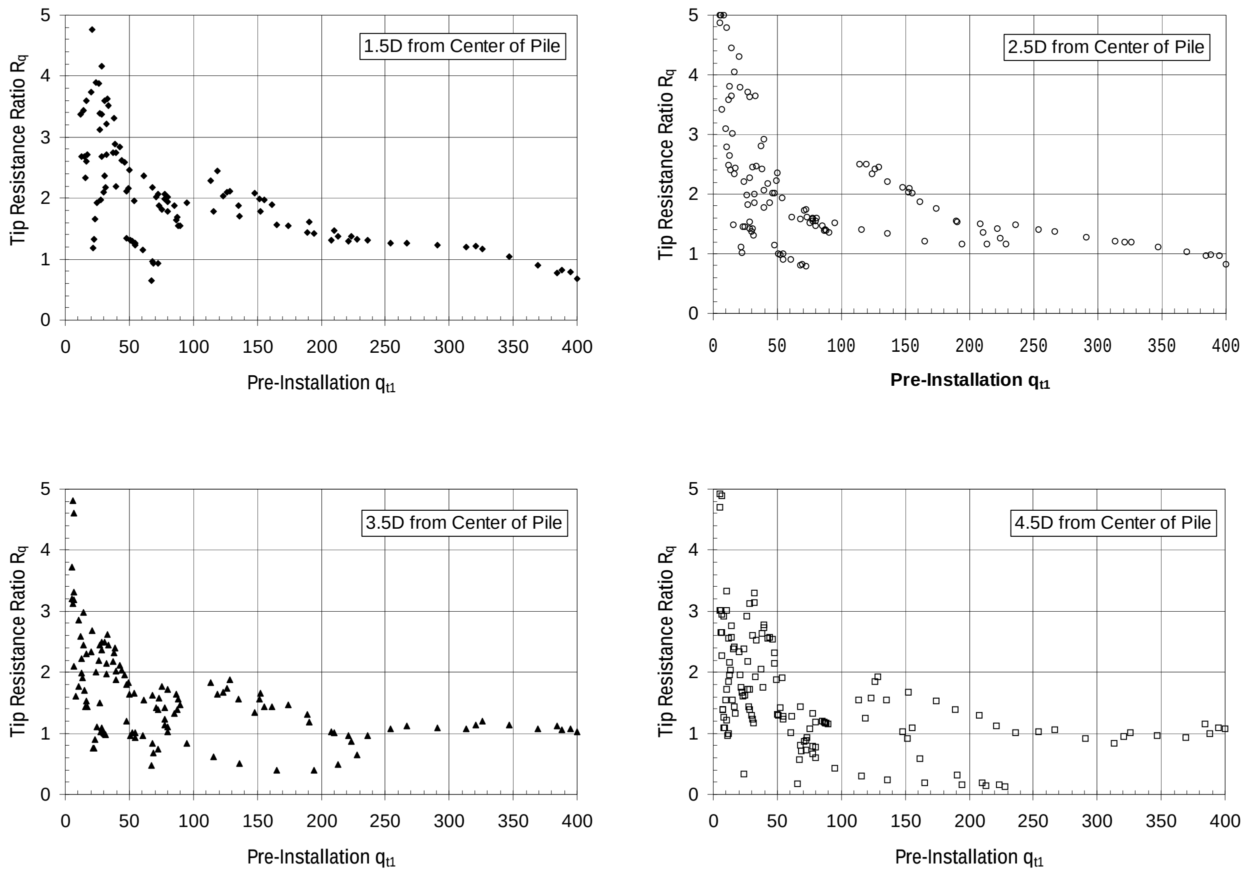

Figure 3. Tip Resistance Ratio Near A Single Drilled Displacement Pile – North Myrtle Beach Site

Orlando (FL) Site

The subsurface profile at the Orlando (FL) site consists of sand in the upper 13 m (about 43 ft) overlying interbedded silts and sands. The testing was performed within a rectangular group of four 406 mm (16 in) diameter piles and a square group of piles with a center-to-center spacing of 1218 mm (48 in). The area replacement ratios were 0.087 and 0.1, respectively. Figure 5 graphically compares the results of cone penetration testing for the pre-installation tip resistance to the post-installation tip resistance for the area replacement ratio of 0.1. As shown, the pre-installation tip resistance in the upper sand generally ranges from 5 to 15 MPa (about 50 to 150 tsf). The post-installation tip resistance in the upper sand ranges from 15 to 30 MPa (about 150 to 300 tsf).

Arcadia (FL) Site

The conditions at the Arcadia (FL) site consist of an upper 7.5 m (24.5 ft) of sand underlain by clayey sand and silt. The testing was performed at the approximate midpoint within a square group of four 457 mm (18 in) diameter piles installed at a center-to-center spacing of 1800 mm (71 in). The area replacement for this pile configuration is 0.049. Figure 6 graphically presents the cone penetration testing results for the pre-installation conditions with the post-installation tip resistance for comparison. The pre-installation tip resistance in the upper sand generally ranges from 2.5 to 10 MPa (about 25 to 100 tsf) and the post-installation tip resistance generally ranges from 5 to 15 MPa (about 50 to 150 tsf).

Washington D.C. Site

The subsurface profile at the Washington D.C. site consists of an upper 4.5 m (14.75 ft) layer of sand, an intermediate 1.5 m (5 ft) layer of silt, and a lower layer of sand. The testing was performed at the approximate midpoint within a square group of 406 mm (16 in) diameter piles with a center-to-center spacing of 1218 mm (48 in). The area replacement ratio for this pile configuration is 0.087. Figure 7 graphically presents the results of the cone penetration testing for the pre-installation conditions. The post-installation tip resistance is also presented

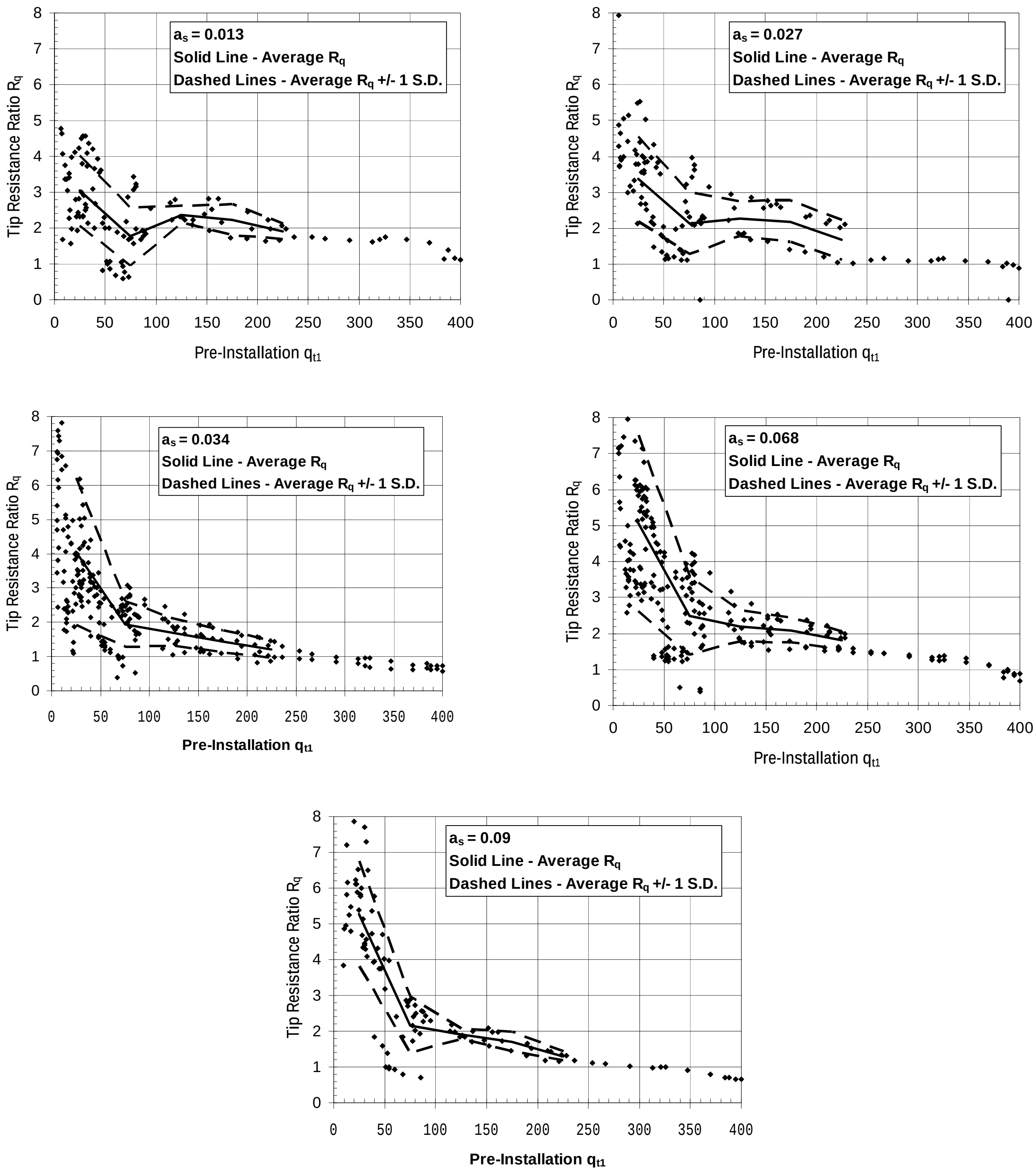

Figure 4. Tip Resistance Ratio for Various Area Replacement Ratios – North Myrtle Beach Site

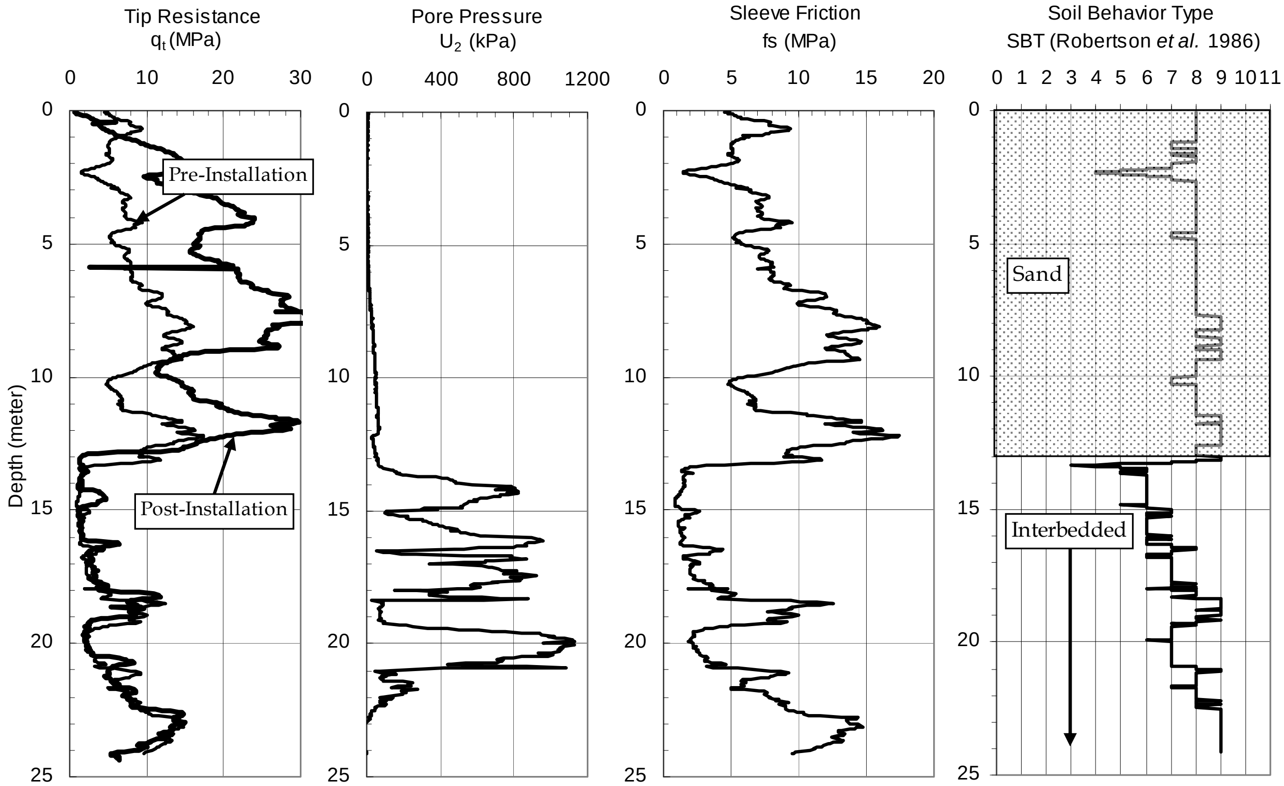

Figure 5. Orlando FL Site Subsurface Conditions

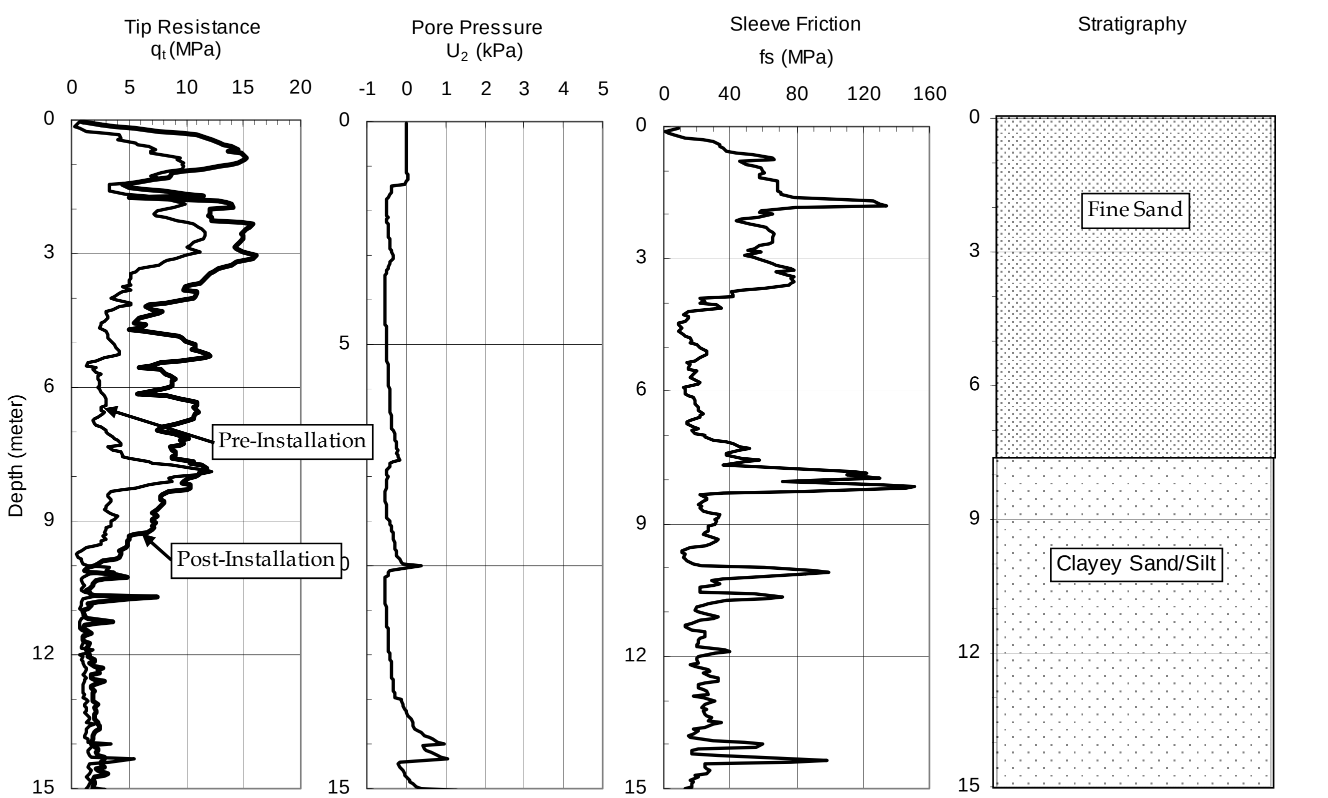

Figure 6. Arcadia FL Site Subsurface Conditions

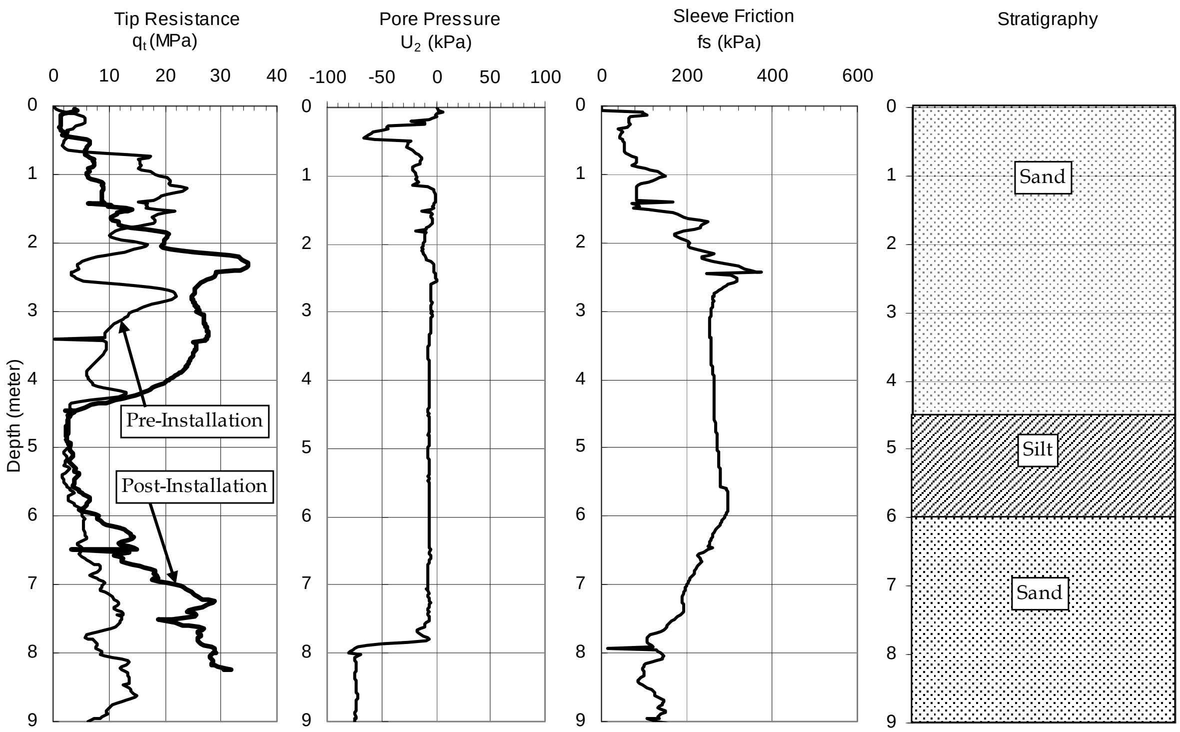

Figure 7. Washington D.C. Site Subsurface Conditions

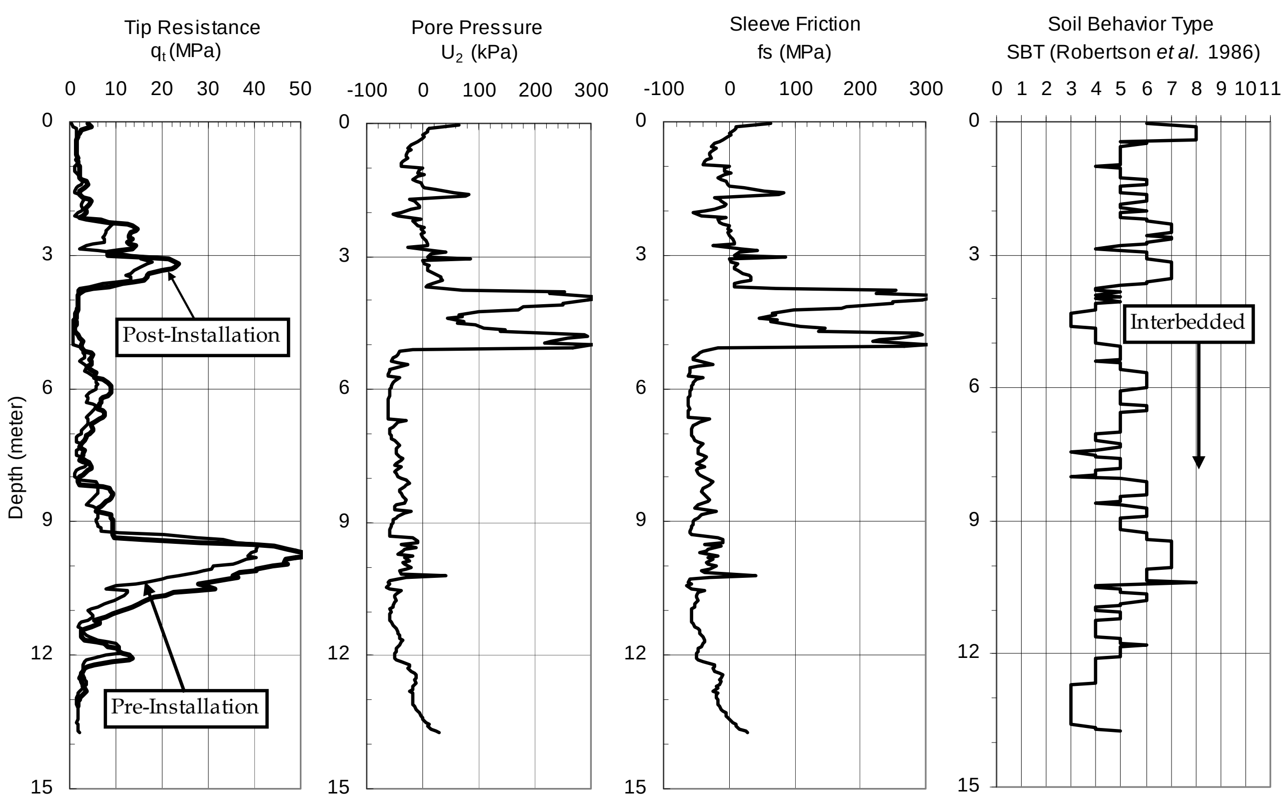

Figure 8. Milpitas CA Site Subsurface Conditions

for comparison. The pre-installation tip resistance in the sand generally ranges from 2.5 to 20 MPa (about 25 to 200 tsf). The post-installation tip resistance ranges from 15 to 30 MPa (about 150 to 300 tsf).

Milpitas (CA) Site

The subsurface profile at the Milpitas (CA) site consists of interbedded sands, silts and clays (Knutson & Siegel, 2006). The testing was performed at the approximate midpoint between a square group of 406 mm (16 in) diameter piles with a center-to-center spacing of 1218 mm (48 in). The area replacement ratio for this pile configuration is 0.087. Figure 8 graphically presents the results of the cone penetration testing for the pre-installation conditions. The post-installation tip resistance is also presented

Summary

The cone penetration test profiles illustrate that the subsurface conditions, as well as the degree of increase in tip resistance, vary between the sites and at different depths at each site. Given that granular materials are much more reliably densified as compared to clays and silts (which are susceptible to undrained distortion), the evaluation of the data was limited to sands and materials that classify silty sands (SBT=7) and sands (SBT=8 or 9) according to the sleeve friction based system proposed by Robertson *et al.* (1986). The application of methodology proposed by Siegel *et al.* (2007) considers, at least in part, the initial soil conditions. That is, by correlating the tip resistance ratio R_q (as defined by Equation 1) to the normalized cone tip resistance for the initial ground conditions then both the initial stress and soil density are part of the correlation with improvement. The mean values of R_q computed for the study sites are summarized in Table 1. A proposed relationship between R_q and a_s is graphically presented in Figure 9.

Table 1. Mean Values of R_q

		Range of normalized tip resistance				
Site	as	0 to 50	50 to 100	100 to 150	150 to 200	200 to 250
Arcadia	0.049	-	-	1.5	1.5	-
Milpitas	0.087	-	-	1.7	1.4	-
Myrtle Beach	0.013	3.0	1.8	2.4	2.2	1.9
Myrtle Beach	0.027	3.4	2.1	2.3	2.2	1.7
Myrtle Beach	0.034	4.1	1.9	1.7	1.4	1.2
Myrtle Beach	0.068	5.1	2.5	2.2	2.1	-
Myrtle Beach	0.090	5.3	2.2	1.9	1.7	-
Orlando	0.087	3.0	2.8	2.0	1.7	-
Orlando	0.100	5.3	3.1	1.8	1.6	-
Wash DC	0.087	4.3	4.0	2.4	1.7	1.6

This study did not attempt to establish the influence of time on R_q. A number of published field studies show that the tip resistance continues to increase for some time after the application of various soil densification techniques (Mitchell & Solymar, 1984; Schmertmann, 1987; Mesri *et al.*, 1990; Charlie *et al.*, 1992). However, the effect of aging on the behavior of sands is not well understood as illustrated by the laboratory study by Baxter & Mitchell (2004) that was unable to reproduce the increase in tip resistance over time that is typically observed in the field.

It is proposed that the increases in tip resistance resulting from the installation of drilled displacement piles in sands of varying density are conservatively represented by the values of R_q presented in this paper. That is, the testing for this study was performed within a few days of pile installation and the tip resistance is expected to increase with time rather than decrease. Furthermore, the testing within pile groups was performed very near or at the midpoint of the pile configuration which is believed to provide added conservatism to the application of these values as an estimate for the entire soil volume.

Additional study is required to evaluate the influence of soil variability as essentially all of the sites included in this paper exhibited some degree of varying consistency. The authors' anticipate that granular soil profiles of more uniform relative density will exhibit trends similar to those observed in this study.

Conclusions

Drilled displacement piles are installed by the displacement of the soil within the pile volume and the placement of fluid cement grout within the evacuated volume. Depending on the *in situ* soil conditions and the pile diameter and layout, the installation process can result in densification and an increase in lateral stress. Cone penetration tests were performed at five sites around the United States in an effort to characterize the degree of ground improvement resulting from installation of drilled displacement piles. This evaluation was limited to sands and silty sands in the upper 13 m (about 43 ft) but is believed to conservatively represent the degree of improvement, in terms of increase tip resistance, that may be expected within groups of the drilled displacement piles.

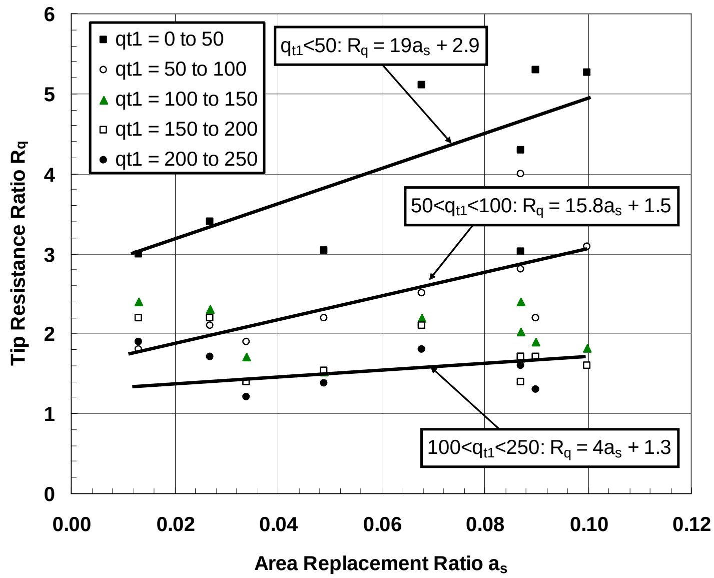

Figure 9. Proposed Relationship Between R_q and a_s

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