Testing of Augered Cast-in-Place Piles Installed with Varying Auger Rotations

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ABSTRACT. Augered cast-in-place piles are installed by the excavation of the soil by rotation of a continuously flighted auger into the ground and then placement of a fluid cement grout into the evacuated volume as the auger is extracted. The soil conditions immediately after excavation for augered cast-in-place piles will be related to the *in situ* soil conditions, the auger specifications, and the rates of penetration and auger rotation. Intuitively, the potential for soil removal will increase proportional to the number of auger rotations; however, the soil transport mechanism involved is complex. To evaluate the effect of augering on the axial behavior of full-scale augered cast-in-place piles, four piles were installed with varying auger rotations and then load tested in axial compression. The soil conditions were primarily sand above the water table. The results of cone penetration testing indicate that the number of auger rotations did not significantly influence the cone resistance in the sand above the water table. Limited data suggest that some loosening occurs in the sand below the water table. The results of the load tests indicate that the geotechnical resistance – and notably the shaft resistance – is not sensitive to the number of auger rotations for the study conditions.

INTRODUCTION

Augered cast-in-place (ACIP) piles (also called continuous flight auger piles, augered pressure grouted piles, or auger-cast piles) were initially developed in the United States in the late 1950's and subsequently experienced a rapid growth in their use worldwide during the 1970's and 1980's. ACIP piles are installed using a continuous flight auger to excavate a cylindrical volume of soil and then pumping fluid cement grout through the hollow stem of the auger into the evacuated volume as the auger is extracted. The fluid cement grout serves to stabilize the sides of the excavation while the reinforcing steel is placed and then becomes a structural component after curing. The soil conditions immediately after excavation for ACIP piles will be related to the *in situ* soil conditions, the auger specifications, and the rates of penetration and auger rotation. The post-installation soil conditions and the grouting procedure will determine the available geotechnical resistance. Intuitively, the potential for soil removal, particularly in sand, may be expected to increase proportionally to the number of auger rotations per unit depth involved in drilling. Consequently, a greater number of auger rotations may be detrimental where it leads to a reduction in lateral stress and soil density (which influence shaft resistance) and undermining of the overlying soil and potentially ground surface subsidence. However, the mechanics of soil augering depend on several inter-related factors including the forces developed between the borehole, the soil cuttings and the auger, the stability of the borehole walls, and the efficiency of the auger. Given the complexity of the soil auger mechanics, full-scale load testing is an important step to a better understanding the influence of the auger rotations on ACIP pile capacity.

The influence of the auger rotations on full-scale ACIP piles was studied at a confidential site in western Illinois. The *in situ* conditions in the test area were characterized as primarily sand using the results of cone penetration tests. Four test piles were installed using conventional ACIP equipment with varying numbers of auger rotations during drilling. The test piles were instrumented with strain gages to allow the evaluation of the distribution of the geotechnical resistance mobilized during load testing. To evaluate the influence of installation on the nearby soil, cone penetration testing (CPT) was performed at specific increments of radial distance away from the test piles after their installation. Once the piles had sufficiently cured, they were subjected to axial compressive tests. The subsequent analysis focused on comparing the number of auger rotations involved during drilling to: (1) the changes in cone tip resistance in the nearby soil, and (2) the differences in interpreted shaft resistances of the test piles.

AUGER DRILLING IN SAND

Thorburn *et al.* (1993) present a detailed description of the process of auger drilling in sand and divide it into two parts: (1) cutting action and (2) transport action. The sand is cut by the blades at the tip of the auger and then is passed onto the flighting. The cutting action induces shear strains and can result in volume change (van Os and van Leussen, 1987). Dense sand will dilate and experience the development of negative pore pressure. Loose sand will tend to collapse during shear and experience the development of positive pore pressure. The rotation of the cutting blades creates cyclic stresses that can generate positive pore pressure, where the sand conditions will permit.

The transport action requires that the flights of the auger remain filled by the sand that is delivered by the cutting blades. A continuous ribbon of soil along the flights provides the rotational resistance so that the transport process can occur. Loose sand is expected to experience a volume reduction of 5 to 10% during shearing while dense sand is expected to experience a volume increase. The volume reduction expected in loose sand is offset by the auger volume, which is typically 10 to 15% of the theoretical excavation volume. In dense sands, the dilation helps to keep the flights filled. The efficiency of the auger is also involved in determining whether the flights are filled. That is, more efficient flights will require a greater volume of soil to remain filled than less efficient flights. If the rate of advancement is not sufficient to fill the flights, then the transport action may be inhibited. This may also allow the sides of the excavation to become unstable resulting in sand moving from the excavation face onto the auger. The stability of the excavation face is related to the apparent cohesion of the sand and the effect of the auger sweep. Terzaghi (1943) showed that the lateral stresses around an open vertical shaft are redistributed (known as arching) so that the radial stress is reduced at the exposed face. Consequently, the excavation face remains stable where the sand has sufficient cohesion to stand up under its self weight. The contact between the excavation face and the flights provides intermittent lateral support during rotation and may also promote excavation stability. However, the cyclic stresses created by the auger can also inhibit the development of arching, especially in loose sand.

Where the auger penetrates the water table, the stability of the excavation face will depend on the permeability of the sand. In free-draining sand, there will be minimal gradient between the excavated volume occupied by the auger and cuttings and the adjacent ground and the effect of the free water will be negligible. In relatively impervious material, the flow rate will be much slower than the pile installation process so that the excavation will essentially behave as if there were no free water surface. It is in sand of moderate permeability that a substantial gradient is able to develop and that the excavation face may destabilize when flow into the excavation occurs. Carrier (2007) theorized, based on field observations of pile installation, that saturated loose sand can experience liquefaction and associated densification due to the cyclic shear induced by auger drilling.

The transport mechanics of auger drilling have been modeled as an Archimedean screw (Viggiani 1993; Van Impe 1994), as a screw feeder (Metcalf 1964; Thornburn *et al*. 1993; Slatter *et al*. 2000), and as a numerical model using the distinct element method (Schmitt and Katzenbach 2003). The Greek mathematician Archimedes is credited with discovering that rotating screw contained within an outer tube will transport granular material along its helical flights. While there are similarities between it and auger drilling, the Archimedean screw is based on several assumptions that are not valid for auger drilling (Slatter *et al.* 2000). Thorburn *et al*. (1993) used a screw feeder model that assumed that the sand fully fills the auger and that the gravitational and centrifugal forces were negligible compared to the frictional forces. These assumptions allow calculation of the efficiency for various auger specifications. Fleming (1994; 1995) also assumed that sand fully fills the auger in computing a term defined as the *flighting force ratio* (*i.e.*, the sum of the forces driving the soil ribbon upward divided by the sum of the forces driving the soil ribbon downward). When the flighting force ratio is greater than 1, the auger may be expected to transport soil upward.

Kenny *et al.* (1997) performed model tests and compared the auger efficiency for different rates of auger penetration to the change in sand density (as indirectly determined using thermal conductivity measurements) and subsidence surrounding the borehole. Results of the model tests were used to compute an optimum auger penetration rate for a given auger efficiency, pitch, and rate of rotation. An auger penetration rate lower than the computed optimum rate would result in loosening of the sand and surface subsidence. An auger penetration rate greater than the computed optimum rate would result in sand densification and surface heave. It was observed that the optimum auger penetration rate increased for loose sand and for a smaller stem diameter-to-flight diameter ratio. Model tests admittedly may not fully represent full-size auger behavior due to scale effects.

Van Weele (1988) present CPT data collected before and after the installation of a full-scale ACIP pile in sand that shows that the q_c reduced from approximately 15 to 20 MPa (approximately 150 to 200 tsf) to approximately 2 to 3 MPa (approximately 20 to 30 tsf). Leznicki *et al*. (1992) observed that the process (required due to operational difficulties) of augering, extracting the auger without grouting the borehole, and then re-augering in sand below the water table resulted in greater settlement of nearby structures. By avoiding re-augering and by adjusting the auger rotation and penetration to reduce the volume of sand excavated, ACIP piles could successfully be installed within 1.2 to 4.6 m (4 to 15 ft) of existing structures. Thornburn *et al.* (1993) examined several case histories of ACIP pile installation in medium dense sand below the water table and concluded the following:

1. ACIP pile installation in sand does not necessarily cause ground surface subsidence considering that only a slight amount of cohesion is sufficient to achieve stability of the borehole walls;
2. The risk of ground surface subsidence is greatest for loose sand below the water table;
3. Moist sand above the water table exhibit sufficient apparent cohesion for borehole stability;
4. Loose sand below the water table may exhibit a reduced shaft resistance; however, the shaft resistance for medium to dense sand is not reduced as a result of augering.

Mandolini *et al.* (2002) performed a study consisting of the installation and testing of three ACIP piles in silty sand. The results suggest that the behavior of these ACIP piles under axial compression was intermediate to that of drilled shafts (where full relaxation of the borehole walls is expected) and displacement piles. A study by Bustamante (2009) installed an ACIP pile in an interbedded sand and clay. Pre- and post-installation CPT showed that installation had negligible effect on the q_c. Furthermore, a comparison with the results for adjacent driven piles showed that, even with the soil removal associated with augering, showed similar shaft resistances.

In the United States, the installation control of ACIP piles has focused on the grout factor (*i.e.,* the volume of grout pumped into the borehole divided by the theoretical borehole volume) and the grout return (*i.e.,* the depth of the auger when grout is observed exiting the ground surface) rather than the augering aspects, even in sand.

The FHWA publication, Design and Construction of Continuous Flight Auger Piles (Brown *et al*., 2007) suggests maintaining the number of revolutions per auger pitch penetration between 1.5 and 2. Greater emphasis has been placed on the drilling aspects in European engineering literature. One reason for this is that the European type ACIP pile is typically installed with a fixed mast rig that can generate a substantial downward crowd force. In contrast, much of the U.S. contractors use crane-mounted augers on swinging leads where the auger penetration rate cannot be controlled by the application of a crowd force. Three parameters: (1) auger pitch, p in meters, (2) auger rotation rate, n in rotations per minute, and (3) auger penetration rate, v in meters per min, have typically used to numerical define number of rotations relative to auger penetration rate (Kenny *et al.*, 1997; Mandolini *et al*., 2002; Brown et *al.*, 2007). Kenny et al. (1997) define the *penetration rate* as shown in Eq. 1.

$$Penetration\ rate = \frac{np}{v} \tag{1}$$

Brown *et al.* (2007) define the *rate of penetration* as shown in Eq. 2.

$$Rate\ of\ \ penetration = \frac{v}{np} \tag{2}$$

where

v	=	Auger penetation rate (m/minute)
n	=	Rotations/minute
p	=	Auger pitch (m)

It is the writer's opinion that the values represented in Eqs. 1 and 2 are better described as ratios rather than rates, given that the resulting units will be revolutions per auger pitch penetration or its inverse. Both equations will yield a value of unity where the auger penetrates the ground a distance of one auger pitch with each auger rotation. Unfortunately, both the term *penetration rate* and *rate of penetration* are easily confused with the actual rate (distance per unit time) that the auger moves relative to the ground. To avoid confusion, this paper will adopt the term *auger penetration ratio* for the results of Eq. 2.

TEST SITE CHARACTERIZATION

The test site is located adjacent to the Mississippi River approximately 24 km (15 mi) upstream of downtown St. Louis, Missouri. Geologically, the site is part of the Central Lowland physiographic province (Hunt 1967). The soil overburden is a glacial outwash consisting primarily of a medium to very dense, well- to poorly graded sand. A glacial till consisting of a hard, high plasticity clay is present at depths ranging from approximately 40 to 45 m (130 to 150 ft) below the ground surface. Figure 1 presents a typical CPT profile for the site showing that the pore-pressure corrected cone tip resistance (q_t) of the sand typically ranges between 10 to 20 MPa (100 to 200 tsf) with some denser layers.

TEST PILE INSTALLATION

The test piles were installed using a Berkel manufactured gear box, power unit, and grout pump. The gear box included a KYB hydraulic motor. The power unit included a Caterpillar 3408 V-8 diesel turbocharged engine capable of 5000 N-m (3700 ft-lb) of torque. The grout pump (ball and seat style) pump was capable of delivering 0.023 m^3 (0.82 ft^3) per stroke and approximately 46 m^3 (60 yd^3) per hour. The auger and gear box were mounted on swinging leads and suspended by a Linkbelt 238 crane. The auger tip depth, auger penetration rate, and grout flow were automatically recorded by a Pile Installation Recorder provided by Pile Dynamics, Inc. Three test piles, designated S-1, S-2, and S-3 were drilled to a depth of 12.2 m (40 ft) using an auger with a flight diameter (D) of 410 mm (16 in), a stem diameter of 114 mm (4.5 in), and a pitch of 260 mm (10.25 in).

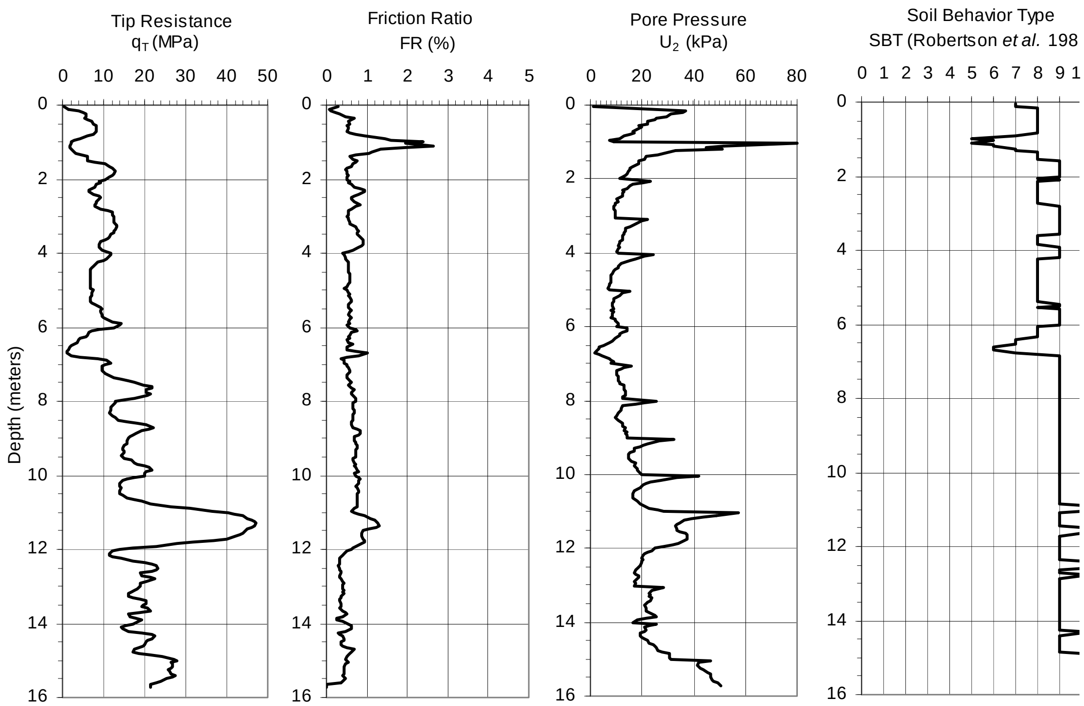

Fig. 1 Typical CPTU Profile from the Project Site

The auger rotation rate for these three test piles was 23 rotations/min during pile installation. The drilling times and consequently the auger penetration ratios were intentionally varied to determine the influence of augering on the ground conditions and pile shaft resistance. The ground conditions after pile installation at distances of 1.5D, 2.5D, and 3.5D from the pile center were characterized using the CPT. Figures through 4 present comparisons of the pre-and post-installation CPT results and the incremental auger penetration ratio and the grout factor for test piles S-1, S-2, and S-3, respectively.

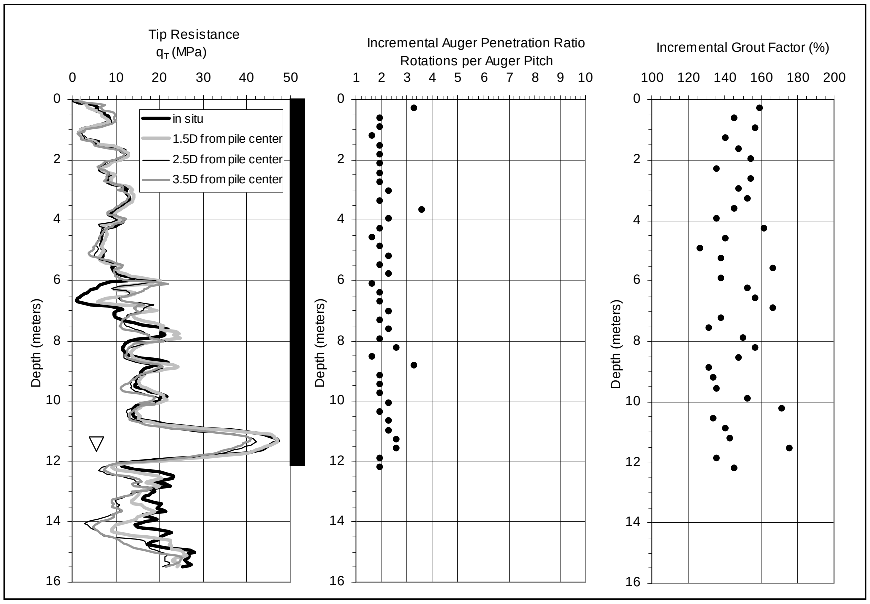

Fig. 2 CPT and Installation Data for Test Pile S-1, D - 410 m (16 in)

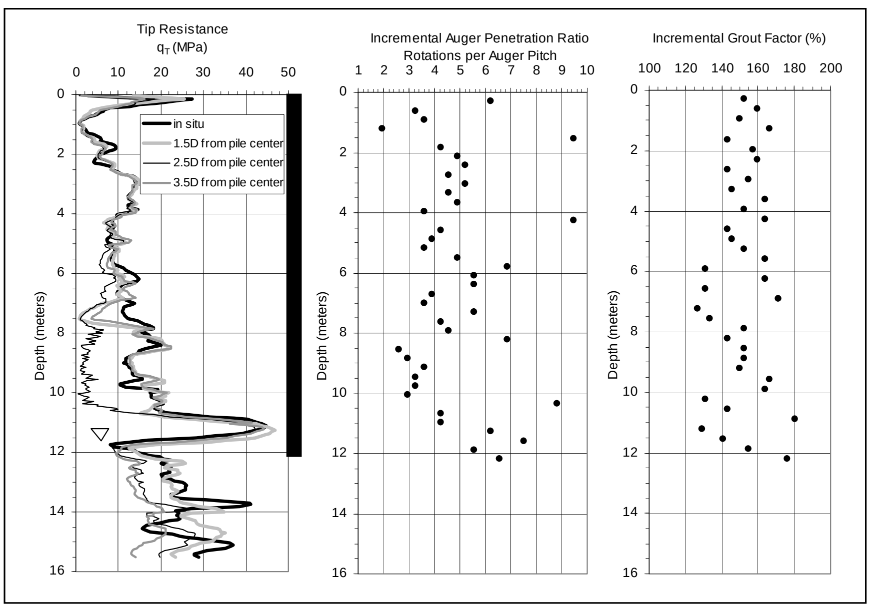

Fig. 3 CPT and Installation Data for Test Pile S-2, D - 410 m (16 in)

Test Pile S-4 was drilled to a depth of 18.3 m (60 ft) using an auger with a flight diameter (D) of 610 mm (24 in), a stem diameter of 114 mm (4.5 in), and a pitch of 356 mm (14 in). The auger rotation rate was 22 revolutions per min during pile installation. Figure 5 presents a comparison of the pre-and post-installation CPT results and the incremental auger penetration ratio and the grout factor for Test Pile S-4. The CPT results for S-2 and S-3 show a significant reduction in q_t from a depth of 8 to 11 m (about 26 to 36 ft) below the ground surface at a horizontal distance of 2.5D from the center of the pile. This reduction is not apparent in the data collected at distances of 1.5D or 3.5D from the pile center. A review of the testing and data interpretation procedures did not reveal any errors or equipment malfunctions that would suggest that the data are incorrect. It may be relevant that there were other site activities in progress at the time of testing. At this time, however, the writer has not identified a reason that the aforementioned portion of the data should be anomalous with a high degree of certainty.

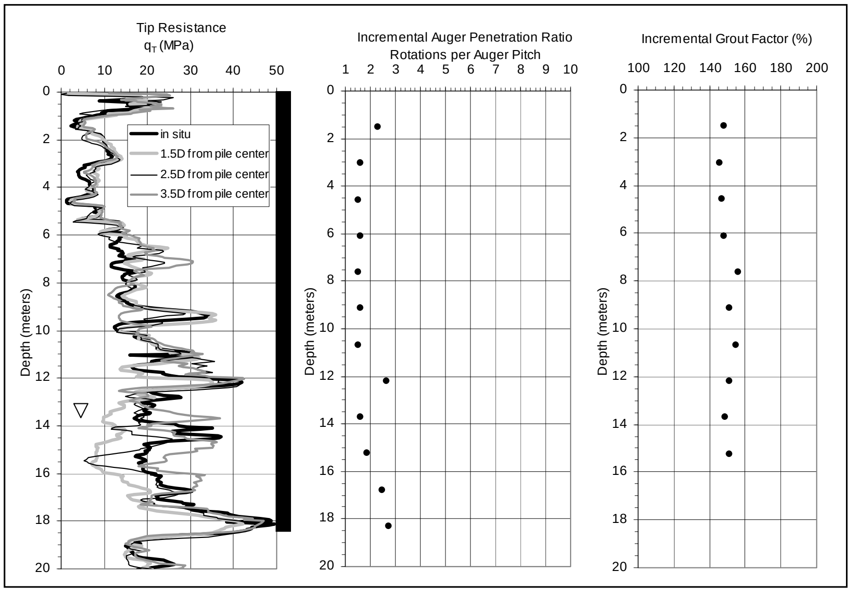

Fig. 4 CPT and Installation Data for Test Pile S-3, D - 410 m (16 in)

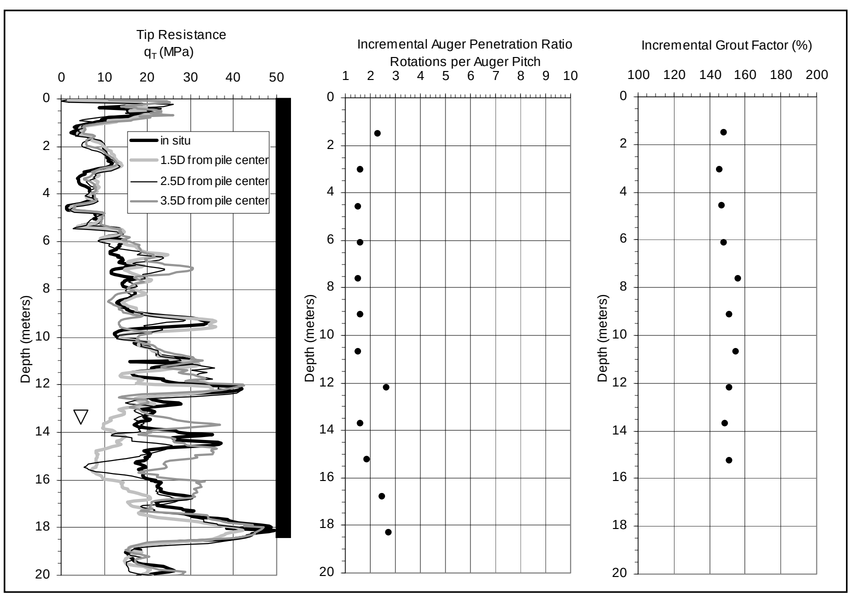

Fig. 5 CPT and Installation Data for Test Pile S-4, D - 410 m (16 in)

With this qualification, the profiles of q_t indicate that the installation of ACIP piles, regardless of the auger penetration ratio, has essentially a negligible influence on the nearby ground conditions when augering above the water table. The results for S-4 show a reduction in q_t adjacent to the portion of pile below the water table which was at a depth of approximately 13.7 m (45 ft) below the ground surface. This reduction is greatest in the data collected closest to the pile and no reduction in q_t is apparent for the test performed 3.5D from the pile center.

AXIAL COMPRESSION LOADING TEST

Axial compression loading tests were performed on test piles S-1 through S-4 in accordance with the quick load procedures presented in ASTM D1143M-07 Standard Test Method for Deep Foundations Under Static Axial Compressive Load. The 410 mm (16 in) diameter test piles (S-1 through S-3) were reinforced with a cage of eight 25.4 mm (No. 8) bars with a 23 mm (No. 11) full-length center bar and 9.5 mm (No. 3) spiral ties with a 102 mm (4 in) pitch. The reinforcing cage extended 6.1 m (20 ft) from the top of the pile. The 610 mm (24 in) diameter test pile (S-4) was reinforced with a cage of twelve 25.4 mm (No. 8) bars with a 23 mm (No. 11) full-length center bar and 12.7 mm (No. 4) spiral ties with a 102 mm (4 in) pitch. All of the steel reinforcing had a minimum yield strength of 250 MPa (36 ksi). The design grout strength was 28 MPa (4000 psi). The load-deflection data from the load tests are illustrated in Figure 6. The ultimate geotechnical axial compressive resistance was interpreted using the Hansen 90% criterion (Hansen 1963). The load-deflection response of Test Pile S-4 was extended above the actual maximum test load using a hyperbolic curve extrapolation to allow the application of the Hansen 90% criterion.

The test piles were instrumented with Geokon Model 4911-4 Vibrating Wire Gages and gage readings were collected using a Geokon LC-2 16 Channel data logger during the tests. The strain data were converted to internal pile loads using the modulus estimated from the strain-load relationship for the gage nearest the pile head. The pile diameter was assumed to be nominal diameter of the auger. The loading tests were performed within 7 to 10 days after installation. Available data suggest that the residual load that is developed within this time frame is relatively small (Siegel and McGillivray 2009) and therefore no adjustments to the strain gage data were made to account for it. The evaluation of the test results focused on the shaft resistance considering that it, rather than the toe resistance, is likely to be influenced by the number of auger rotations. Figures 7 through 10 show the ultimate shaft resistance calculated from the LCPC method (Bustamante and Gianeselli 1982) based on the CPT data prior to load testing and the interpreted ultimate geotechnical shaft resistance based on the measured strain with depth below the ground surface. It is recognized that the difference between the calculated and measured ultimate shaft resistances results from the uncertainty present in the LCPC calculation and the influence of the number of auger rotations. Unfortunately, it is impossible to separate the influences of these two variables from one another in the analysis of the results of this field study.

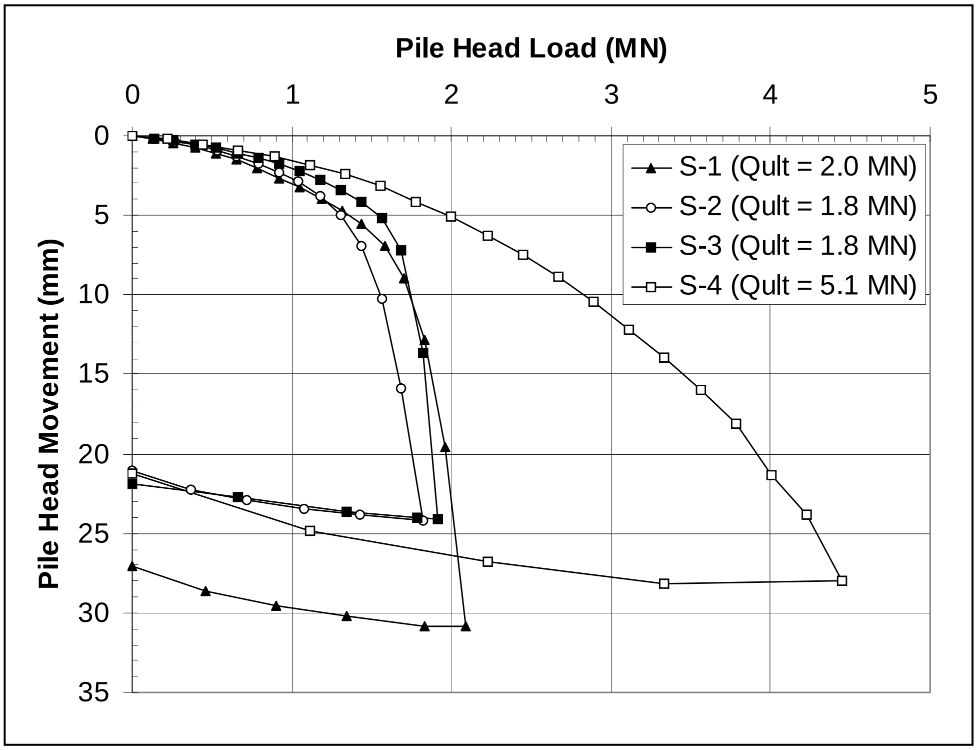

Fig. 6 Pile Head Load-Movement from Test Piles

DISCUSSION

Test piles S-1, S-2, and S-3 were placed with a horizontal spacing smaller than 5 m (16.4 ft). These 410 mm (16 in) diameter piles and installed and tested with essentially identical procedures to one another, except that the number of rotations during drilling was intentionally varied. As shown in Table 1, the average auger penetration ratios are 2.2, 4.9, and 9.8 for test piles S-1, S-2, and S-3, respectively. The measured shaft resistances ranged from 50% to 91% of the calculated shaft resistances. This range narrows to 73% to 91% when only considering the shaft resistance for the entire pile. The calculated resistance best matched the measurements for Test Pile S-1 where $Q_{measured}$ =91% of $Q_{calculated}$. The next best match was for S-3 ($Q_{measured}$ =81% of $Q_{calculated}$) and last was S-2 ($Q_{measured}$ =73% of $Q_{calculated}$).

These comparisons suggest that a measurable, through relatively small, reduction in the shaft resistance can result from increasing the number of rotations during augering in medium to dense sand. The reduction does not appear to be predictable as a proportion to the number of rotations or the auger penetration ratio. Furthermore, the reduction in the shaft resistance observed between the lowest number of rotations (*i.e.,* an auger penetration ratio of 2.2) and the highest number of rotations (*i.e,* an auger penetration ratio of 9.8) does not appear to be as severe so as to dramatically decrease the factor-of-safety routinely applied to pile foundations.

Test Pile S-4 was installed with an average auger penetration ratio of 1.9 at the same site as the other test piles, but it was 510 mm (24 in) in diameter and installed to a depth of 18.3 m (60 ft). This test pile penetrated the water table which was present at a depth of approximately 13.7 m (45 ft).

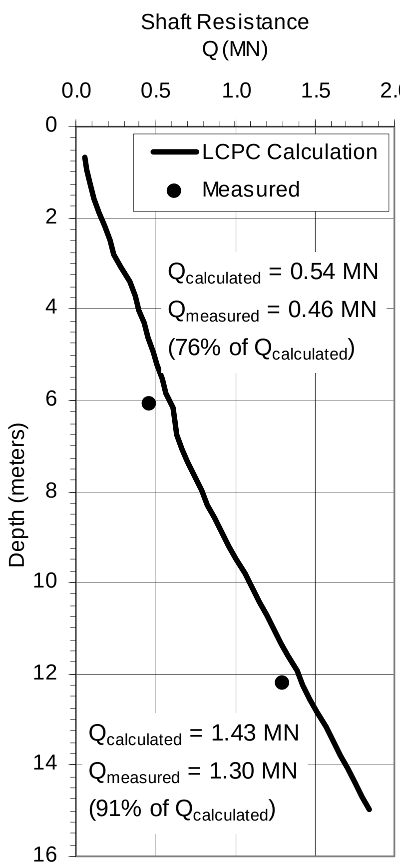

FIG. 7. Ultimate Shaft Resistance for S-1

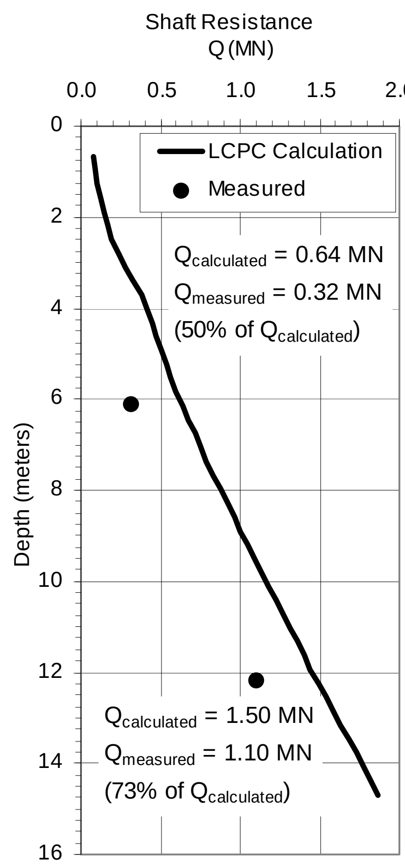

FIG. 8. Ultimate Shaft Resistance for S-2

Figure 10 shows that the measured shaft resistance slightly exceeds the calculated shaft resistance for the upper portion of the pile and matches the predicted shaft resistance quite well for the entire pile. The CPT results provide additional evidence that the number of rotations does not dramatically influence the conditions of a medium to dense sand above the water table. That is, comparisons of pre- and post-installation CPT generally show negligible change as a result of augering. A significant reduction in q_t occurred immediately below the depth of the water table adjacent to Test Pile S-4 despite that a relatively low auger penetration ratio (approximately 1.5 to 2.5) was maintained while augering. It is hypothesized that the sand loosened because of seepage pressure that destabilized the borehole wall during augering. For sand above the water table, the apparent cohesion without the seepage pressure was sufficient to maintain borehole wall stability.

Overall, the results of this study show that the ultimate shaft resistance in ACIP piles installed in medium to dense sand is not sensitive to the number of auger rotations during augering. The CPT data support that loosening occurs in sand below the water table even at a relatively low number of auger rotations. The comparisons made herein indicate that the LCPC method is well-calibrated for ACIP piles in medium to dense sands and sufficiently robust to continue to be appropriate where loosened sand conditions exist below the water table.

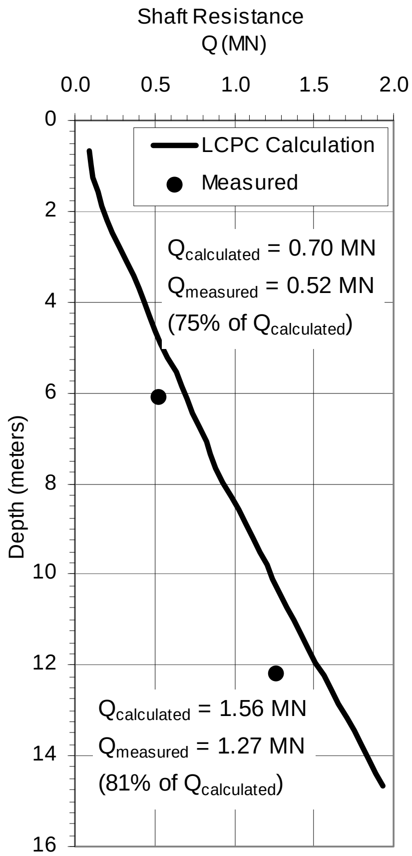

FIG. 9. Ultimate Shaft Resistance for S-3

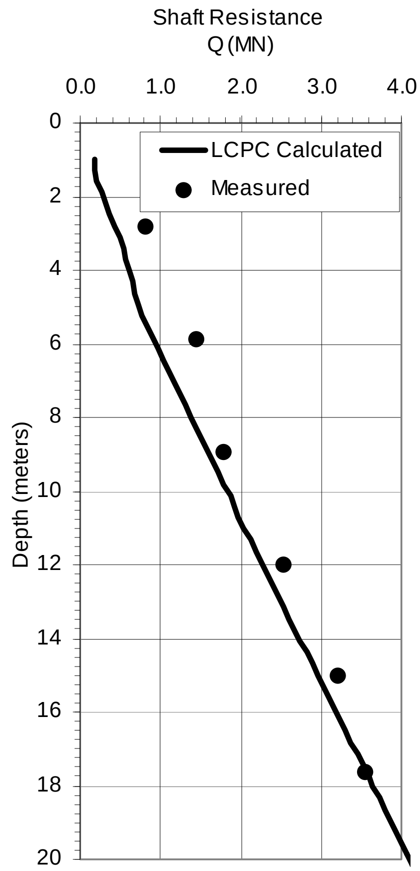

FIG. 10. Ultimate Shaft Resistance for S-4

Table 1. Summary of Installation Data for Test Piles S-1, S-2, and S-3

Test Pile Number	Drill Depth m (feet)	Average Auger Penetration Ratio (Revolutions per Auger Pitch)	Grout Factor (%)
S-1	12.3 (40.3)	2.2	150
S-2	12.2 (40.1)	4.9	151
S-3	12.2 (40.1)	9.8	152

CONCLUSIONS

1. The shaft resistance developed in ACIP piles is relatively insensitive to the number of auger rotations during drilling for the conditions that were examined in this study. It is proposed that an increase in the number of auger rotations or a decrease in the rate of auger penetration results in a reduction in auger efficiency. Provided that the borehole walls remain stable, the auger could theoretically rotate at a constant depth without excavating additional sand.

2. The augering process can loosen the sand below the water table. It is hypothesized that the cause is that seepage toward the auger destabilizes the borehole wall. As the sand grains move from the borehole wall to the flights, reductions in both relative density and lateral stress result. It is noted that the sand loosened adjacent to a pile (S-4) was installed with a relatively low auger penetration ratio (1.9) that would otherwise suggest a relatively low potential for loosening.

3. The CPT data indicate that essentially no ground disturbance occurs as a result of ACIP pile installation at a distance greater than 2.5D from the pile center. Therefore, it may be concluded that there will be no overlapping reduction in q_t due to ACIP pile installation for a group spacing of 2.5D or greater.

4. The LCPC method is well-calibrated for ACIP piles in medium to dense sands and sufficiently robust to continue to be appropriate where loosened sand conditions exist below the water table. This supports the conclusion by Gavin *et al.* (2009) that the direct correlation between q_t and shaft resistance better represents the condition surrounding ACIP piles than methods that assume that the sand is fully loosened (O'Neill and Reese, 1999).

5. There are specific conditions where the borehole walls can become unstable (e.g., where piping is likely to develop) that are not addressed in this paper.

RAMIFICATIONS TO STATE-OF-PRACTICE

In Europe, it is popular to install ACIP piles using a fixed mast rig that is capable of generating significant crowd. Considering this, it is no surprise that much of the European ACIP pile literature focuses on maintaining an auger penetration ratio of essentially one or slightly greater to accommodate the volume of the auger. In other words, the auger is screwed into the ground at a sufficient rate of penetration so that the volume of the excavated soil is offset by the auger volume. Such an approach has very little potential for loosening the surrounding sand. It is the application of a downward crowd force, made possible only by the use of a fixed mast rig that allows a high level of control of the auger penetration ratio during installation. The U.S. state-of-practice uses primarily crane-mounted augers supported with swinging leads where the rate of auger penetration depends on the effectiveness of the cutting blades and the dead weight of the auger, leads, and gear box. The practical effect is that the operator does not have total control of the rate of auger penetration and consequently the auger penetration ratio can be significantly greater than one.

It has become evident that the geotechnical engineers in the U.S. are becoming more interested in the influence of auger rotations on the shaft resistance of ACIP piles, particularly in sand. It is believed that this current study has the following ramifications to the use of typical U.S. ACIP pile drill rig setup (which has operational and economical advantages):

- The shaft resistance is insensitive to the auger penetration ratio in soil that has sufficient apparent cohesion (including medium to dense sand above the water table) so that the borehole wall is stable. It is unlikely that the shaft resistance in loose sand, either above or below the water table, will be significantly reduced considering that its *in situ* strength represents a near lower bound condition.

- The results of this study do not support that there is a reduction in shaft resistance (in comparison to the shaft resistance calculated using the LCPC method) for an ACIP pile installed in medium to dense sand below the water table even in conditions where there appeared to be a reduction in q_t.

- A center-to-center spacing of 2.5D should be maintained for ACIP piles in groups in sand below the water table to reduce the potential for overlapping installation effects.

- The ACIP pile installation procedure should be evaluated on a project-specific basis by performing full-scale load testing. A test program similar to the study described herein may be used to address concerns regarding the influence of the number of auger rotations on ACIP pile capacity.

- Subsidence of the adjacent ground may be a concern when augering in loose sand below the water table. This condition is generally considered most susceptible to collapse at the borehole walls.

- The risk of ground subsidence in loose sand below the water table may be mitigated using a European type fixed-mast rig fitted with a displacement tool (NeSmith, 2002) which allows the installation of a cast-in-place pile without conveying soil to the ground surface. Such a system can be used to replace conventional ACIP piles or to create a barrier between the proposed ACIP piles and adjacent sensitive areas.

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