EVALUATING INSTALLATION DISTURBANCE OF HELICAL ANCHORS IN CLAY FROM FIELD VANE TESTS

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In order to evaluate the level of disturbance produced in clays during installation, a series of single-helix and multi-helix anchors were installed at a test site consisting of a stiff overconsolidated clay crust overlying softer near normally consolidated clay. Field vane tests were then conducted over the top of the helical plates at various depths to determine the undrained shear strength after installation and were compared with undrained shear strength measured in adjacent undisturbed ground. The tests represent the first time that the degree of installation disturbance has been evaluated directly and show that even with perfect installation practice the clay is disturbed as a result of rotation of the helices during installation. The results show that the soil is not completely remolded but that the strength is below the peak undrained strength of the adjacent undisturbed ground. Measurement of the installation torque and the rate of advance are used to define an "Installation Disturbance Factor" which may help to evaluate the quality of the installation by the Contractor and degree of soil disturbance.

INTRODUCTION

An important consideration in the design of Helical Anchors is the degree of disturbance to the soil during installation. This may be especially important for saturated fine-grained soils where the disturbance from installation may produce a reduction of the undrained shear strength. Even though this was recognized as early as 1950 by Skempton, soil disturbance is often ignored by engineers using current design procedures. Field investigations were performed to obtain both directs and indirect evaluation of the degree of disturbance produced by the installation of single-helix and multi-helix anchors in clay and the influence of disturbance on behavior. The investigations involved measurement of torque and advance during installation, load tests performed to determine load-displacement behavior and ultimate capacity and field vane tests performed over the helical anchors to evaluate changes in undrained shear strength as compared to adjacent undisturbed ground. The characteristics of the site and details of the installation are presented. Results of the field vane tests are shown for a number of helical anchor installations and results of load tests are presented. The results indicate that a reduction should be made to the undisturbed undrained shear strength for design and that the reduction may be related to the Sensitivity of the clay and quality of installation.

INVESTIGATION

Test Site

Tests were performed at the Geotechnical Experimentation Site located at the University of Massachusetts – Amherst. The site is situated in a thick deposit of the Connecticut Valley Varved Clay (CVVC). Geotechnical characteristics of the area have been extensively documented (Lutenegger 2000). The soils consist of approximately 5 ft. of stiff silty-clay fill overlying a thick deposit of late Pleistocene lacustrine varved clay locally known as Connecticut Valley Varved Clay (CVVC). The clay is composed of alternating layers of silt and clay as a result of deposition into glacial Lake Hitchcock. The individual varves of the CVVC are on the order of 2 to 8 mm thick. At the site, the fill consists of CVVC placed about 40 years ago after excavations at the Town of Amherst Wastewater Treatment Plant, adjacent to the site.

Below the clay fill, the CVVC has a well-developed stiff overconsolidated crust that was formed as a result of surface erosion, desiccation, ground water fluctuations and other physical and chemical processes. The CVVC below a depth of about 20 ft. is near normally consolidated. The site has been previously used for other field studies involving prototype scale foundation behavior and other soil properties (e.g., Cerato & Lutenegger 2004; Lutenegger 2008; 2009; 2011). Fig.1 shows the soil characteristics in the upper 20 ft. near the location of the anchor tests. Results of CPT tests conducted near the anchor tests are shown in Fig. 2.

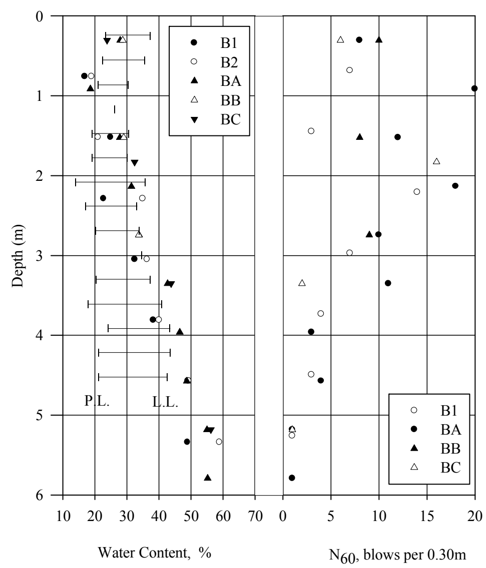


Figure 1. Site Conditions.

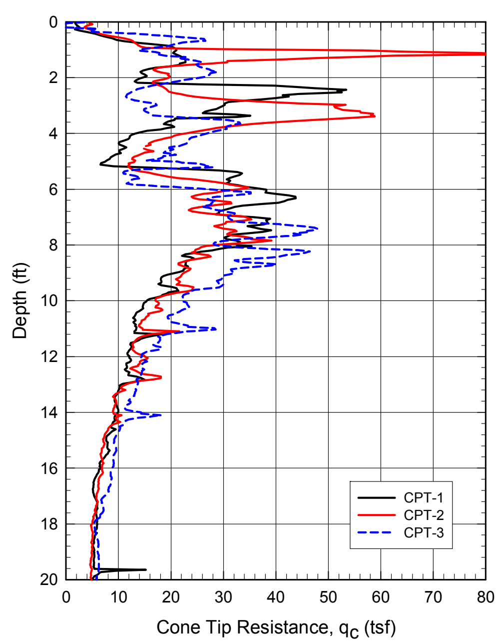


Figure 2. CPT Results Near Helical Anchors.

Field Vane Tests

To evaluate the degree of disturbance produced during installation directly, a series of miniature field vane tests were performed directly over the helices of single-helix and multi-helix screw anchors installed in clay. The tests were conducted over the top of the helices after load tests were performed and were compared with adjacent vane tests performed in undisturbed ground outside the helices and away from the influence of anchor installation. Tests were performed at 1 ft. intervals in 2 in. diameter hand auger holes drilled about midway between the shaft of the anchor and the edge of the helical plates using a vane with a diameter of 1 in. and a height of 2 in. Torque was applied slowly at the top of the vane rods and measured with a portable digital readout. For each test both the peak and remolded undrained shear strength were determined using the traditional interpretation given in ASTM D2573. Remolded strength was determined after rotating the vane 10 times. In undisturbed ground, the vane results indicate that the Sensitivity ranges from about 4 to 8 with an average of about 5 for the soils in the upper 15 ft. at the site.

Installation and Load Testing of Helical Anchors

Commercial helical anchors with typical configurations of helical plates were installed using a hydraulic torque head attached to a mini-excavator. The installation torque was measured for each one ft. of advance using an in line digital torque indicator placed between the hydraulic torque head and helical anchor. In addition, the number of rotations of the anchor for each one ft. of advance and the installation time for each ft. were also recorded. The water table was located at a depth of about 1 ft. during the testing.

Load tests were performed using the incremental maintained load method using the general procedures described in ASTM D3689 *Standard Test Method for Individual Piles Under Static Axial Tensile Load*. Load was applied by a single acting hollow ram 250kN hydraulic jack placed on top of two reaction beams centered over the anchor and resting on wood cribbing. Load was transferred from the jack to the anchor using a threaded rod as shown in Fig. 3. The load was measured using a Geokon donut load cell placed over the threaded rod on top of the hydraulic jack and was read using an electronic digital indicator. Deformation measurements were made using two digital dial indicators with a resolution of 0.0127 mm (0.0005 in.) attached to an independent reference beam and placed equidistant on opposite sides of the anchor. The dial indicators were referenced to a steel plate threaded to the top of the anchor. Loads were applied incrementally in the range of approximately 5% of the estimated ultimate capacity of each anchor. Each increment of load was maintained for 2.5 minutes giving a time to reach a relative displacement of 20% of the helix diameter on the order of 50 to 60 minutes. Loads were applied until a relative displacement of 20% of the plate diameter was achieved or the anchors failed by plunging, whichever occurred first.

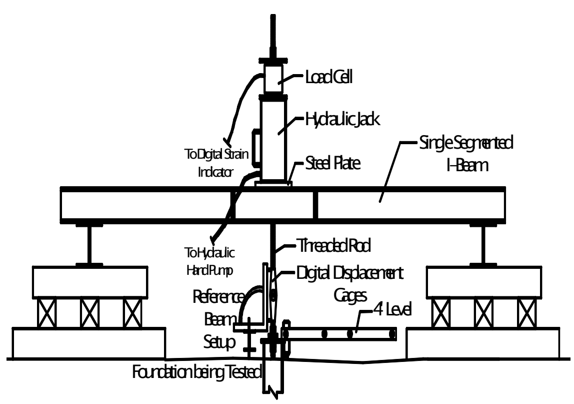


Figure 3. Typical Load Test Arrangement for Tension Tests.

RESULTS

Vane Tests over Single-Helix Anchors

Initially, vane tests were conducted over the top of two round shaft (RS) open end helical anchors and a square shaft (SS) anchor that had been installed to a shallow depth at the site to evaluate uplift capacity. The sanchors were fabricated from a single pipe section, one with a 2.875 in. diameter pipe shaft and the other with a 4.5 in. diameter shaft. The square shaft anchor consisted of a 1.5 in. x 1.5 in. central shaft. All three anchors had a single 14 in. helical plate with a thickness on 3/8 in. and a pitch of 3 in. attached at the end. The helical plate was installed to a depth of 9 ft. The anchors were load tested in uplift 7 to 8 days after installation to allow any excess pore water pressures to dissipate. After load testing, a vane profile was conducted over the top of the helix about 3 in. from the edge of the shaft. Fig. 4 shows the results of the field vane tests performed over the anchors and also shows vane results from two profiles of tests performed in undisturbed ground outside the influence of the anchors. In general the vane results indicate that the undrained shear strength over the helical anchors is lower than the undisturbed values although there is some scatter as might be expected. The reduction in undrained shear strength is not uniform but on average is about 75% of the undisturbed values. It can also be seen that there was a large reduction in strength indicated for the 2.875 in. round shaft anchor between depths of about 5 to 7 ft. with the undrained shear strength approaching the remolded value. This would indicate excessive disturbance and complete remolding of the soil.

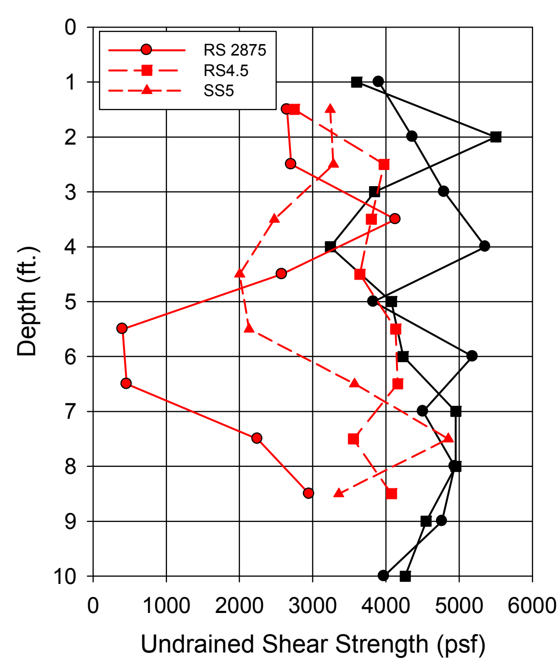
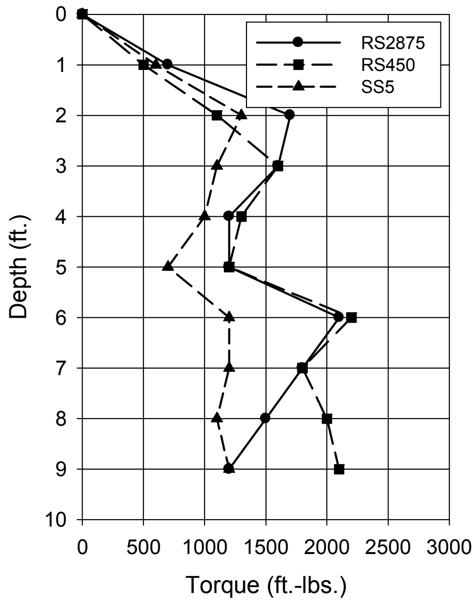


Figure 4. Results of Field Vane Tests over Single Helix Round Shaft and Square Shaft Anchors.

In order to further evaluate the strength reductions noted in Fig. 4, the installation data were reviewed. Fig. 5 shows the installation torque and the advance or number of rotations per foot for all three anchors.



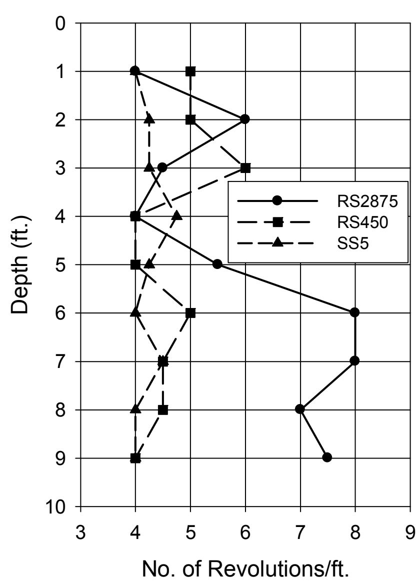


Figure 5. Installation Torque and Advance for Three Single-Helix Anchors.

Fig. 5 shows that the installation torque on the round shaft anchors generally increases with depth as more of the pipe shaft is engaged with the soil as the anchor advances. The installation torque is expected to be higher for round shaft anchors as compared to a square shaft anchor with the same size helical plate. However, as noted in Fig. 5, the 2.875 in. round shaft anchor shows a decrease in installation torque near the end of the installation which is consistent with the increase in the number of helical plate rotations need to advance the anchor starting at a depth of about 5 ft. That is, the anchor is not advancing at a rate of 3 in. per revolution (equal to the pitch) but instead is requiring up to 8 revolutions per foot to complete the installation. This means that the helical plate is “churning” the soil rather than advancing. This increased rotation produces additional remolding of the soil and a corresponding decrease in undrained shear strength.

An additional set of tests were conducted over four square shaft anchors consisting of 1.5 in. x 1.5 in. square shafts with a single 12 in. helical plate. Two of the anchors were installed as carefully as possible to obtain examples of high quality “good” installations; the other two anchors were installed to represent poor quality or “bad” installation. The “bad” installations are sometimes difficult to perform, depending on the soil conditions as the rotation action of the helical plates has the natural tendency to advance the anchor with each revolution. In this case, the operator of the mini-excavator was instructed to hold back on the anchor during rotation in an attempt to intentionally produce more soil disturbance. Results of the vane tests and installation advance are shown in Fig. 6.

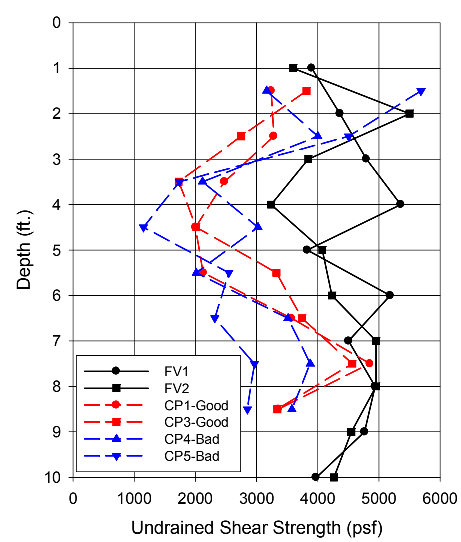


Figure 6. Results of Vane Tests and Installation for “Good” and “Bad” Installation.

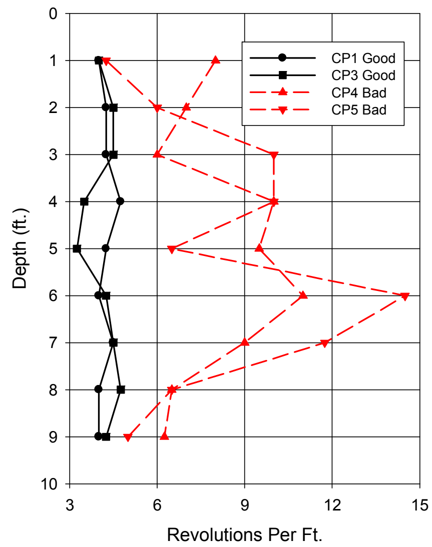


Figure 6 cont'd.

The results presented in Fig. 6 suggest that there is a link between the quality of the installation and the reduction of undrained shear strength resulting from rotation and installation of the anchors. Even the best installation produces a reduction in shear strength. The degree of reduction in strength is complex but is clearly related to the advance rate but also must be related to the soil conditions through which the helix is passing, in this case Sensitivity.

Vane Tests over Multi-Helix Anchors

Multi-helix anchors are commonly used in practice to provide additional load capacity. Tests were performed over a two sets of multi-helix anchors with different plate configurations to investigate if additional plates would produce additional disturbance and reduction in shear strength.

Square-shaft anchors were used for all tests in this series and all anchors were installed with the top helix at a depth of 15 ft. In the first set of tests, a single-helix 12 in. anchor was compared with a 10/12 in. and an 8/10/12 in. anchor. In the second set of tests the single-helix 12 in. anchor was compared with a double-helix and triple-helix 12 in. anchor. The results are shown in Fig. 7.

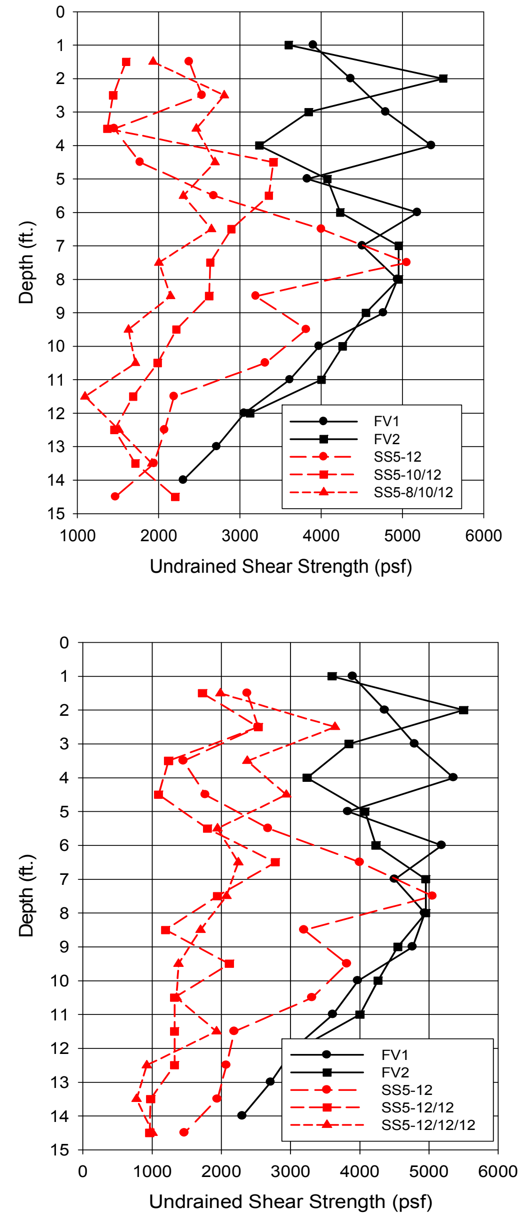


Figure 7. Undrained Shear Strength over Single-Helix and Multi-Helix Anchors.

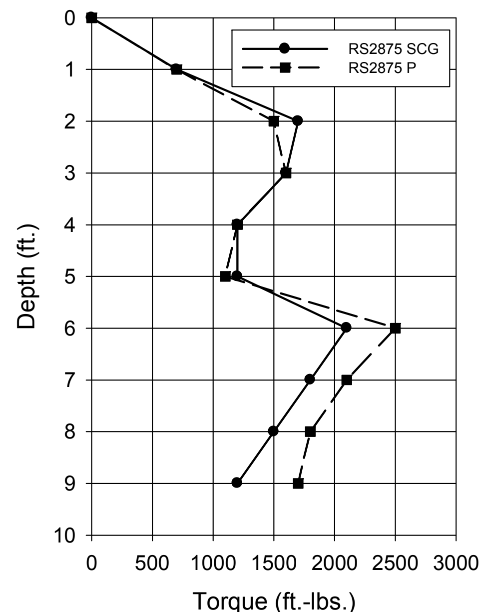
These results indicate that double-helix and triple-helix anchors do produce more disturbance than a single helix. Even though some manufacturers take great care to produce multi-helix anchors with plate spacing that theoretically should have trailing plates following in the same path as lead plates, it is likely that this rarely occurs during installation. This means that in clays having additional plates with likely produce more soil disturbance and a greater reduction in strength, producing an anchor which has a combined plate efficiency of less than 100%. That is, in tension, where the soil strength behind the plates governs capacity, the mobilized strength available to develop load capacity decreases progressively with each additional plate. Fig. 7 suggests that this was less of an issue for plates of the same diameter as compared to plates with progressively increasing diameter along the shaft, although this one set of tests needs to be verified with other tests.

A review of the installation data for all seven anchors of Fig. 7 shows that the installations were near perfect with only 4 to 5 revolutions per foot needed to advance all anchors. So even with good installation the multi-helix anchors produced a reduction in undrained shear strength of about 50% of the undisturbed strength. It would be expected that similar tests in soils with greater sensitivity would have an even greater effect on the undrained shear strength. One possible observation that might be made from Fig. 7 is that the undrained shear strength measured behind the both the double-helix and triple-helix anchors with the same diameter helical plates appears to have reached a lower level, that is, they gave about the same strength values. This behavior would also need to be investigated further with additional tests and with other soils.

Influence of Disturbance on Ultimate Capacity

Once it is recognized that installation of helical anchors in clay produces disturbance and a reduction of available strength, what is really of importance to the designer is to understand how installation disturbance may produce a reduction in load capacity of an anchor. In order to illustrate this, the load test results from the 2.875 in. round shaft helical anchor previously described in Figs. 4 and 5 were compared with an adjacent 2.875 in. round shaft anchor in which the quality of installation was considered better.

Fig. 8 shows a comparison of the installation torque and the advance for the two anchors. Initially, the installation torque is the same, but after a depth of about 5 ft. it can be seen that the torque developed by the two anchors start to diverge. This is the result of the larger number of rotations required for the SCG anchor as compared to the P anchor. As the number of rotations increases, the torque decreases as the soil is remolded.



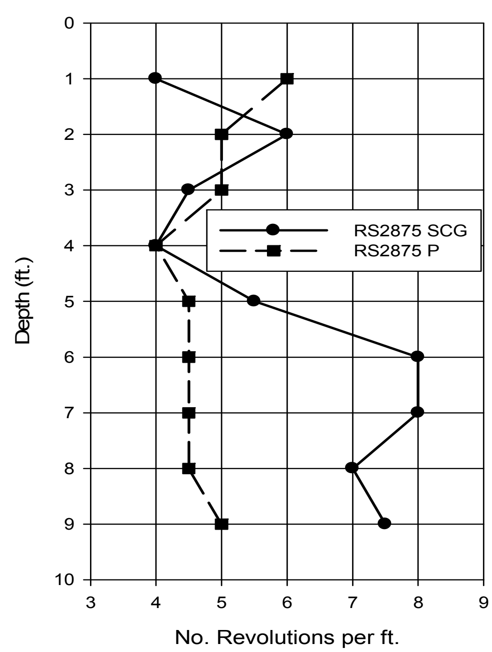


Figure 8. Installation Torque and Advance for two 2.875 in. Round Shaft Helical Anchors.

Results of load tests performed on these two anchors are shown in Fig. 9 and demonstrate the influence of disturbance on capacity. The additional disturbance produces a lower stiffness and lower load capacity of the anchor.

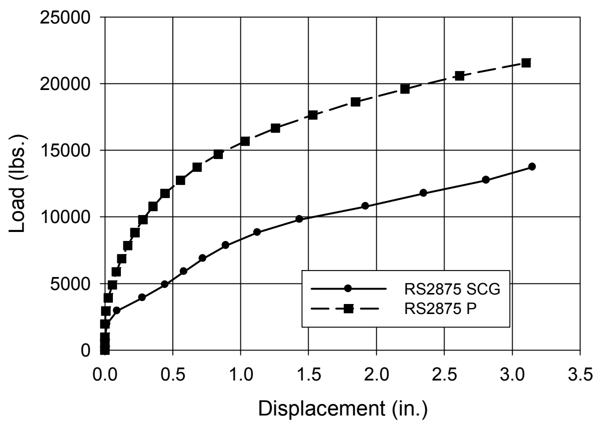


Figure 9. Comparison of Load-Displacement Curves Between two 2.875 in. Round Shaft Helical Anchors.

The Suggestion of Skempton

In 1950 Prof. A. Skempton presented a valuable discussion to the paper of Wilson (1950) on the behavior of screw-piles in clays (Skempton 1950) noting that for multi-helix screw-piles it was important to recognize that the clay beneath the upper screws had been remolded by the passage of the first screw. However, Skempton (1950) further noted that all of the clay contributing to the bearing capacity of the upper screws would not be fully remolded and, as a rough approximation, suggested that it might be reasonable to assume that the average shear strength of the clay would be equal to:

$$c_{p2} = c - [\tfrac{1}{2}(c - c_r)] \qquad [1]$$

where:
c_{p2} = operational undrained shear strength
c = peak undrained shear strength
c_r = remolded undrained shear strength

This observation and suggestion by Skempton brings into importance the Sensitivity of the clay. While Skempton (1950) found that his suggestion provided reasonable results for several cases available at that time, additional analyses using the current tests obtained by the authors is being performed to further evaluate the practical use of Eq.1.

QUANTIFYING INSTALLATION DISTURBANCE

It has been established that installation of helical anchors in clay produces varying degrees of disturbance and a corresponding reduction in undrained shear strength. The reduction in shear strength appears to be related to the quality of installation for a given soil. It therefore is of interest to make some initial quantification of the degree of disturbance that can affect the load capacity of an anchor and relate the disturbance to the quality of the installation. This then becomes an important field quality control procedure.

Ideal "Perfect" Installation

Initially it may be useful to consider the ideal or best possible installation that would represent "perfect" installation of a screw-pile or helical anchor. In this situation the helical plate would advance one pitch distance for each complete revolution of the shaft and plate. So for example if the pitch of each helical plate is 3 in. then the ideal or "perfect" advance would be 4 revolutions per ft. of advance. In the field, this is often difficult to achieve either because of the soil conditions or the equipment operator is using a rotation rate that is too fast, or a combination. Generally, slow rotation allows the lead helical plate to "dig" into the soil and advance the pile/anchor. In some cases, a small down-force or "crowd" on the shaft is needed to start the advance but once it begins, it usually progresses with little or no need to apply down-force. It is common in the field to record 4 to 5 revolutions of a 3 in. pitch helical plate for each 1 ft. of advance.

The advance can be slowed the accumulation of shaft resistance along the central shaft, especially in the case of round-shaft screw-piles and anchors. This produces a higher number of revolutions per advance and is created by an imbalance of forces between the shaft resistance and the plate resistance. That is, if the accumulated shaft resistance overcomes the plate resistance, advance will effectively stop unless a down force is applied to assist the advance. Sometime this occurs if a soft weaker soil layer is encountered by the helical plate while the shaft is still in stronger soil layers. The use of multiple helical plates helps keep the balance of forces in favor of the helical plates to improve the advance. This is usually not a problem in the use of square-shaft helical anchors which accumulate little to no shaft resistance.

“Imperfect” Installation

In contrast to the ideal or “perfect” installation described above, it is more likely that most field installations occur in a more “imperfect” manner. That is, the number of rotations of the helical plate for each unit of advance is greater than the ideal case and in some extreme cases may even approach stationary condition or no advance. Operators in the field refer to this condition as “spinout” which effectively signals when the helical plate is no longer moving. Imperfect installation produces substantial disturbance to the soil simply because the helical plate is now acting partially or completely as a section of auger and is in effect simply churning the soil. Since different degrees of imperfect installation can occur depending on the geometry of the pile/anchor and the subsurface conditions encountered by the helical plates it is not unusual in the field to record 6 to 16 revolutions per ft. of advance on a 3 in. pitch helical plate as compared to 4 to 5 which is preferred.

Installation Disturbance Factor

Considering the possible range of installation quality from “perfect” to severely imperfect, it would be useful to have a simple quantitative measure of the installation quality that can be measured directly during installation and used as a quality control measure on the Contractors work. One approach is to simply define the Installation Disturbance Factor, IDF, as the ratio of actual measured installation to the ideal or “perfect” installation:

$$IDF = (R)/(A/P) \qquad [2]$$

where:
R = measured number of Revolutions per unit of advance
A = ideal number of Revolutions per unit of advance
P = Pitch of helical plate

For example, for ideal or “perfect” installation of helical plates with a pitch of 3 in. the value of IDF would be equal to 1. That is, 4 revolutions to advance 1 ft. Values of IDF should be close to 1 for a high quality installation but may be as high as 4 or 5 is difficulty or poor quality is experienced during the installation. Fig. 10 shows the Installation Disturbance Factors for the two 2.875 in. round shaft anchors previously presented in Fig. 8. It is important to note that from traditional bearing capacity theory the zone of influence contributing to the load capacity in clays in tension is only about 1 to 2 diameters above the helical plate and therefore it is in this zone where disturbance is most important.

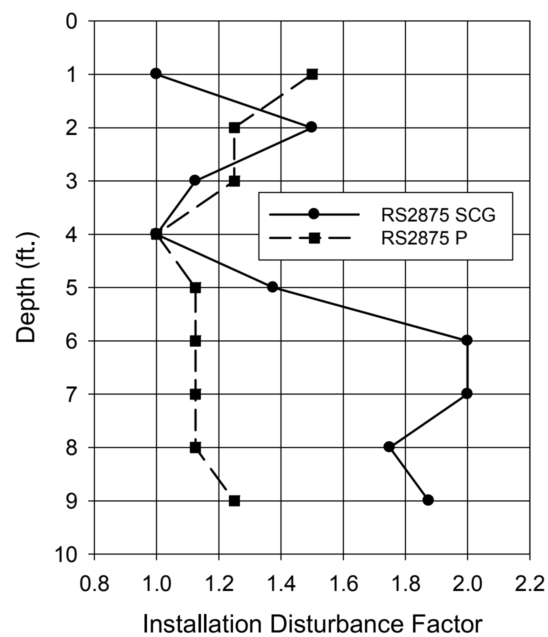


Figure 10. Installation Disturbance Factors for two Round Shaft Helical Anchors.

Conceptual Framework for Disturbance and Available Shear Strength

One possible way to quantify the effect of installation disturbance may be to consider the available undrained shear strength in the context of the initial undisturbed undrained shear strength as a ratio. That is, what percentage of the undisturbed shear strength is still available for developing load capacity after installation? Logically, as the Installation Disturbance Factor, defined above, increases, the soil becomes more disturbed and remolded and less strength is available. Also, for two soils with different

Sensitivity (low vs high) the same Installation Disturbance Factor will produce different degrees of disturbance.

A simple conceptual framework which incorporates these observations is shown in Fig. 11. Based on the results obtained to date, it appears that values of low Sensitivity would fall in the range of about 1.5 to 4; values of high Sensitivity may be somewhere in the range of 4 to 10. Special sensitive clays with Sensitivity of 50 to 1000 may not be considered as appropriate candidates for helical anchors. Extreme disturbance leading to fully remolded soil approaches the lower limit of Available Strength Ratio of Fig. 11 which is equal to 1/Sensitivity. Fig. 11 does not represent actual data since only limited results are currently available from a single site; it is a conceptual framework only and needs to be validated. Data from a number of sites with identical anchor geometries are needed to populate Fig. 11.

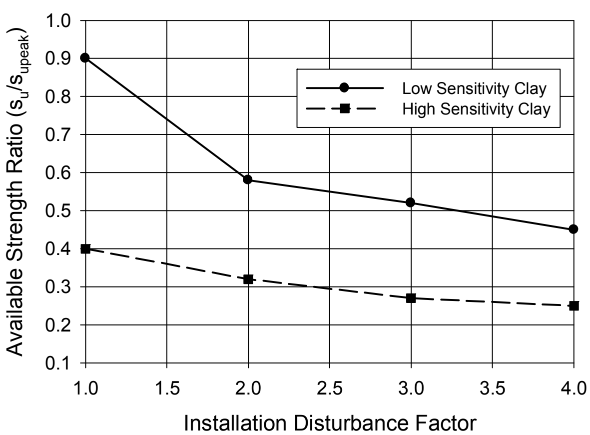


Figure 11. Conceptual Framework for Relating Installation Disturbance Factor to Available Shear Strength.

CONCLUSIONS

Field vane shear tests were performed in clay after the installation of single-helix and multi-helix helical anchors to obtain a direct evaluation of the degree of disturbance produced during installation. The results indicate that:

1) The installation of helical anchors in clay produces some disturbance of the soil and a reduction in undrained shear strength as the helical plate passes through the soil;
2) The degree of disturbance is greater for multi-helix anchors as compared to single-helix anchors;
3) The degree of disturbance is related to both the soil characteristics, especially Sensitivity, and the quality of the installation;
4) It appears that a simple Installation Disturbance Factor can be used to quantify the degree of disturbance, however this will require that the advance rate (revolutions per foot) be recorded during the installation of every helical anchor;
5) A basic framework has been suggested to relate the degree of disturbance to the available undrained shear strength which is also likely related to the Sensitivity of the clay.

The results presented in this paper reflect the initial tests performed by the authors but to the authors' knowledge represent the first set of direct measurements of the influence of installation of helical anchors on the undrained shear strength in clay. Additional work is underway to provide further results to help develop a simple model and recommendations that can be used by engineers to refine the design of helical anchors in clay and to compare the results obtained with the suggestion of Skempton (1950). It should also be noted that the results presented in this paper do not consider any long term aging or strength regain effects, similar to those for driven piles, which will likely occur in most clays between the time of installation and time of loading. This also needs to be evaluated.

ACKNOWLEDGEMENTS

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