USE OF IN-PLACE INCLINOMETERS (IPI) DURING LATERAL LOAD TESTING

Joel Swenson[1], Tom Richards[2], and John Rowley[3]

ABSTRACT

Inclinometers can be used to measure the deflected shape of the micropile during lateral load testing. From this shape, actual p-y curves can be calculated. Lessons learned from the planning, installation, testing, data reduction, and data analysis are presented.

INTRODUCTION

During design, strength and deformation properties of soils are typically used to create p-y curves, or load-deformation curves, for laterally loaded micropiles such that deflections, shear, rotation, and moments can be calculated and applied to the design. Lateral load tests are often performed to verify the design and should probably be performed more often. In a standard lateral test, lateral micropile deflection at the ground surface, and less frequently rotation, are the only measured results. Consequently, there are numerous possible combinations of soil strength and stiffness profiles that could be back calculated to match the measured results. The use of in-place inclinometers (IPI) data provides a method for refining models and more accurately determine bending moments for combined stress analysis of the laterally loaded micropile.

This paper presents lessons learned in the planning, execution, and evaluation of IPIs in lateral load tests.

DESIGN PROCESS

Typically, micropiles subjected to lateral loads are tested to verify the design prior to constructing the remainder of the production micropiles. In most instances this approach is sufficient for micropile design. The typical design process is:

<u>Typical method</u>

A. Evaluate foundation type(s)
B. Estimate foundation depths
C. Perform Investigation
D. Measure soil properties
E. Choose p-y curve model in LPILE (Reese, 2007)

[1] Geotechnical Engineer, Barr Engineering Company, 4700 West 77th Street, Minneapolis, MN 55345| Phone 952-832-2799, Fax 952-832-2601, jswenson@barr.com

[2] Chief Engineer, Nicholson Construction Company, 12 McClane Street, Cuddy, PA 15031 Phone 412-221-4500, Fax 412-221-3127, trichards@nicholsonconstruction.com

[3] Design Engineer, Nicholson Construction Company, 12 McClane Street, Cuddy, PA 15031 Phone 412-221-4500, Fax 412-221-3127, jrowley@nicholsonconstruction.com

F. Design micropile
G. Construct test micropile
H. Perform load test to verify design
I. Install remainder of micropiles or redesign

However, some instances such as variable ground, lack of shallow ground exploration data, small allowable deflections, etc; require micropile response evaluation prior to design completion. To determine micropile behavior below the ground surface, the deflected shape of the micropile can be calculated using inclinometer readings from within the test micropiles under loading. In addition, the test micropile can be tested to failure unlike production micropiles. The deflected micropile shape data can be compared to output from lateral micropile design software such as LPILE and GROUP to create design parameters such as p-y curves and evaluate toe fixity. This approach has been used on several recent micropile designs and is listed below:

<u>Alternate method</u>

A. Estimate micropile design (steps A to F above)
B. Construct test micropile
C. Instrument and test micropile measuring:
    a. Deformations thru depth of micropile
    b. Top deflections
    c. Curvature
    d. Inflection points
D. Analyze data
E. Model micropile
F. Develop p-y curves from data
G. Design micropile and micropile group
H. Construct micropile
I. Load test as necessary

PLANNING

An instrumentation program for the design of laterally loaded micropiles must exhibit redundancy, instrumentation efficacy, reliability, and the collection of high quality data (Dunnicliff, 1993). For instance, typical load test programs only measure deflection, and less frequently rotation, at the top of the micropile during the load test. Rotation can be included reasonably easily by placing an additional dial gauge above the loading point as shown in Figure 1. Additionally, an independent measurement system consisting of wire and mounted rulers should be used in the event dial gauge readings become jeopardized. These additional gauges and a redundant measurement should always be used and required in specifications.

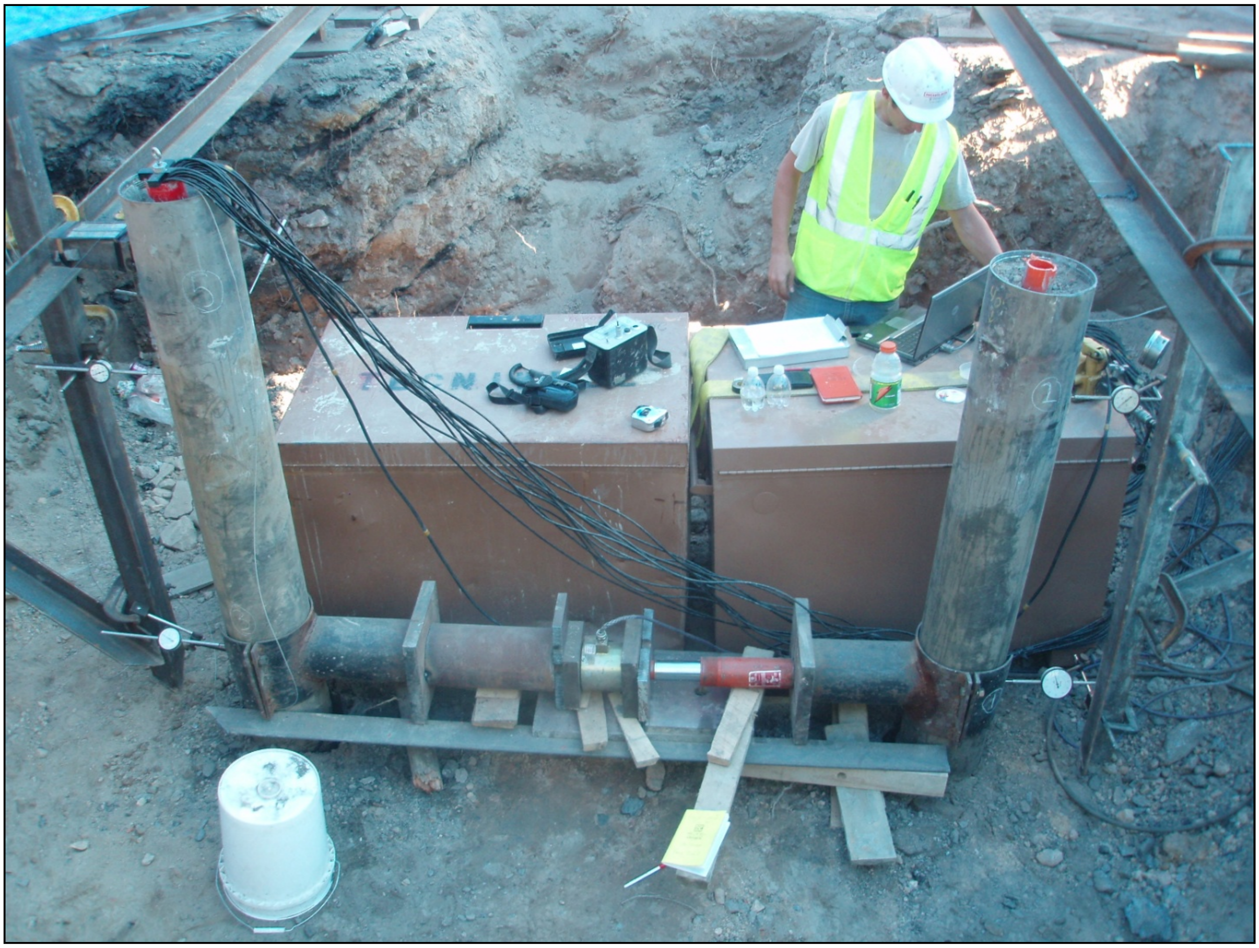

Figure 1 Typical Lateral Load Test Setup

However, more information is required to develop site specific p-y curves. The method discussed herein for developing site specific p-y curves utilizes in-place inclinometers installed within the test micropile.

Inclinometers collect rotation data at specified depths within a laterally loaded micropile using either a string of in-place inclinometers (IPIs) or through the use of standard traversing inclinometers. Most conventional IPIs or standard inclinometers operate through either biaxial or triaxial accelerometers. A new class of IPIs use MEMS-technology and were used for our recent work. The MEMS IPIs and strandard inclinometers were used within a single micropile for comparison purposes with success. However, limited space within the test micropile and inclinometer casing may prohibit the use of both types of inclinometers. In order to obtain useful results, testing preparation needs to address several factors that have an effect on inclinometer data. These factors are depth, spacing, inclinometer plan orientation, and toe fixity.

Lateral load testing is expensive and the loss of data collected during a test or lack thereof can add to costly increases to the design, and in these instances, redundancy is appropriate. However, the lowest cost of an instrument is rarely a valid reason for its choice unless high quality can be specified adequately (Dunnicliff, 1993). Additionally, micropile testing is limited by construction schedule. Time lost on poor test results directly affects client schedule. Therefore inclinometer redundancy and quality instrumentation are relatively inexpensive given micropile installation and testing costs.

Length of Inclinometer

A micropile consists of two sections, a cased and an uncased section. The cased section consists of micropile steel casing extending through the unstable zone to the top of the bearing stratum or bond zone. The uncased section of the micropile begins at the bottom of the steel casing and extends to the bottom of the boring within the bearing stratum.

Inclinometers sense rotation, a scalar value, which is not lateral displacement. Rotation is then converted to displacement through the use of a reference point which must be located below a depth of zero rotation or toe fixity.

This depth of zero rotation can be within the uncased portion of the micropile. It is imperative that all inclinometer measurements begin below this depth which is typically the toe of the test micropile. It is often best to install the casing to the toe or uncased section of the micropile so that any toe movement can be evaluated. In very deep applications where lateral movements are not expected at depth, the casing may be installed only to a point of fixity within a portion of the total casing depth. This depth needs to be estimated in the initial design. We recommend looking at the detailed output from LPILE and extending at least 2 feet past the depth where all rotations below are less than 0.001 radians. For shallow applications, it is generally best to install the inclinometer casing to full depth.

Spacing of Readings

Closer spacing of sensors will result in a well defined deflected shape. A traversing inclinometer is typically read at 2 foot increments of depth, On the other hand, in-place inclinometers (IPI) can be used with closer sensor spacing. Cost, cable diameter and number of cables govern spacing of IPIs within the inclinometer casing. In the last few years, chains of accelerometers (Measurand SAA and others) that have very close measuring intervals, high accuracy, and small diameters have become available and used in industry (Holman 2010 and Rollins et. al 2009).

Timing/Frequency of Readings

IPIs allow for automated data recording and readings can be collected in several seconds either at programmed time intervals or manually by initiating each measurement. In contrast, traditional inclinometers require as much as 15 minutes per run depending on the length of micropile with a minimum of two runs. This time is longer than allowed for certain loading procedures outlined in ASTM D3966-07. The amount of time required for traversing inclinometers depends on the length of the pile and reading frequency. Traditionally, a two foot interval reading frequency has been used with success. However, a micropile longer than 50 feet may require twenty minutes of testing since the traversing inclinometer is pulled up the inclinometer casing four times, twice for each direction, to eliminate sensor bias. Subsequently, traditional inclinometer data is collected less frequently than IPI data although an extra set for data comparison is invaluable.

Redundancy/Verification

Figure 2 shows the plan view of a typical lateral load test micropile. The figure shows two inclinometer casings placed adjacent to one another perpendicular to loading. Both inclinometer casings should be installed past an expected depth of zero rotation.

Figure 2 – Inclinometer Casing Orientation

One inclinometer casing will house the IPIs and the other will allow for the use of a traditional traversing inclinometer which will be traversed only at certain load increments due to time constraints. The purpose of the traversing inclinometer is to validate IPI data and provide redundancy data at certain loading increments.

Two for the Price of One

Lateral tests need a reaction which is frequently another micropile. It is difficult to estimate which micropile will perform worse. By placing dial gauges and inclinometers in both piles, two lateral test results can be collected at the same time with minimal expense (except for second IPI string). An IPI string can be expensive at approximately $15k for 40 feet. The project team must consider using more than one IPI string or determine if one IPI string and a traversing inclinometer are adequate. Even if this is the case, an inclinometer casing should be placed in the reaction micropile. This can then be read occasionally with the traversing inclinometer

Schedule

Planning needs to include time and human resources to:

1. install and test all sensors
2. read the dial gauges – minimum of four
3. monitor the datalogger/PC
4. enter and marry all of the data

INSTALLATION

After the micropile steel casing and unbonded lengths have been set and bored, inclinometer casing is inserted into the micropile and then grouted into place. During placement and especially during grouting, the inclinometer casing wants to float. This can be resisted by tying or taping to the coresteel bar and by filling the inclinometer casing with water.

Prior to grouting, the grooves of the inclinometer casing need to be oriented in the direction of the applied load. The inclinometer casing should not be forceably oriented due to the risk of twist of the grooves. This introduces uncertainty into the results, especially for longer piles, if not corrected. The twist must be diagnosed using the initial reading cycles after installation. In any case the as-built groove orientation as shown in Figure 2 should be measured and documented using good carpentry skills (string lines, squares, and distance measurements).

We used 9 MEMS IPI (GeoKon Model 6150) in 3 inch inclinometer casing. Because each of the MEMS is wired, each consecutive MEMS device increases the size of the bundled wires that must extend through the inclinometer casing. We found there was little room for more wires in the 3 inch inclinometer casing using 9 MEMS IPIs. As a result the string of IPIs had to be pushed down with moderate force.

TESTING

In addition to the use of inclinometers which evaluate the micropile deflected shape, measurements should be performed at the pile top during the test. Dial gauges or LVDTs should be used at or very near the opposite side of the micropile loading point elevation and the other a few feet above the loading point. It is important to set the uppermost IPI and end traditional inclinometer readings at the point of loading such that comparing dial gauge readings to inclinometer readings provides additional quality control. Actual stickup and depth measurements of the dial gauge/LVDT and inclinometer pipe need to be documented within 6 mm (0.25 inches) so that deflections relative to point of applied load can be determined. Figure 3 shows a typical set up.

Figure 3 – Lateral Load Setup

The IPIs and load cell were connected to a datalogger connected to a PC. The load cell readings in this database provide a tie between inclinometer and load in the datafile. The datalogger can be programmed to collect data by either:

a. Programmed time intervals require the lateral load test and load intervals to be closely timed. If an IPI measurement occurs while the loading is changing, the measurement must be noted such that it is not used in analyses.
b. Manually initiating by a keystroke on the PC at each increment so that the data collected matches the loading increments and reading times. This prevents interim measurements between loading cycles. However, human error can result in missing measurements.

We prefer method b to account for imperfections in the timing and to more easily marry data from various sources.

In either case, the data collected needs to be observed to verify that all sensors are recording. The data can also be downloaded directly to a spreadsheet provided a PC is attached.

We used manually read mechanical dial gauges because of the preference for simple mechanical devices and minimal electronics (only where needed). If more electronics are used, we recommend at least some mechanical and human verification, such as redundant dial gauges or piano wire.

The IPI and load-deflection data are then married together by time. Therefore, it is important for both records to use the datalogger time.

Additional details of lateral load testing are presented in Richards and Rothbauer (2004).

As stated above, both IPIs and traditional inclinometers can be used within the same lateral test pile provided adequate space is available. Traversing inclinometer readings were obtained on both micropiles at important load increments typically 1.0, 1.5 and 2.0 times design load. For the micropile containing the IPI's, an additional inclinometer casing was installed to allow for use of the traversing inclinometer. With each traversing inclinometer reading, the standard deviation of the values is used as a check between the two runs on each micropile.

While performing a lateral load test, the lateral force from the load cell and jack pressure gauges, all dial gauges, and the IPIs should be read as the target force is reached and at several hold times depending on which ASTM D3966 testing protocol is followed. Most testing protocols require hold times of varying length for each load sequence. After testing has started and the lateral loading increases, monitor rotations measured by the IPIs. If the bottom most IPI is placed at a proper depth, no rotation should be measured throughout the testing process. However, if the bottom most IPI shows signs of rotation, note the lateral loading at which it began.

EVALUATING

Raw inclinometer, IPI, load cell, dial gauge data and jack pressure gauge data are married together in a spreadsheet. An initial quality control check is to calculate the rotation of the micropile at the loading point using dial gauge readings for each loading sequence. Compare these results to the rotations measured in the IPI and traversing inclinometer measurements. These results should closely resemble each other. If they do not resemble each other, check instrumentation calibrations and depth.

Plot the deflection versus load from the dial gauges and from the inclinometers. These plots should agree. Frequently, the elevations of inclinometer deflection measurements do not agree exactly with the elevation of deflection measurement. This causes a difference in the two plots because of the rotation and curvature of the pile near the point of applied load. Even a few centimeters elevation difference can can make a difference. Interpolate one set of measurements to the same elevation for this comparison.

Using sensor calibrations and the length between IPIs or traversing inclinometer measurement points, calculate lateral micropile deflections for each loading sequence and hold time. Plot these measurements relative to micropile depth for individual loading sequences. Normally, the initial reading is used in these plots while the inclinometer readings from hold times are used to analyze creep. Compare bottom dial gauge displacement to IPI and traversing inclinometer data, when applicable. Agreement among IPIs, traversing inclinometers, and dial gauges in addition to no movement measured in the bottommost IPI indicates data was collected successfully. If the bottom most inclinometer senses rotation, the test may be discounted since lateral displacement measurements determined from each inclinometer must begin from a point of zero rotation. However, the inclinometer plots can be translated to agree with the deflection measurements. Figure 4 shows deflection versus depth at various load increments and for both IPI and traversing inclinometers.

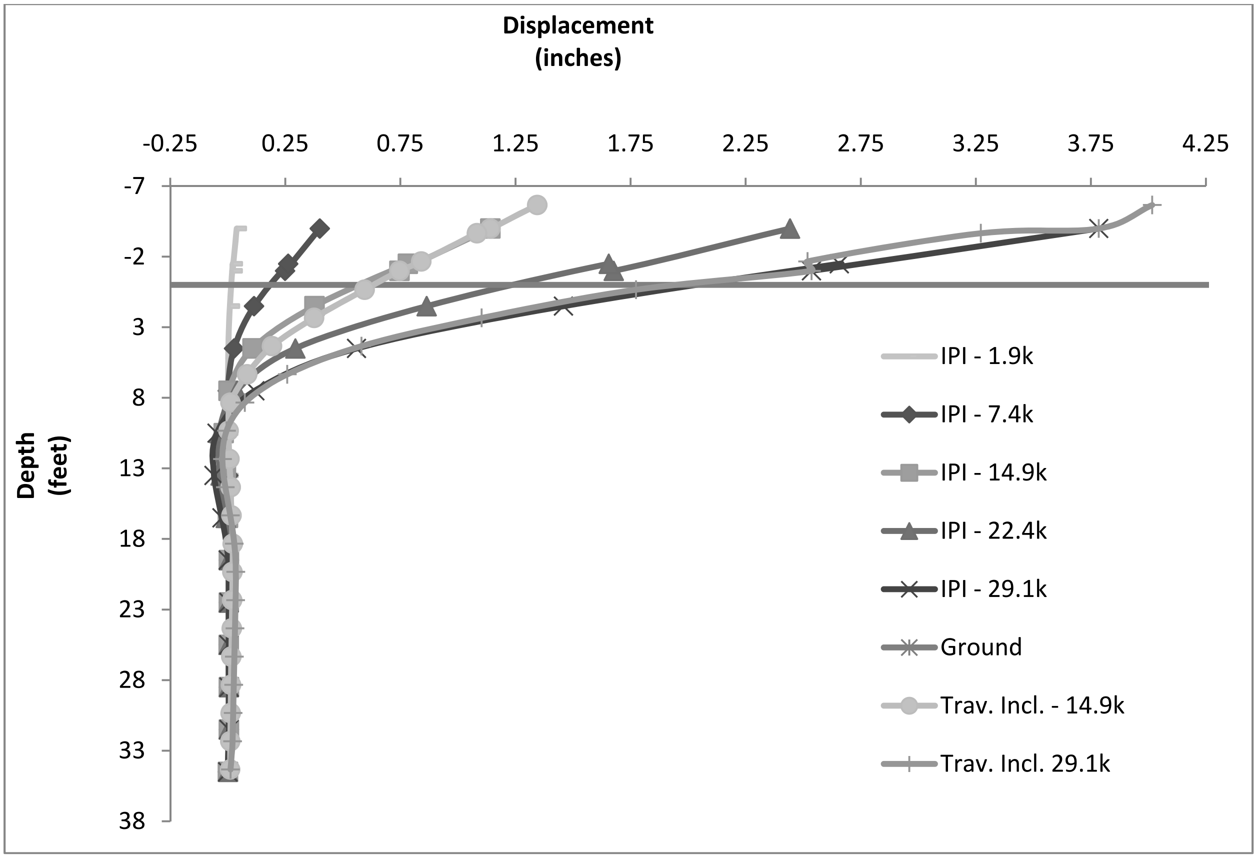

Figure 4 – Micropile Deflected Shape Measurements

Having created plots showing several sets of micropile deflections resulting from several lateral loadings, use LPILE to estimate p-y curves. The LPILE models will be based on installed depth and stratigraphy and be analyzed for each load increment. To eliminate the composite bending stiffness variable, the nonlinear section analysis within LPILE can be used. First, choose a P-y material model from LPILE most closely resembling the in-situ materials. Through trial and error, adjust soil parameters (starting with strengths at maximum loads and then initial stiffness at lower loads) while noting that several different soil layers may be required to match the deflected micropile shapes. Adjust parameters for each material model accordingly such that the deflected micropile shapes resemble the LPILE deflected micropile shapes for the entire loading schedule. Figure 5 contains an example.

It is theoretically possible to double differentiate the deflection versus depth curve to estimate curvature and bending moment, then double differentiate again to get lateral pressure. However, with discrete measurements at 1 to2 foot intervals and even with fitting the deflection versus depth curve to a best fit 6th order polynomial , the second author’s experience in applying this method has yielded strange and poor results for distributed loads (p). Therefore, the iterative method proposed above is suggested.

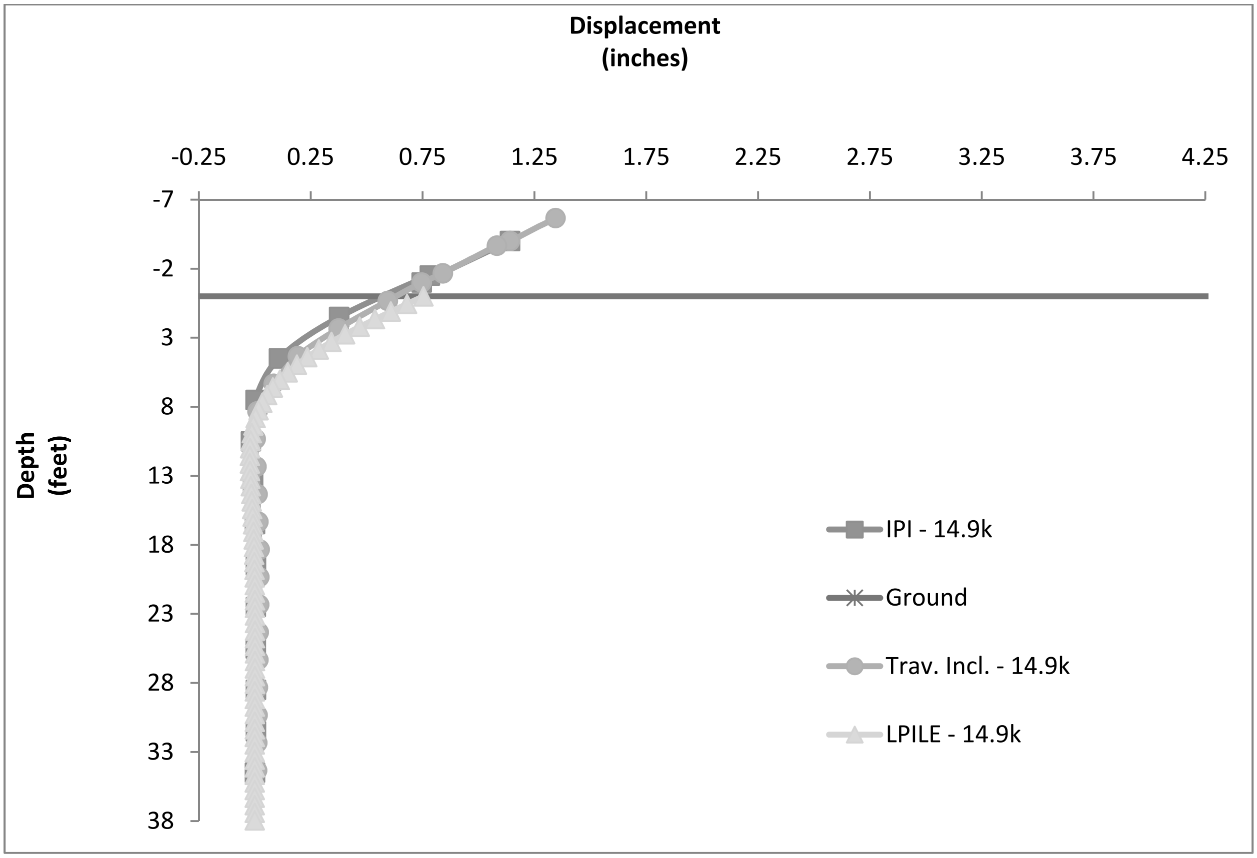

Figure 5 – Deflected Micropile Shape and Modeled Deflected Shape

After the p-y curves have reasonably estimated micropile deflections, LPILE can compute shear and bending moment plots. These plots are used to design the micropile for combined stresses.

If the proposed foundation consists of multiple micropiles, then P-y curves created from LPILE are entered into GROUP. Export the p-y curves from LPILE to GROUP. Then, perform micropile group analysis for the various loading conditions.

CONCLUSIONS

Careful use of IPIs can refine a micropile design for lateral loading, especially with stringent deflection criteria.

Careful use includes:

- Planning the depth of IPIs
- Documentation of as-built elevations of various sensors relative to point of applied load
- Occasional verification of IPIs using standard traversing inclinometer
- Comparisons of rotations above the point of applied load determined by dial gauges/LVDT
- Comparison of deflections from various sensors interpolated to a given elevation

REFERENCES

1. Reese, L.C., and Wang, S.T. (2007) LPILE Version 5.0.44 [computer program]. Ensoft, Inc., Austin, TX.
2. Dunnicliff, J. (1993). “Geotechnical Instrumentation for Monitoring Field Performance. Wiley and Sons, New York, NY.
3. Richards, T. D., Rothbauer, M. J. (2004). “Lateral Loads on Pin Piles (Micropiles).” ASCE Geo-Support Conference, Orlando, FL.
4. Holman, T (2010) personal communication
5. ROLLINS, K., Herbst, M., Gerber, T. and Cummins, C. (2009). “Monitoring Displacement vs. Depth in Lateral Pile Load Tests Using Shape Accelerometer Arrays.” Procs. 17th Intl. Conf. on Soil Mech. and Geotech. Engrg. ISSMGE, IOS Press, Vol. 3, p. 2016-2019.