Originally Published for the ASCE in Geo-Denver 2007: New Peaks in Geotechnics.
Denver CO, USA. February 2007.

Quality Control Of Drilled Displacement Piles Through An Integrated Automatic Data Acquisition System

W. Morgan NeSmith[1] and Willie M. NeSmith, P.E.[2]

[1]Berkel & Co. Contractors Inc. - 834 Dekalb Avenue Unit B, Atlanta GA 30307
PH (678) 528-1653 FAX (678) 528-8216 email: morgan_nesmith@comcast.net
[2]Berkel & Co. Contractors Inc. - 1503 Milner Crescent, Birmingham AL 35205
PH (205) 933-8900 FAX (205) 933-8979 email: wnesmith@bellsouth.net

ABSTRACT

In a set of companion papers presented at GeoCongress 2006, the authors described a Data Acquisition System that is included on the installation platforms for drilled displacement piles and, in general terms, defined how the acquired pile installation data can be used both for quality assurance / control and as an element of the pile design process. The system described was subsequently used by Berkel and Co. Contractors Inc (Berkel) as part of a design-build project in Orlando FL in March and April of 2006.

The acquired installation data was used in the following manner. First, the pile installation data acquired during the preliminary foundation design and performance testing phase was used for final design of the foundation system for the project. Secondly, the data acquired during production pile installation was used, in real-time, for quality assurance / control during the project's entire pile installation phase.

In addition, daily review of the acquired pile installation data revealed subsurface anomalies in one portion of the site that were subsequently attributed to other subsurface construction activities that occurred immediately prior to pile installation. The authors demonstrate how these anomalies were detected, how appropriate capacities were assigned to the piles in question and how appropriate remediation measures were planned and executed.

Unless otherwise noted, the use of the term "pile" or "displacement pile" in this paper refers to the Berkel Displacement Pile (as described in NeSmith, 2002). Likewise, design methodologies and construction recommendations described herein also refer specifically to this foundation system.

INTRODUCTION

The scope of services for this project was to provide design-build services for deep foundations for a parking structure in downtown Orlando FL. The facility will occupy an area approximately 1 x ½ city blocks in size and will have 5 above ground levels. Column loads ranged from about 200 to 1500 tons.

Based on the available subsurface information, Berkel proposed to design and install 16-inch diameter full displacement piles with an allowable compressive load of 140 tons.

A supplementary site investigation was performed as part of the above scope of services. Additionally, the drilling platform used for pile installation included an onboard data acquisition system to monitor and record pile installation data as described in NeSmith and NeSmith (2006a). This acquired data, along with the engineering parameters associated with this data (NeSmith and NeSmith, 2006b), was used to set production pile installation depths and to verify the adequacy of the foundation system.

PROJECT AND TEST PROGRAM DETAILS

Figure 1 is a proposed pile layout also showing boring and cone penetration test location (CPT) details. The exploration locations include data provided by the owner, as well as data collected in the supplementary site characterization program.

The foundation performance test program at the project site included installation and performance testing (static incremental loading) of two 16-inch diameter test piles. Test pile locations also appear on Figure 1.

A composite plot of tip resistance (q_c) data is presented along with a generalized stratigraphy on Figure 2. This data is from the CPTs performed during the supplementary investigation. The ground surface elevations at the time of the CPT program, test pile installation and pile production were all similar. Analysis of the available site characterization data indicated that 16-inch diameter displacement piles installed to between 60 ft and 75 ft below the ground surface would have a compressive capacity of at least 280 tons.

Test piles were installed as follows:

- TP-1: 16-inch diameter pile to 60 ft below the ground surface
- TP-2: 16-inch diameter pile to 75 ft below the ground surface

Parameters recorded during installation of these two test piles are presented in Figures 3 and 4. Note that *Penetration* and *Withdrawal* refer to the rate at which the drilling tool was advanced into (drilling phase) and retracted from (grouting phase) the ground. *KDK Pressure* is the fluid pressure of the motors driving the rotary head of the drilling tool. *Incremental Installation Effort (IE)* is a unit-less parameter derived from the KDK pressure and penetration rate of the drilling tool. *Cumulative IE* is an integration of the Incremental IE curve. *Grout* refers to the pressure of the grout pumped into the pile as measured at the **top** of the drilling stem. Further details regarding these measured and derived parameters are presented in NeSmith and Nesmith, 2006a and 2006b.

LOAD TEST RESULTS AND ANALYSIS

Plots of applied load verses pile head displacement are presented on Figures 5 and 6. Also presented in these plots are hyperbolic extrapolations of the load-displacement relationship (according to Chin, 1970). It has been the experience of the authors that the Chin methodology produces a reliable load-displacement model for (at least) displacement piles installed through primarily granular materials.

The compressive capacities of the piles were defined as the lesser of the following two loads (as per NeSmith, 2002):

- The load at which the slope of the hyperbolic model of the pile head load-displacement relationship becomes 0.02 inches/ton
- The load at which the pile head deflection is equal to 6% of the pile diameter

Applying the above criteria, as well as additional analysis regarding the toe and shaft components of the test piles, the ultimate loads for the test piles at this site were estimated as follows:

- TP-1 – Total: 331 tons   Shaft: 286 tons   Toe: 45 tons
- TP-2 – Total: 396 tons   Shaft: 345 tons   Toe: 51 tons

PRODUCTION PILE INSTALLATION CRITERIA

Production piles were to support compressive loads of 140 tons. In light of information collected during the site characterization phase and with particular regard to the information collected by the on-board data acquisition system for each pile installed, a factor of safety of 2 was considered more than sufficient for these piles. The recommendations described in this paper were with specific regard to the installation of 16-inch diameter displacement piles with a compressive capacity of 280 tons (deriving capacity as described above).

Minimum Depth

The compressive capacity of Test Pile 1 (installed to 60 ft below the ground surface) was estimated to be about 331 tons. While this was well in excess of the required ultimate compressive capacity of 280 tons, production piles were installed to a minimum depth of 60 ft below the current ground surface to penetrate the loose / soft materials encountered between depths of 40 ft to 58 ft below the ground surface.

Maximum Required Depth

The compressive capacity of Test Pile 2 (installed to 75 ft below the ground surface) was estimated to be about 396 tons. Analysis of the available subsurface data suggested that clean to slightly silty sands encountered at the installation depth of TP-2 (about 75 ft) provided adequate bearing capacity to allow for expected variations across the site in shaft resistance of the soils above this level.

It was therefore considered that the maximum required depth of installation for piles described in this report to achieve a working compressive capacity of 140 tons was 75 ft below the ground surface at the time of the load test.

Installation Effort as Termination Criterion for Production Piles

Analysis of the available subsurface data indicated that variation in shaft capacity across the project site occurred primarily in the medium to dense, clean to slightly silty sands encountered from about 10 ft to 45 ft. The shaft capacity developed in this stratum typically dictated the depth between 60 ft and 75 ft at which production piles might be terminated. The methodology for determining pile termination levels between 60 ft and 75 ft depth is described below.

The relating of the total effort involved in installing a pile to that pile's capacity has been used with increasing frequency over the past few years (NeSmith and NeSmith, 2006b). It is noted that the drilling platforms used to install Berkel's drilled displacement pile system include a real time automated monitoring system. The system provides on-board calculation and presentation of Incremental and Cumulative Installation Effort (IE), which are estimations of the energy expended during pile installation. Incremental IE is derived from the individual recordings of penetration rate of the drilling stem and hydraulic fluid pressure (KDK pressure) applied to the rotary head to rotate the drilling stem (NeSmith, 2003). Incremental IE is calculated for each record and plotted versus depth. Cumulative IE is an integration of the Incremental IE curve, also plotted again depth. Plots of IE vs. Depth are included on the installation records (Figures 3 and 4) included herein. The Cumulative IE values for the two test piles, at their respective termination points, were as follows:

- TP-1: 811
- TP-2: 994

Compressive capacities (total and shaft) of the test piles were correlated to the recorded Cumulative IE values according to the method described by NeSmith (2003). It was thus estimated that piles with an IE of about 700 were would have a shaft capacity of about 244 tons, requiring a toe capacity of 36 tons (less than the 45 tons to 51 tons mobilized during the load test program). The pile termination criteria was then the depth at which the Cumulative IE for the pile in question was equal to 710 (chosen to ensure a final IE in excess of 700) with a minimum depth of 60 ft and maximum depth of 75 ft as described above.

Piles with Varying Cut-off Levels

Pile cut-off elevations in the area of proposed elevator shafts were approximately 5 ft below the cut-off elevation of the majority of the piles at the site (a total of 10 ft below the working grade at the time of pile installation). With respect to possible effects of pile cut-off elevations on pile capacity, analysis and recommendations were as follows:

- Analysis of the installation records of the test piles and initial production piles indicated that the Cumulative IE in the first 10 ft of was about 75 to 100 [-].

- As this material would be penetrated, but eventually excavated for the proposed elevator shafts, it was determined that piles in these areas should be installed with an additional 100 IE units to compensate for what would be lost due to future excavation.
- Therefore, piles in the area of the elevator shaft were installed as per the specifications presented in the preceding sections of this report, with a minimum installation depth of 60 ft and a maximum required depth of 75 ft below the ground surface.
- After penetrating to at least 60 ft below the current ground surface, Berkel displacement piles were terminated at such a depth that the Cumulative IE equaled to 810.

INSTALLATION EFFORT AS A QUALITY CONTROL MECHANISM FOR PILE PRODUCTION

During the foundation production phase of the project, pile installation records were generated on site daily and reviewed by the authors. Towards the end of the project (day 19 out of 23 days of production), review of pile records indicated lower than expected soil resistances at some production pile locations in the Northeast corner of the site (the area outlined in red on Figure 1). The subsequent review of additional installation records in the following days indicated that the soils in this area provided consistently lower than expected soil resistances during production pile installation.

Figure 7 shows an enlarged view of the area referred to above, along with specific pile numbers. Also shown are the approximate locations of two 24-inch diameter steel casings (for hydraulic elevators) that were installed prior to the production pile program. Detailed analysis of the records of the piles shown on Figure 7 showed generally lower soil resistances (as a function of the Installation Effort required at these pile locations) during pile installation than were encountered in other areas of the site. Piles 90169, 90355 and 90357 showed specific areas of reduction in soil resistances that did not appear to be naturally occurring variations of the general site stratigraphy. A composite plot of the Incremental IE of pile 90169 along with other piles in the area of pile 90169 is shown on Figure 8 as an example of the condition described above. Of note is that the IE increases as more piles are installed in the area. The first three piles installed (90169, 90167 and 90165 in that order) had the lowest calculated IE. Piles installed on subsequent days (including 90168 and 90166 in between the three piles listed above) showed significant increases in IE though the installation of pile 90171, the final pile installed in the sequence shown.

Referring back to the composite q_c profile of the site on Figure 2, BC-6 (in the Northeast corner) indicated lower densities of the coarse grained materials from 0 ft to 40 ft depth than in other areas of the site.

It is believed that the installation of the steel casings, which included jetting ahead of the toe of the casing to facilitate penetration, exacerbated a condition where the soil densities were already at about the minimum density required to develop pile capacities similar to the remainder of the site.

It was determined that the potential issue of pile capacity related to the lower than expected soil resistances could be remedied by the installation of additional displacement piles, some solely as ground improvement members, others as load-bearing and ground improvement elements. Approximate locations of the required additional production piles are also shown on Figure 7. Only at one of these locations (90398) was the final spacing between piles less than three times the pile diameter. This pile was installed as a ground improvement member and not considered for capacity evaluations. These piles (90393 to 90398) were required to penetrate to 60 ft below the working grade.

It is noted that there was no down-time between the completion of the originally planned piles and the installation of the additional piles. The recognition of the potential issue, the proposed solution and the resolution of the issue occurred in a 4 day period, with the solution adding less than 4 hours to the original scope of work.

CONCLUSION

This project provided the opportunity to demonstrate both of the primary benefits of the automated data acquisition system for drilled displacement piles with real time analysis and display capabilities along with important ancillary benefits. First, the use of the data acquired during the test pile installation phase of the load test program allowed for the application of efficient, rational pile installation criteria for the project. Second, review and analysis of the data provided for each pile on a daily basis led directly to the observation of a potentially problematic situation as well as the proposed solution for the situation. As importantly, the system provided for the timely resolution of the problem and allowed the project to be completed with minimal additional foundation construction time.

Systems such as the one described in this paper provide a range of potential benefits for the design and production installation monitoring of drilled displacement piles. The process of developing production installation criteria that embrace expected variations in subsurface conditions can be done on a rational basis, rather than simply setting a pile toe level based on a load test at the perceived worst case condition (that is discovered during exploration). As a minimum, these systems provide an indication of the stratigraphy at all pile locations, which can be compared to the range of conditions assumed in design. The application of the relationship between Cumulative Installation Effort and pile capacity provides a platform for the analytical evaluation of the impact of unanticipated changes in stratigraphy, should they occur.

REFERENCES

Chin, F.K., (1970). Estimation of Unit Load on Piles not carried to Failure. Proceedings of the 2nd Southeast Asia Conference on Soil Engineering. pp. 81-90.

NeSmith, W. M., (2002). Design and Installation of Pressure-Grouted, Drilled Displacement Piles. Proceedings of the Ninth International Conference on Piling and Deep Foundations. Nice, France. June 2002.

NeSmith, W.M. (2003). Installation Effort as an Indicator of Displacement Screw Pile Capacity. 4th International Geotechnical Seminar on Deep Foundations on Bored and Auger Piles (BAP IV). Gent, Belgium. June 2003.

NeSmith, W.M. and NeSmith, W.M. (2006). Anatomy of a Data Acquisition System for Drilled Displacement Piles. *Geo-Congress 2006: Geotechnical Engineering in the Information Age.* Atlanta GA, USA. 27 February – 01 March 2006.

NeSmith, W.M. and NeSmith, W.M. (2006). Application of Data Acquired During Drilled Displacement Pile Installation. *Geo-Congress 2006: Geotechnical Engineering in the Information Age.* Atlanta GA USA. 27 February – 01 March 2006.

CONVERSION TO SI UNITS

Feet (ft) * 3.280839895 = meter (m)
Tons per square foot (tsf) * 0.010443= kilopascal (kPa)
Pound per square inch (psi) * 0.145038 = kilopascal (kPa)
Bar * 0.00001 = kilopascal (kPa)
Inch (in) * 0.393700787 = centimeter (cm)
Ton * 0.112404472 = kilonewton (kN)

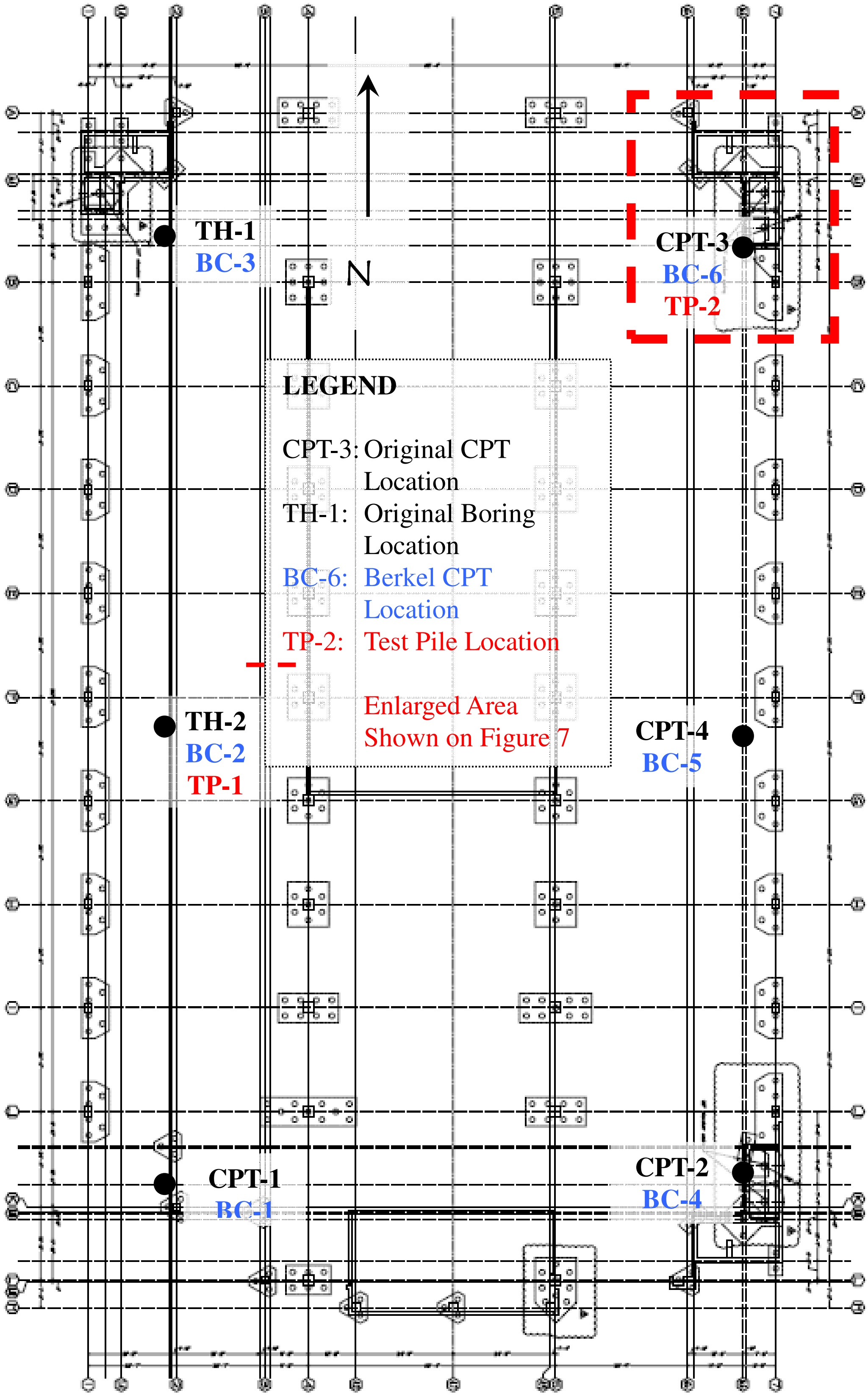


FIGURE 1 – Proposed Foundation Layout with Site Investigation Locations

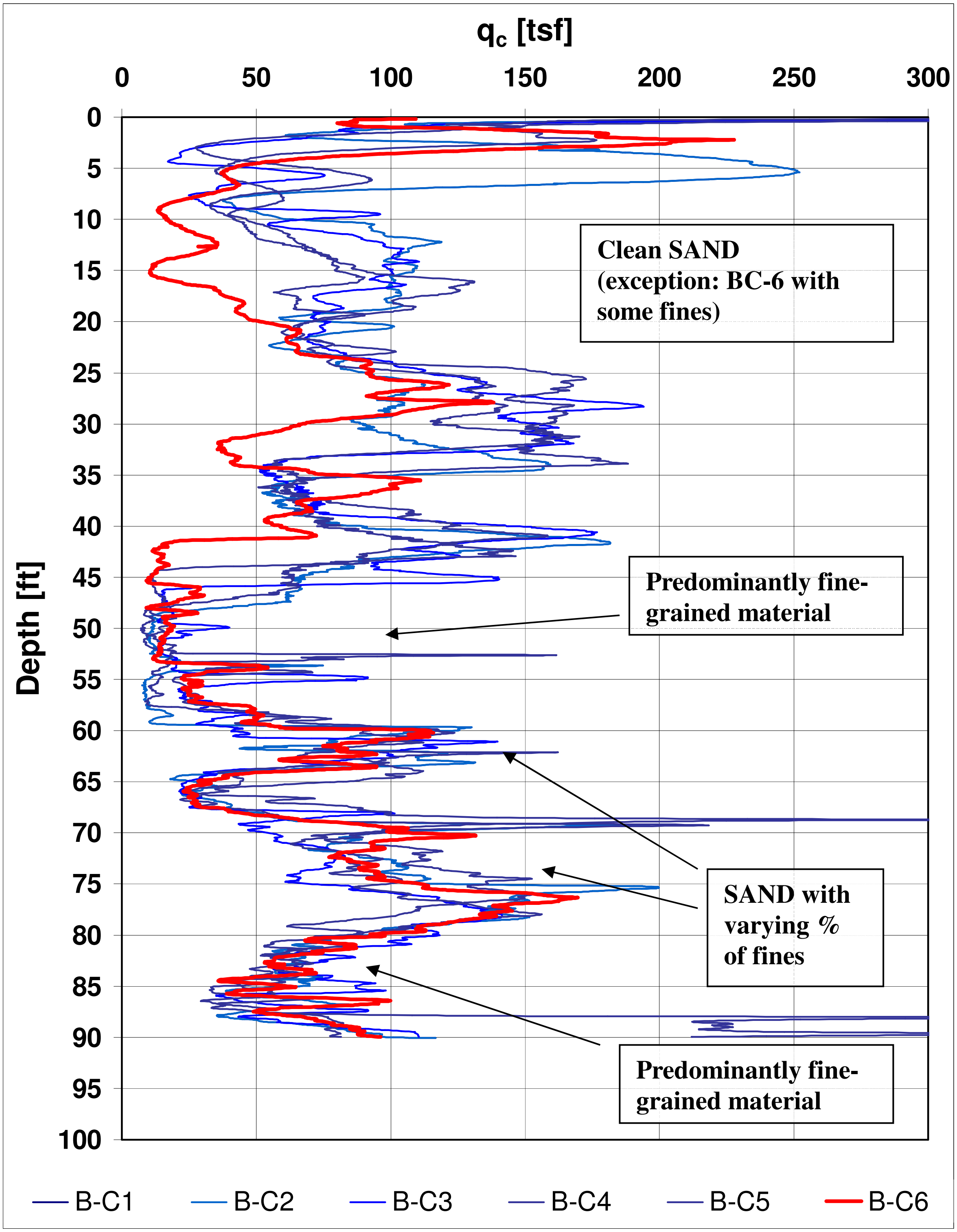


FIGURE 2: Composite Plot of Tip Resistance [q_c] Data from Cone Penetration Tests

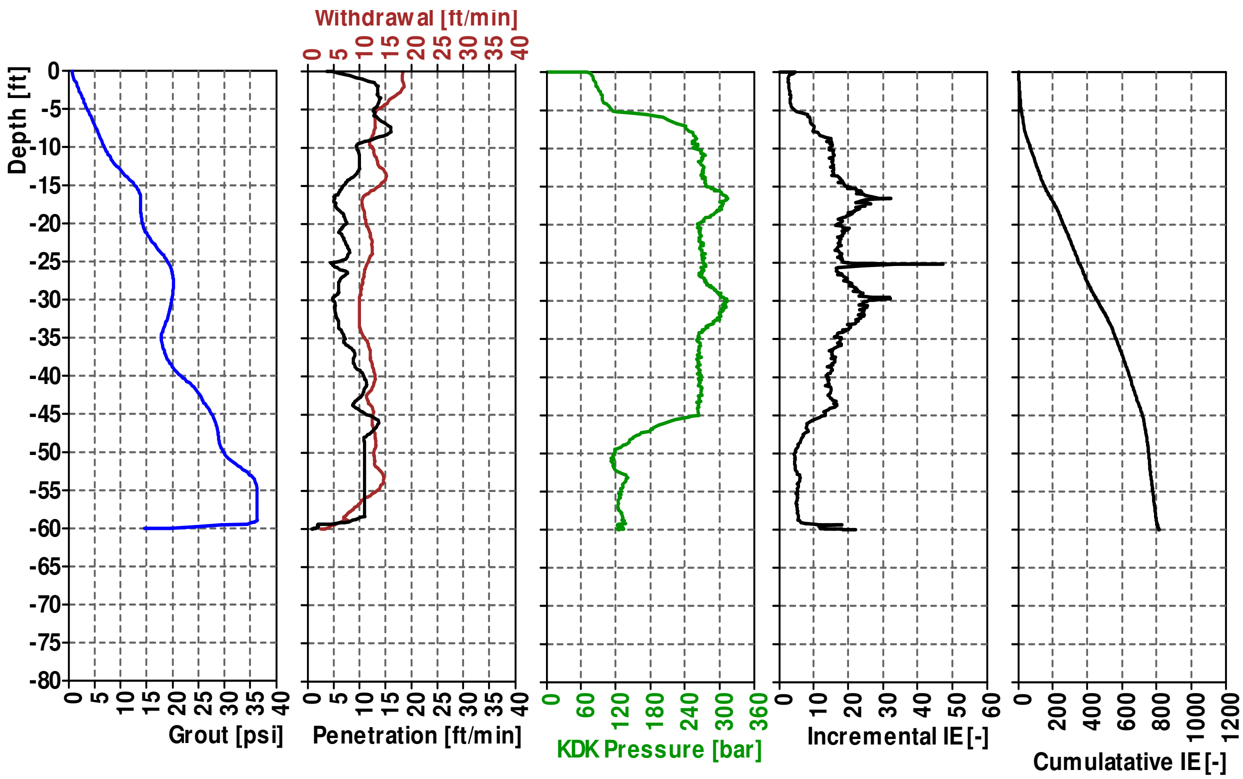


FIGURE 3 – Installation Details: Test Pile 1

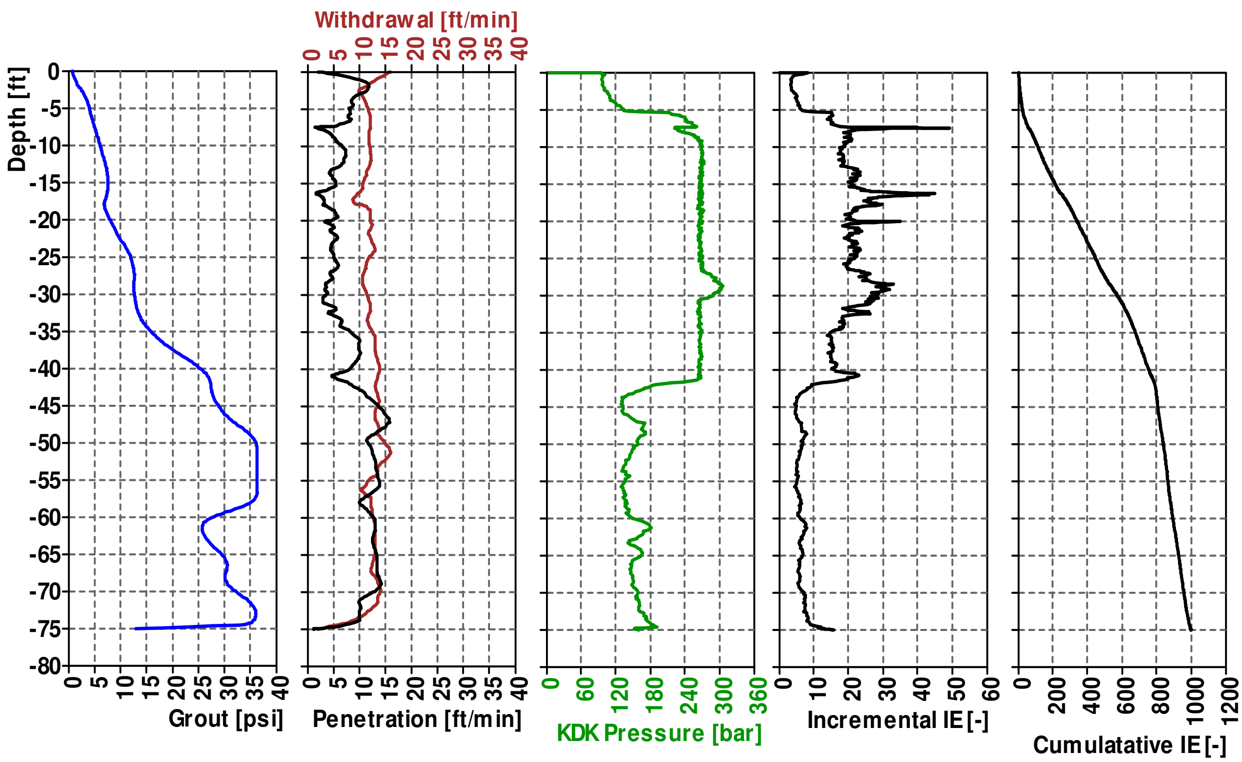


FIGURE 4 – Installation Details: Test Pile 2

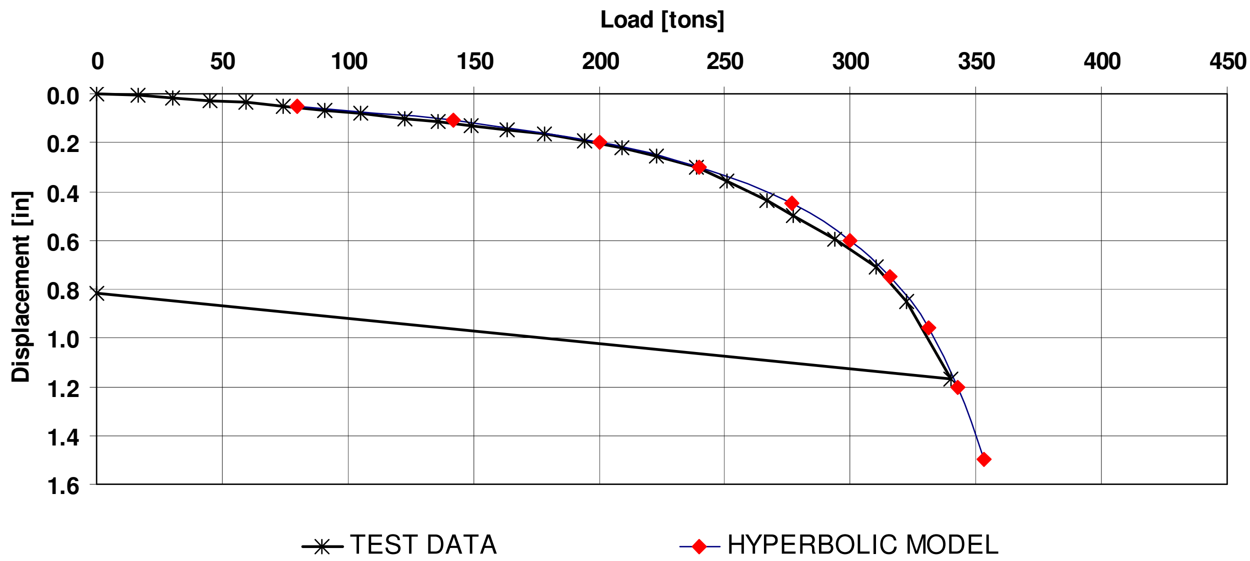


FIGURE 5 – Applied Load vs. Pile Head Displacement
Test Pile 1: 16-inch Diameter, 60 ft Berkel Displacement Pile

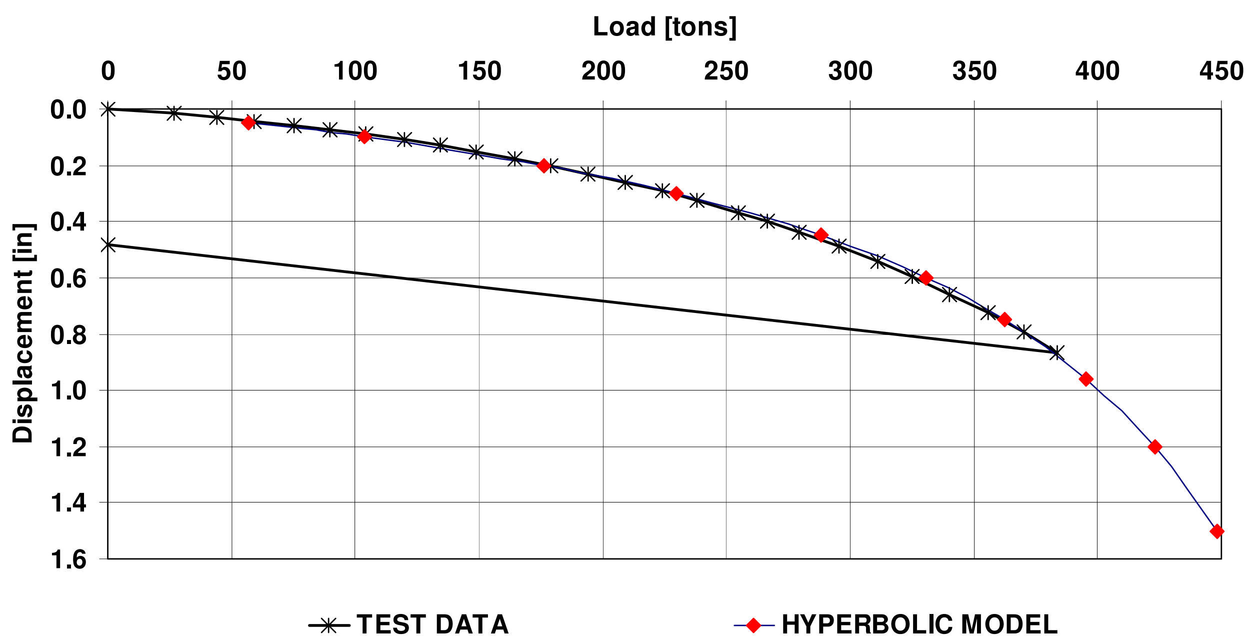
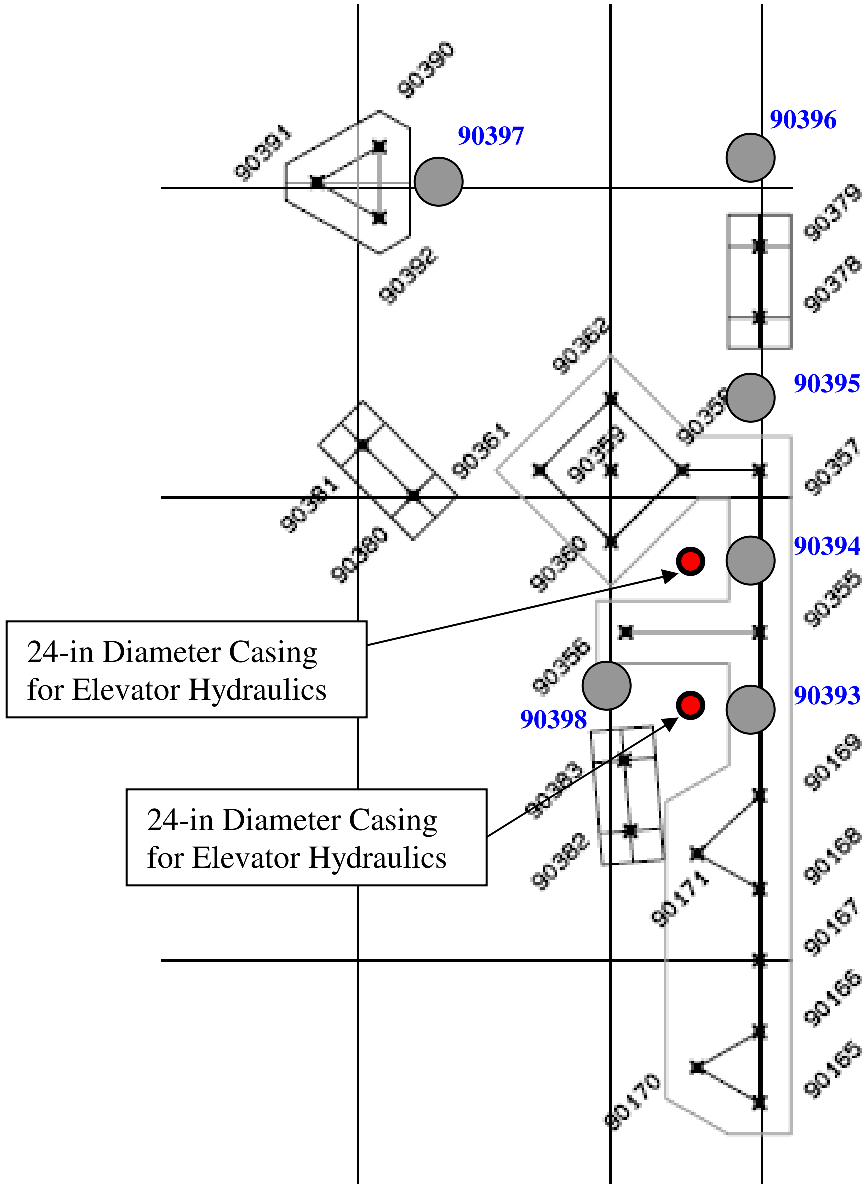


FIGURE 6 – Applied Load vs. Pile Head Displacement
Test Pile 2: 16-inch Diameter, 75 ft Berkel Displacement Pile



x - Production pile locations from initial program

● - Approximate locations of additional production piles

FIGURE 7 – Enlarged View of Northeast Corner of Foundation Layout

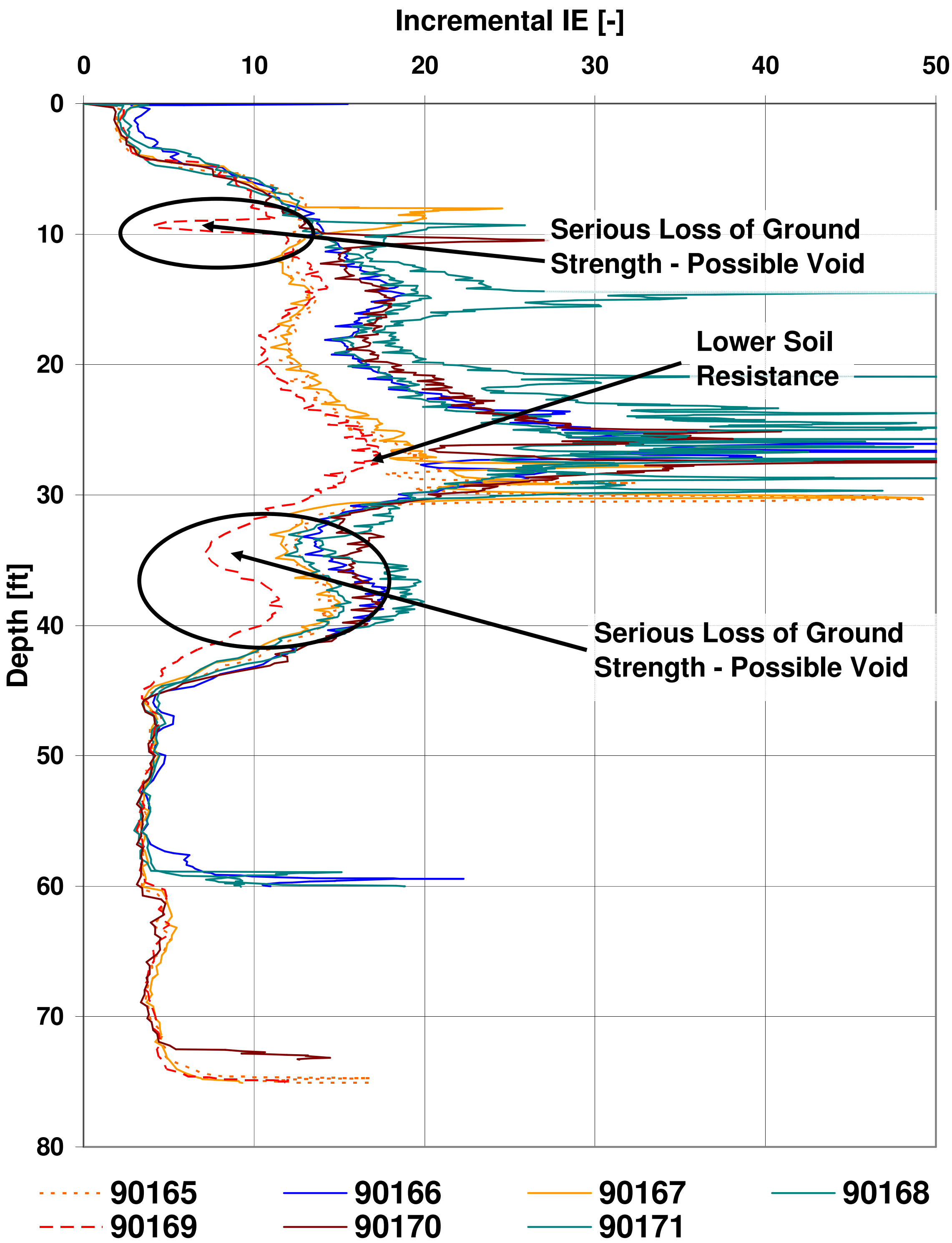


Figure 8 – Composite Plot of Incremental IE of Selected Piles
Northeast Corner of Foundation Layout