Originally Published in the Proceedings of the DFI 33rd Annual Conference on Deep Foundations.
New York NY, USA. 15 – 17 October 2008.

USE OF INSTALLATION EFFORT TO EVALUATE AND DESIGN DRILLED DISPLACEMENT PILES IN FINE-GRAINED SOILS

W. Morgan NeSmith, Berkel & Co. Contractors Inc., Atlanta GA
Pete Burton, P.E., Burns & McDonnell, Kansas City MO

A drilled displacement pile program was utilized for the expansion of an existing power plant in Cohasset MN adjacent to the Mississippi River. The drilled displacement (DD) pile is an innovative foundation type that provides exceptional value in some geologies. In the U.S., DD piles have typically been used in coarse-grained soils due to the large friction capacities that can be generated by the piles in these conditions. This project was the first large scale experience for the project team where it was anticipated that significant portions of the DD pile capacity would be developed in primarily fine-grained soils.

The project site consisted primarily of variable amounts of fill overlying predominantly low plasticity alluvial silts. In some cases, alluvial silty sand layers were encountered within the expected pile installation depths. Alluvial sands were typically encountered below the silts, in some cases within the expected pile installation depths.

The project team developed a probe and pile load test program to address the variable subsurface conditions across the site. The program included monitoring various parameters (including applied torque and tool penetration rate) during the drilling portion of the pile installation using recently developed data acquisition techniques. This data was used to estimate the rig energy, or Installation Effort (IE), required for pile installation.

IE profiles from the test and indicator piles were compared with subsurface data available from a number of previous site characterizations. Additionally, Cumulative IE values were compared to an in-house database of IE vs. DD Pile Capacity. Final production pile toe levels were based primarily on IE values selected from this comparison. The IE data collected during production was also used to address large variations in pile-cutoff elevation (relative to a fairly uniform ground surface elevation).

INTRODUCTION/PROJECT DESCRIPTION

The project team's brief was to provide foundation construction services for the expansion of an existing power plant in Cohasset MN. The expansion consisted of the addition of several new facilities across the project site. A schematic of the proposed expansion is shown on Figure 1. The project team was tasked with proposing an appropriate foundation solution for the new structures, developing and implementing a probe and performance test program for the proposed foundations as well as foundation construction.

The proposed foundation plan called for design loads of 60 tons to 70 tons in most areas with design loads in the Southside SCR area of 80 tons.

SUBSURFACE INFORMATION

Subsurface information consisted primarily of the results of a 2006 geotechnical exploration specific to the current project site. Additional data from previous explorations in 1969 and 1975 was also available (Burns and McDonnell, 2007). Subsurface data primarily included Standard Penetration Tests (SPT) results, visual soil classifications and laboratory test data.

The borings completed for 2006 exploration are shown on Figure 1 and were the primary consideration for foundation evaluation and design. Subsurface materials consisted primarily of variable amounts of granular fill overlying predominantly low plasticity alluvial silts. Often, high plasticity clay was encountered immediately below the fill above the silts. In some cases, alluvial silty sands were encountered within the silt profile. Cleaner alluvial sands were typically encountered below the silts, in some cases within the expected pile installation depths. Figure 2 includes composite plots of SPT results in the Southside SCR Area and the borings in the remaining areas across the site. General soil profiles are included on the plots.

DRILLED DISPLACEMENT PILES

The project team considered the granular fills, underlying alluvial sands and the generally non-plastic alluvial silts to be a good profile in which to use drilled displacement piles. The drilled displacement (DD) pile is an innovative foundation type that provides exceptional value in some geologies. In the U.S., DD piles are often used in coarse-grained soils due to the large friction capacities that can be generated by the piles in these conditions. It was estimated that DD piles would provide the required capacity at significantly smaller depths than other foundation systems considered.

“Drilled Displacement pile” is a general industry term encompassing a variety of proprietary drilled and cast-in-place pile systems. The piles employed here were Auger Pressure Grouted Displacement (APGD) piles. APGD piles are constructed by drilling a displacement auger into the ground utilizing a track-mounted, fixed-mast, hydraulic drilling machine. Once the required penetration is achieved, fluid grout is pressure injected through a grout pipe located centrally within the drill stem and out a port located at the tip of the displacement auger as the displacement auger is slowly retracted. Once the displacement auger is fully retracted, reinforcing steel is inserted into the fluid grout column prior to initial set. Schematics of the APGD tool and installation platform are shown in Figure 3 and Figure 4 respectively.

The forward auger flights and ramp located below the displacement element on the tool displaces soils laterally as the auger is advanced. Soil packed between the forward auger flights upon reaching the final drill depth is retained upon auger retraction and removed to the surface.

Once the final drill depth is achieved, injection is initiated through the grout pipe located centrally within the drill stem and out of the port located at the tip of the displacement auger. Grout injection pressure is monitored continuously during the grouting process by means of a pressure transducer located at the top of the drill stem. Once the target “liftoff pressure” is achieved, retraction of the auger begins. The rate of auger withdrawal is coordinated with the grouting pressure such that target grouting pressures are maintained. Positive (clockwise) rotation of the auger is maintained continuously throughout the grouting process. The reverse auger flights and displacement ramp capture and re-displace any material which may have entered the annular space between the drill stem and the pile wall. The pressure within the fluid grout column resulting from the pressure injection process during the grouting operation and later from gravity following full auger retraction maintains the integrity of the shaft similarly to a heavyweight drilling slurry.

Reinforcing steel is lowered into the fluid grout column following full retraction of the displacement auger. Placement of a center bar (when required) is followed by placement of the reinforcing cage. The center bar and reinforcing cage are centralized within the pile by means of prefabricated spacers.

APPLICATION OF APGD PILES TO THE PROJECT SITE

APGD pile capacity was evaluated according to the methodology detailed in NeSmith, 2002. Shaft and toe resistances were estimated from the SPT results from the 2006 borings, with modifiers appropriate for the characteristics of the expected materials.

Evaluation of the in situ data available based on the method described indicated that 16-in diameter APGD piles installed to between 55 ft and 75 ft below the installation surface would yield allowable compressive capacities as required for the project (60 tons to 80 tons). There was a good bit of variation in density of the alluvial silts and in elevation of the underlying sands.

It was thus deemed appropriate to use an automated monitoring system to collect drilling parameters during the probe and test pile installation and to use this data to set final toe elevations.

DATA ACQUISITION

The drilling platform incorporated into the foundation construction for this project included a data acquisition system for real-time measurement, display and recording of drilling parameters including depth, torque (as estimated as a function of the hydraulic fluid pressure driving the rotation and downward force of the drill stem, referred to as the KDK pressure) and grout pressure. The schematic of the drilling platform in Figure 4 includes the basic layout of the sensors included on the platform. The system is described in detail in NeSmith and NeSmith (2006a). In addition to collecting and displaying the data mentioned above, the system was programmed for the real-time estimation of rig energy expended during the advancement of the drill stem. All of this data is displayed in real time on both the drilling platform and a remote monitor for simultaneous viewing by the drilling platform operator and inspector.

INSTALLATION EFFORT

The relating of the total energy required to install a pile to subsurface stratigraphy and the pile's capacity has been used with increasing frequency over the past few years (NeSmith and NeSmith, 2006b). In the aforementioned reference this estimation of energy has been termed Installation Effort (IE). The 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 versus depth. Plots of IE vs. Depth are included on the installation records (Figures 5 and 6).

PROBE AND TEST PROGRAM DETAILS

Initially, seven probes were drilled across the site. Probes were not drilled in the Southside SCR area (see Figure 1) due to access restrictions. The probes indicated the expected variations in density in the alluvial silts.

Test pile T-1 (in the Southside SCR) was expected to terminate with the pile toe in sand and was installed to a Cumulative IE value expected to provide a working compressive load of 80 tons. Test piles T-2, T-3 and T-4 were installed to a variety of Installation Efforts to evaluate an IE vs. Capacity relationship for this site with regard to the 60 ton to 70 ton design compressive loads.

The 16-in diameter test piles were installed to the IE and depths shown in Table 1.

Table 1 – Test Pile Details

Test Pile	Depth [ft]	Nearest Boring	Cum. IE
T-1	55	B6-02	421
T-2	55	B6-08	461
T-3	60	B6-06	510
T-4	70	B6-07	550

Strain gages were installed in Test Piles T-1, T-3 and T-4. Gages were placed at the following approximate depths from the ground surface:

- T-1: 4 ft 25 ft 53.5 ft
- T-3: 4 ft 30 ft 58.5 ft
- T-4: 4 ft 40 ft 68.5 ft

Installation details for test piles T-1 (pile toe in sand) and T-4 (pile toe in silt) are presented in Figures 5 and 6. All load tests were performed in general accordance with the ASTM D1143 - Quick Load Test Method.

LOAD TEST RESULTS AND ANALYSIS

Plots of applied load and pile head displacement are presented in Figures 7 and 8 along with hyperbolic estimates of the load-displacement relationship. These extrapolations were obtained by applying the method described by Chin (1970). Ultimate load values from a number of interpretation methods are also presented, including those recommended here for drilled displacement piles. Strain gages were installed in piles T-1, T-3 and T-4. Interpretations of the load distribution along the length of test piles T-1 and T-4 are presented in Figure 9.

During load testing of pile T-1, the strain gage installed at a depth of about 25 ft failed. The load distribution plot for T-1 includes an estimation of the load at 25 ft derived from the strain gage data available from test piles T-3 and T-4.

Ultimate compressive load of the test piles was taken as the lesser of the following two loads (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

Toe and shaft components of the test piles were determined from the available strain gage data. Ultimate loads were determined according to the above criteria and are presented in Table 2.

Table 2 – Ultimate Load Calculations

Test Pile	**Total Ult Load [tons]**	**Ult Shaft Load [tons]**	**Ult Toe Load [tons]**
T-1	227	196	31
T-2	175	167	8
T-3	224	208	16
T-4	204	196	8

Piles had design tension loads of up to 30 tons. Common methods for estimating tensile capacity recommend using between 70% and 100% of the compressive shaft capacity. Using the shortest pile above with the lowest shaft capacity (T-2) and applying a conservative estimate of 0.7 times the compressive shaft capacity, an ultimate tensile load of 116 tons (and thus an allowable load of 58 tons) is calculated. Final design called for center bar reinforcing with a grout-steel interface length of about 50 ft. Based on the above, a working tensile load of about 50 tons was estimated for piles with that configuration.

PRODUCTION PILE INSTALLATION CRITERIA

Minimum Toe Depth

The required compressive loads for piles ranged from 80 tons in the Southside SCR to 60 tons to 70 tons in the north and west project areas. However, both 55 ft test piles (T-1 and T-2) demonstrated capacities in excess of 2 times the required loads of 60 to 80 tons. As such, a ***minimum pile installation depth of 55 ft*** below the ground surface at the time of installation was deemed appropriate for the project.

Termination of Production Piles

Analysis of the available subsurface data indicated variations in the shaft resistance of production piles across this site. Test piles T-2, T-3 and T-4 demonstrated that there would be some variation in the toe capacity of piles installed primarily in silts. This variation was due to fluctuations in the density of the subsurface materials encountered as well as whether or not the piles terminated in silts or the underlying sands. Variations in capacity dictated the depth at which production piles might be terminated. The Cumulative IE (CIE) of the test piles was presented in Table 1. Figure 10 is a plot of an internal database of measured CIE vs. test pile capacity, with the results from this project highlighted. The plot includes the mean relationship of the data and plus / minus 1 standard deviation. The relationship developed specifically for the two piles (T-2 and T-4) bearing in silt is also shown.

Referring to the database, the required working loads of 60 tons to 80 tons could be achieved (with factors of safety in excess of 2) with a CIE of about 420 if the piles were installed with the toe in the underlying sands. Piles installed with the toe in the silts could achieve these loads with a CIE of about 460. ***Therefore, a termination CIE of 460 was adopted for all piles across the site*** to account for the possibility of sand not being encountered, even in areas where it was anticipated. In areas where sand was encountered the CIE increased from 420 to 460 within a few feet of encountering the sand and thus did not add significant overall drilled footage.

REAL TIME FIELD MONITORING

Figures 11 and 12 include pictures of the real-time data displays on the drilling platform and at a remote monitor receiving a wireless signal from the platform. Also shown are schematics of the data being displayed on the monitors. The drilling operator can monitor the numerical value of CIE displayed in the upper right corner of the monitor of the platform, while the inspector viewes a plot of Incremental IE and CIE vs. Depth as the drilling tool is advanced. On this project, the drilling operator was responsible for terminating the production piles at a depth beyond 55 ft at which the required CIE was obtained. The CIE was verified by the inspector viewing the remote monitor before grouting of the pile commenced.

The inspector also monitored grout pressure during pile casting from this remote monitor. Again, this system is described in detail in NeSmith and NeSmith (2006a).

LOSS OF SHAFT RESISTANCE IN OVERBURDEN

In the ID fan building area (near TP-3) some pile supported mat foundations for the building columns had pile cutoffs (bottom of mat) about 18 ft below grade due to some electrical duct banks and a pipe trench. The question arose regarding the allowable load for production piles in this area considering the loss of the 18 ft of material to be excavated after pile installation (piles were installed from the existing site grade).

A review of the test pile and probes in the area indicated a CIE value of about 500 at 60 ft, a CIE value slightly greater than 600 at about 72.5 ft and a CIE value of 700 or greater at the maximum drilling depth of 77.5 ft below grade. The strain gauge data indicated a minor amount load transfer to the tip at a 180 ton load (three times the allowable load in this area).

These particular production piles were installed to the maximum drilling depth of 77.5 ft and the CIE value was monitored and manually recorded by the inspector at the overburden depth of 18 ft and the final pile toe elevation. The CIE developed only between the top-of-pile and pile toe elevations was used to estimate ultimate load and to ensure that these piles met the 60-ton design load requirements for this structure.

SUMMARY AND CONCLUSIONS

APGD piles have primarily been used in the U.S. in granular materials due to the significant shaft capacity that can be achieved due to the densification of the materials during pile installation. The load test program here indicated confirmed the general shaft capacity in the silts estimated from in situ data.

The estimation of rig energy, Installation Effort (IE), proved to be a useful tool to confirm stratigraphy and to set variable final pile toe depths based on local site variations in soil type and density. Additionally, IE was used to provide confidence in the capacity of the production piles that were extended due to top-of-pile elevations well below the working surface.

The real-time acquisition and display of drilling parameters along with the calculated Incremental and Cumulative IE profiles provided access for both the operator and inspector to this data, allowing for the implementation of the IE-based pile termination criteria.

REFERENCES

Berkel & Co. Contractors, Inc (2006). Technical Approach – Berkel Drilled Displacement Piles – Cohasset MN

Burns & McDonnell (2007). “Meeting With Berkel & Co. Regarding Auger Cast Displacement Piles”. 20 Febuary 2007.

Chin, F.K., (1970), “Estimation of Unit Load on Piles not Carried to Failure”, Proc. 2nd Southeast Asia Conference on Soil Engineering, 81-90.

NeSmith, W.M. (2002). “Static Capacity Analysis of Augered, Pressure-Injected Displacement Piles”. ASCE Geotechnical Special Publication No. 116, Proceedings from DEEP FOUNDATIONS 2002. Orlando, FL. pp. 1174-1186

NeSmith, W.M. (2003). “Installation Effort as an Indicator of Displacement Screw Pile Capacity” Proceedings of the 4th International Conference on Bored and Augered Piles (BAP IV). Ghent, Belgium. June 2003.

NeSmith, W. M. and NeSmith, W.M. (2006). “Anatomy of a Data Acquisition System for Drilled Displacement Piles”. Proceedings of the the American Society of Civil Engineers GeoCongress 2006. Atlanta GA USA. 26 February – 01 March 2006.

NeSmith, W.M. and NeSmith W.M. (2006). “Application of Data Acquired During Drilled Displacement Pile Installation.” Proceedings of the American Society of Civil Engineers GeoCongress 2006. Atlanta GA USA. 26 February – 01 March 2006

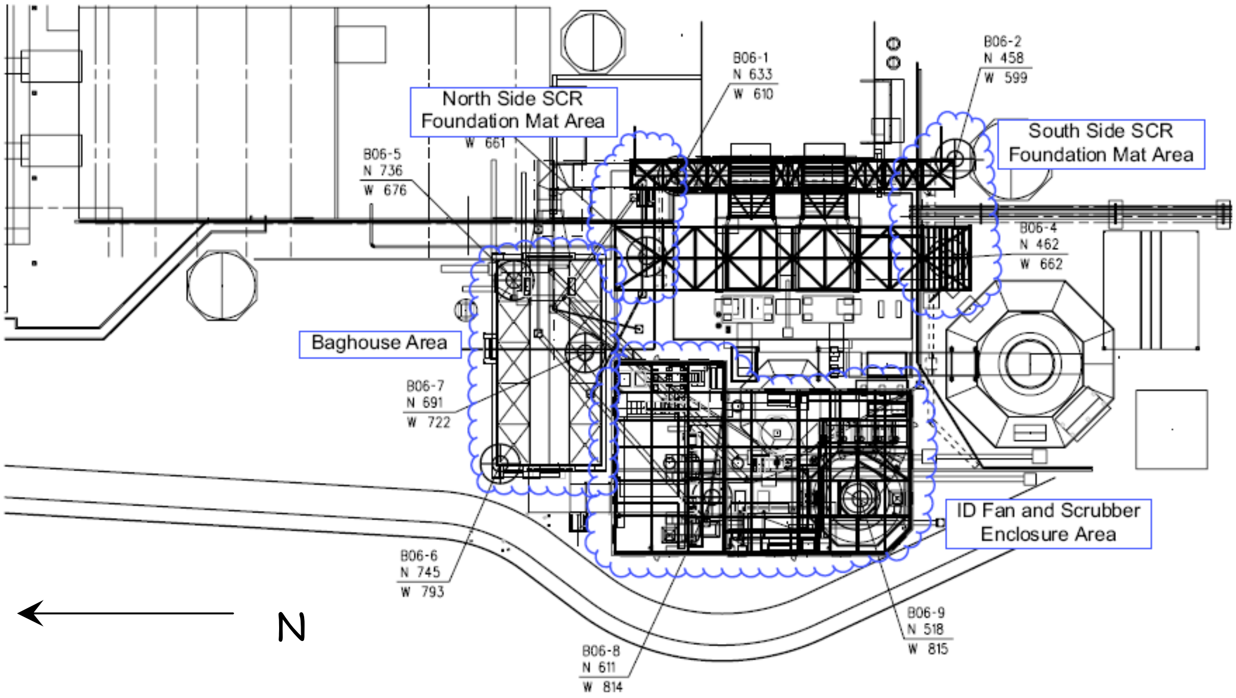


Figure 1 – Proposed Facilities and Boring Location

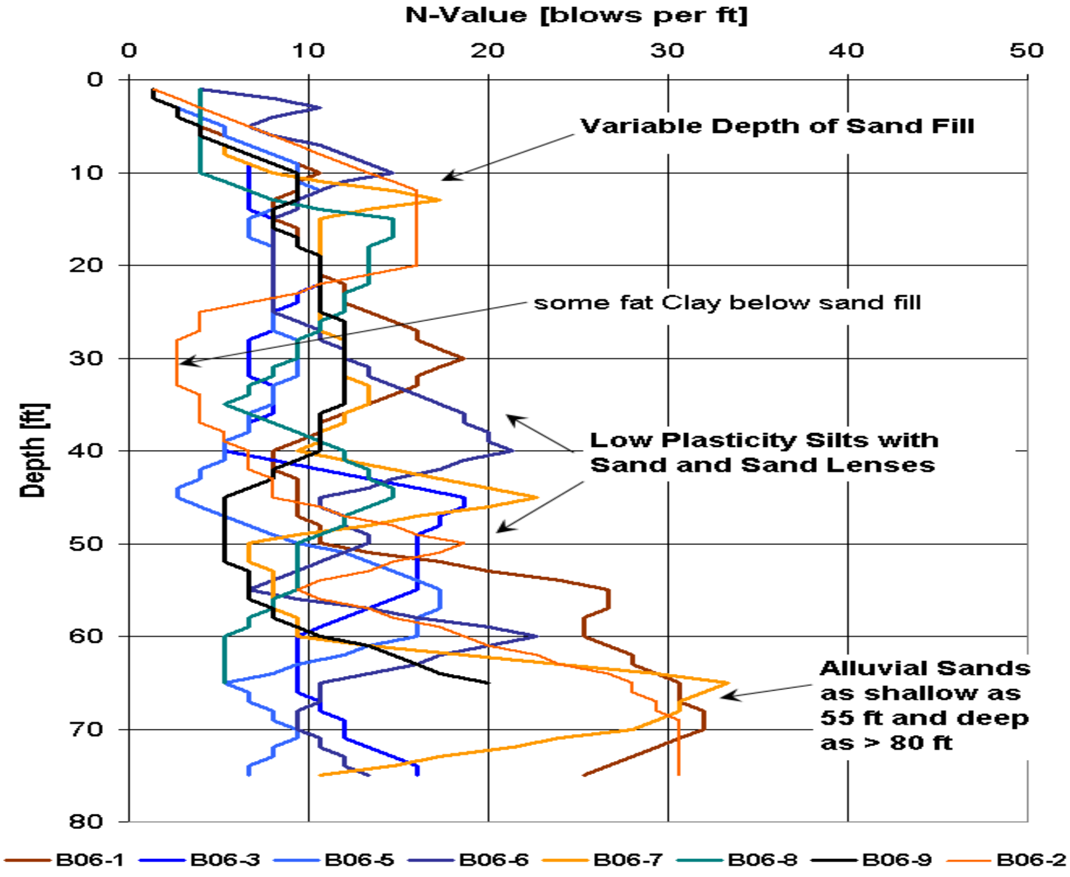


Figure 2 – Composite SPT Results and Generalised Soil Profile
(Note: automatic hammer efficiency ~ 80% efficiency)

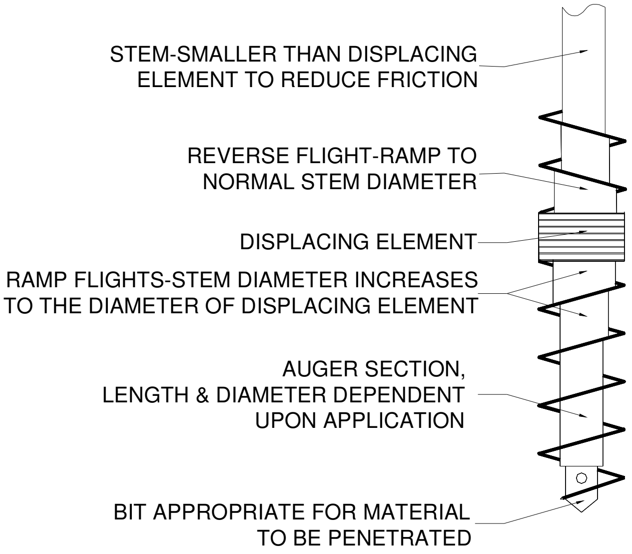


Figure 3 – Displacement Tool

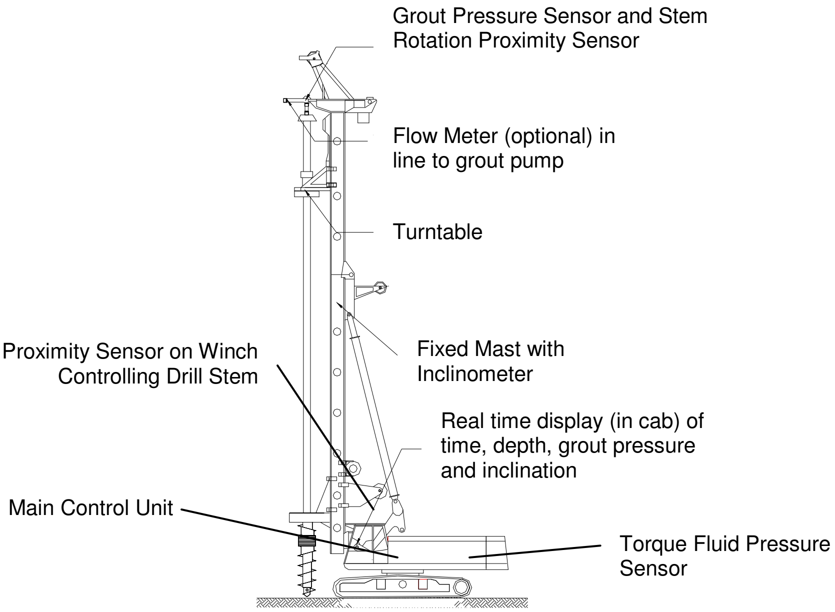


Figure 4 – Schematic of Drilling Platform and Generalization of Data Acquisition System

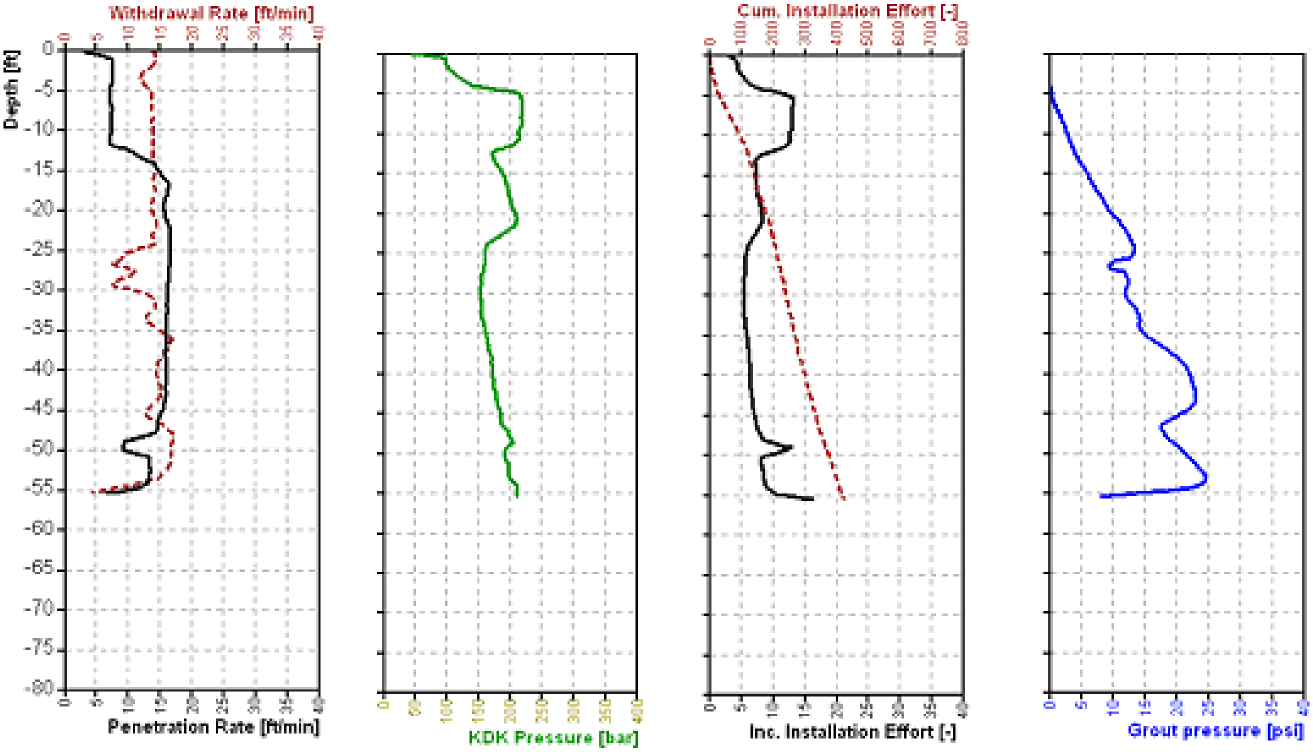


Figure 5 –Installation Details – Test Pile T-1

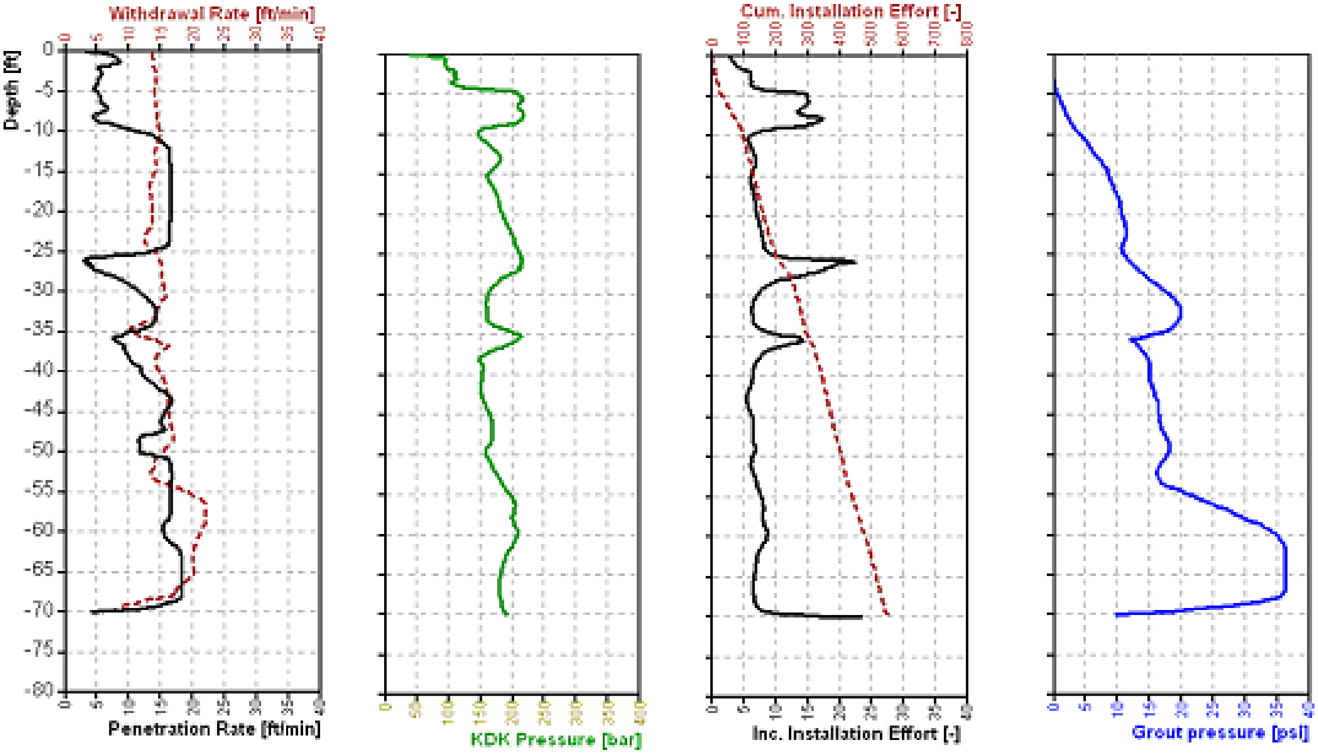


Figure 6 – Installation Details – Test Pile T-4

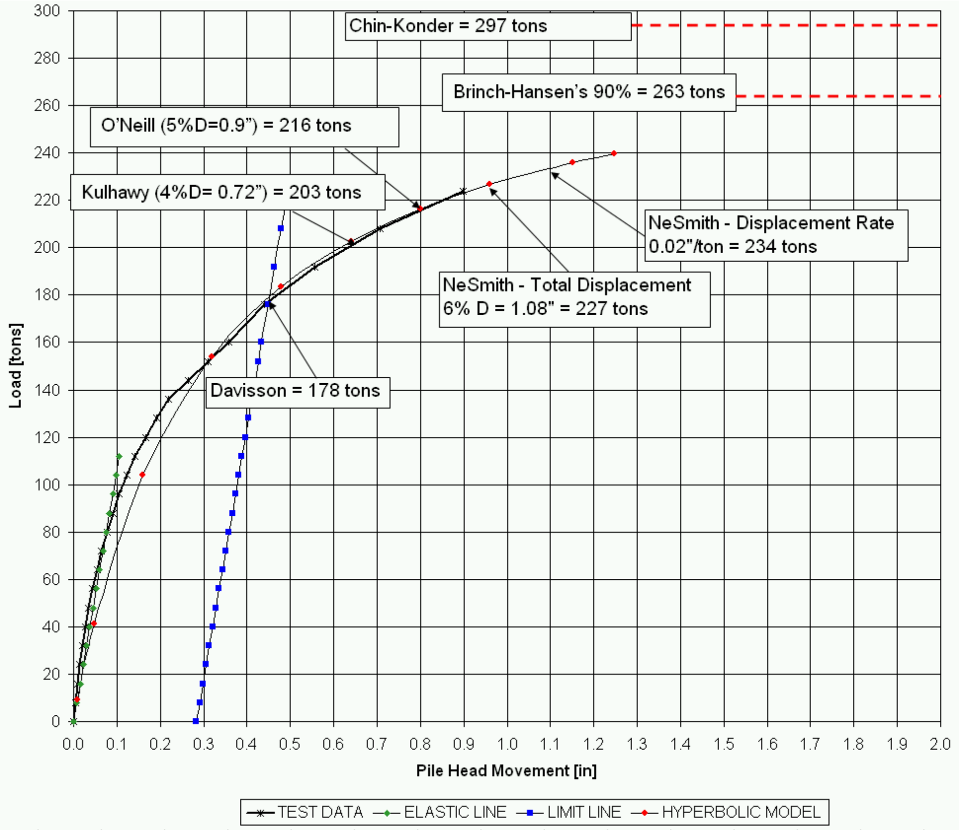


Figure 7 – Load Test Results and Analysis – Test Pile T-1 (55 ft)

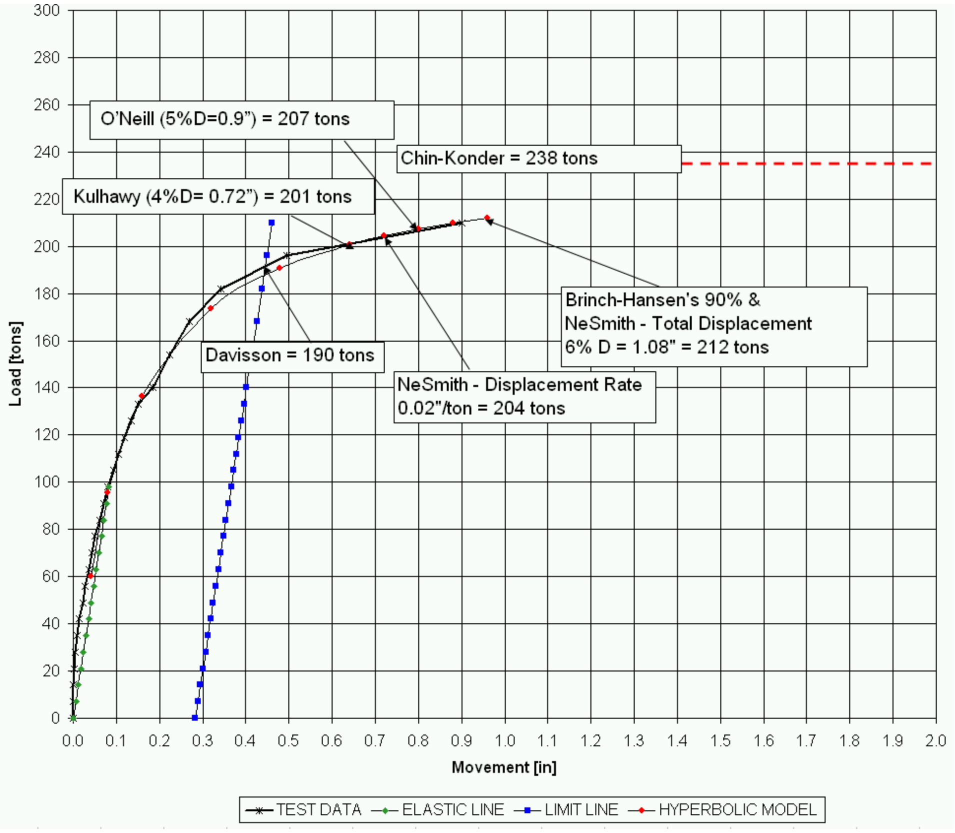
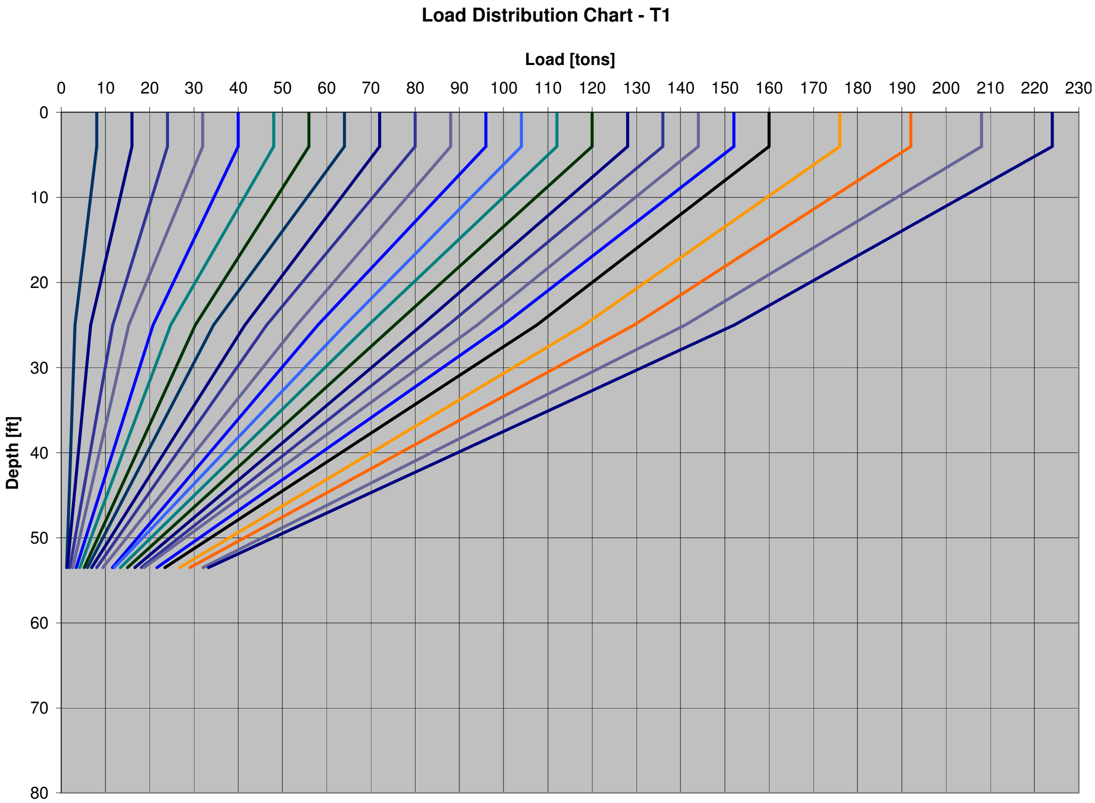


Figure 8 – Load Test Results and Analysis – Test Pile T-4 (70 ft)



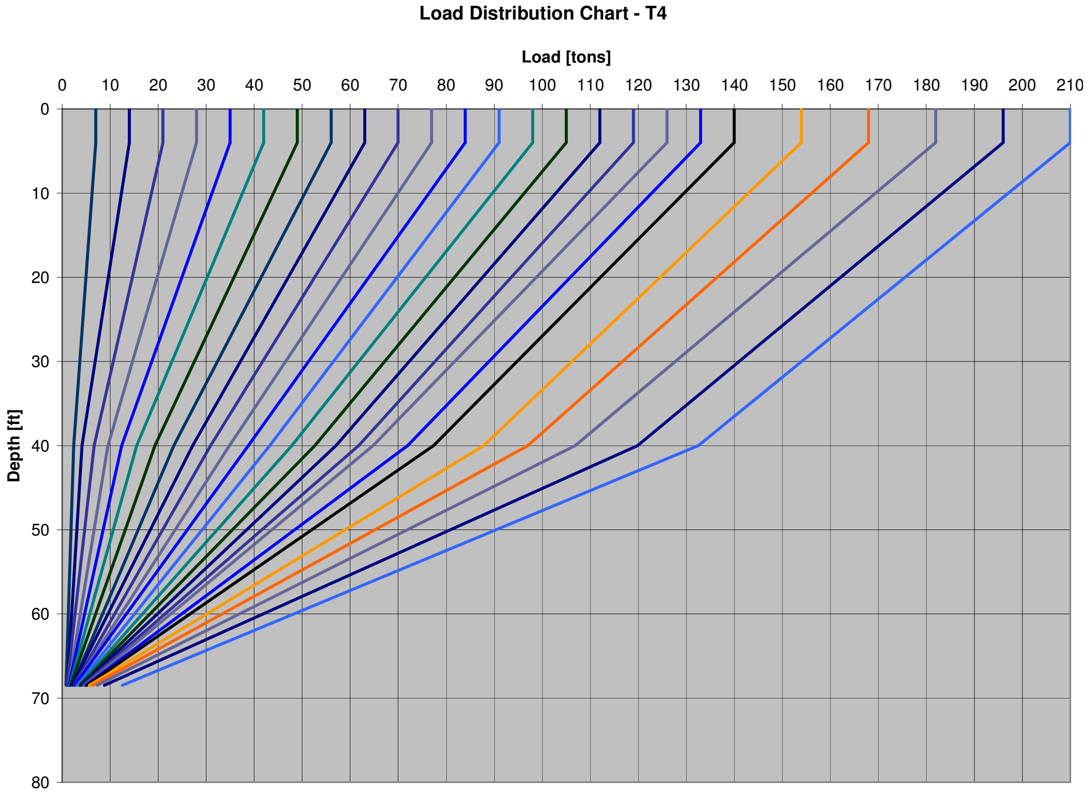


Figure 9 – Load Distribution Charts

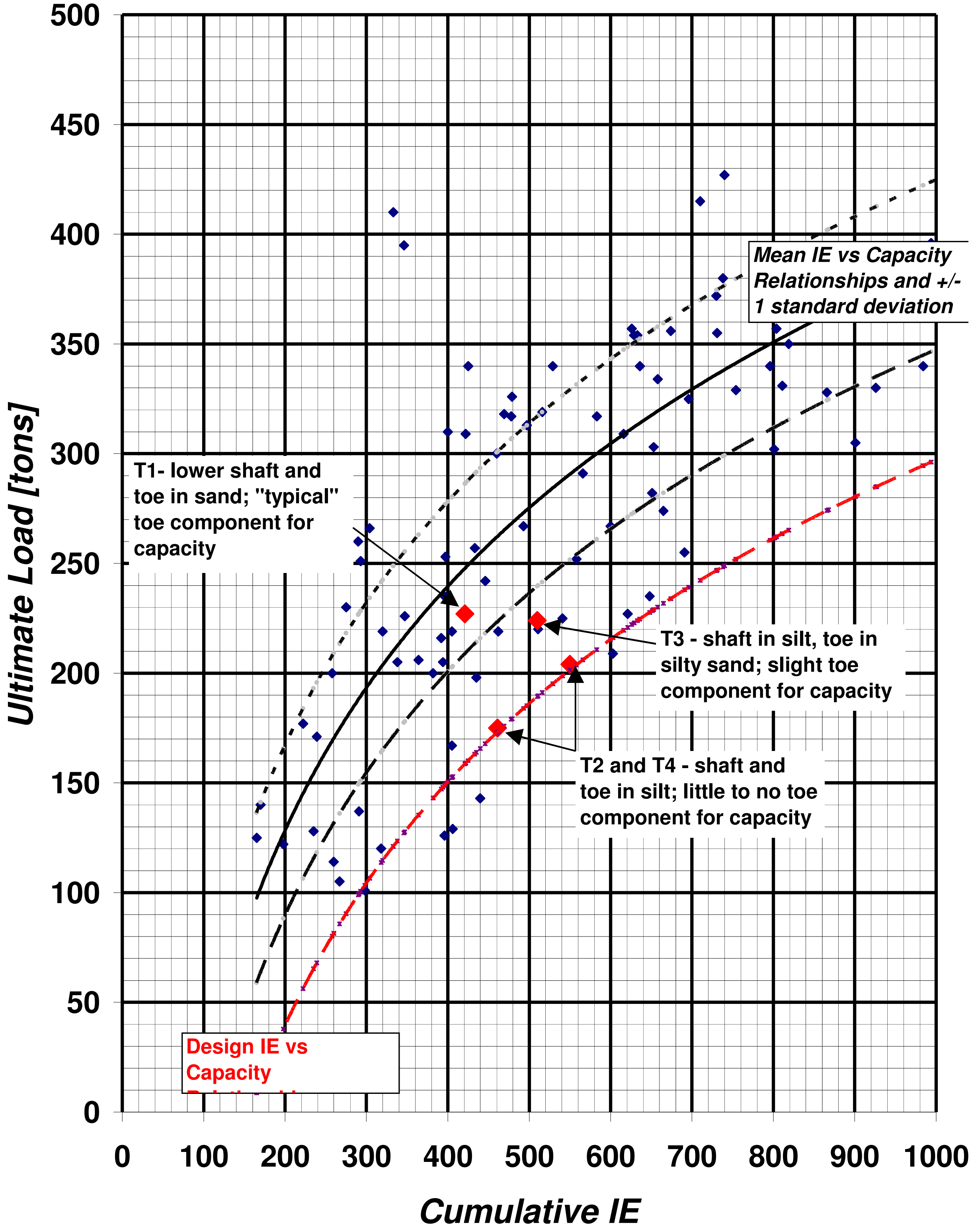
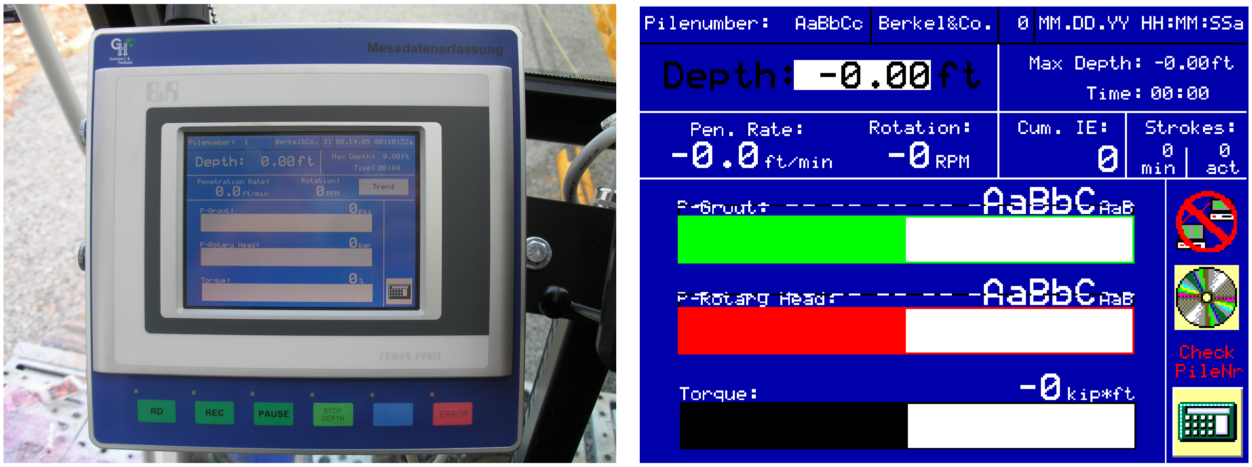
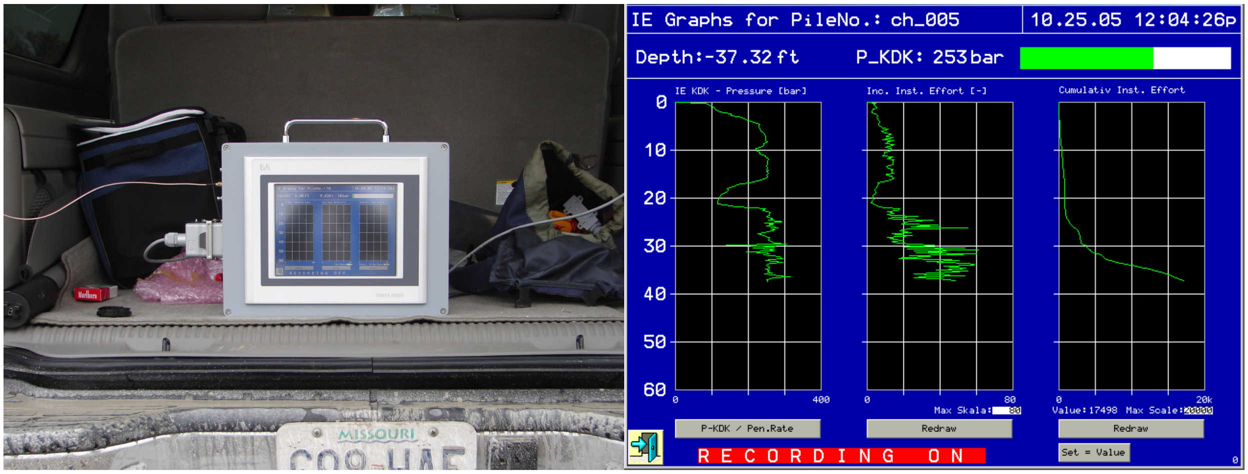


Figure 10 – Composite Plot of IE vs. Capacity



(a) (b)

Figure 11 – (a) Photo of Monitor in Operator Cabin of Drilling Platform
(b) Schematic of Data Displayed on Operator Monitor (Cum. IE towards Upper Right Corner)



(a) (b)

Figure 12 – (a) Photo of Remote Monitor Receiving Wireless Signal from Platform
(b) Schematic of Graphical Data Displayed on Remote Monitor (KDK Pressure, Inc. IE and Cum. IE)