Installation Effort: Current Calculation Methods and Uses in Design and Construction in the U.S.

W. Morgan NeSmith Jr.
Berkel & Company Contractors, Inc - Atlanta GA, USA

Willie M. NeSmith, P.E.
Berkel & Company Contractors, Inc. - Birmingham AL, USA

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ABSTRACT: For BAP IV, one of the ~~authors~~authors (NeSmith, 2003) presented a paper in which the concept of Installation Effort (IE) was introduced, and the potential uses of IE as an indicator of stratigraphy and displacement screw pile capacity were described. Since that time, there have been a number of developments in this field including: improvements in the acquisition of data required to calculate IE; the real time presentation of IE data during pile installation; modifications to the calculation of IE and Cumulative IE; and refinements in the relationship between Cumulative IE and pile capacity. These developments have facilitated the application of IE as a practical tool for design, and for control of production pile installation. This paper describes these developments, provides an overview of the database of Installation Effort vs. Capacity collected by the authors, and demonstrates the calculation, presentation and use of IE and Cumulative IE on recent foundation construction projects in the U.S.

Updated Acquisition of Data

The data acquisition system used by Berkel in 200~~2~~3 was an analog system with a limited number of available signal inputs. Recording grout pressure for quality assurance during pile casting used one of the available inputs, leaving two remaining inputs for data recorded during drilling tool penetration. These were used for recording of stem depth and KDK pressure (the hydraulic fluid pressure applied to the rotary head). Since then, this system has been replaced by a digital system which allows for greater flexibility in the number of inputs that can be acquired and recorded. Two primary additional inputs have been added. The first was the measurement of grout volume during pile casting by means of a flow meter. More recently, the recording of drill stem rotation during pile penetration has been recorded as well. Figure 1 shows a typical drilling platform and the location of these sensors. A detailed description of the data acquisition system can be found in the 2002 paper by the authors.

More importantly, the switch to the digital acquisition system ~~also~~ increased the flexibility of the presentation of recorded data, allowing for real time display of data as well as real-time calculation and display of the Installation Effort described herein. This ~~included~~led to improvements in data display for both the drilling platform operator and the piling inspector. The results of these improvements to the data acquisition system are discussed in the following sections.

Calculation of IE and Real Time Display of Installation Data

The method of calculating Installation Effort as a function of drilling tool penetration rate and torque (as estimated from the KDK Pressure) was described in the previous paper. This calculation method is still in use. IE values are calculated at every 1-second recording interval based on the KDK Pressure and Penetration Rate recorded at that interval. Plots of IE vs. depth are produced in real-time in the field and continue to provide excellent agreement with stratagraphic representations from~~tip resistance (qc) values from~~ Cone Penetration Tests. This agreement has extended beyond the original database to a variety of geologies.

Berkel incorporated a larger monitor for the pile inspector to increase the amount of data displayed during pile production (Figure 2). In addition, this remote monitor communicates with the computer on the drilling platform wirelessly, doing away with the need for the inspector to move the monitor with the drilling platform. More recently, the on-board system has been modified so that the remote data can be viewed on a standard laptop computer rather than a dedicated monitor.

Figure 3 shows the main screen and engineering screen as viewed on the wireless monitor or laptop. The main screen includes general pile information such as date and time, pile number, current depth, etc. as well as graphical representations of KDK and grout pressures.

The engineering screen shows plots of KDK Pressure, Penetration Rate, Installation Effort and Cumulative Installation Effort vs. depth as drilling tool penetration occurs. This real-time display allows the inspector to ~~verify~~observe ~~that~~ the Stratigraphy at the pile location ~~is similar to what was expected and if not, to evaluate the local Stratigraphy~~ and adjust the target pile toe level as appropriate.~~installation requirements as required. .~~ It also allows the inspector to view Cumulative IE as it is developed, to ~~ensure~~verify that the effort required for pile installation meets the specifications developed during the design and load test phases of the project.

Updated Calculation of Cumulative Installation Effort

In the previous paper, the term SumIE was introduced. As the name would indicate, this was an estimate of the total Installation Effort as the sum of the IE values recorded at 1-second intervals during penetration of the drilling tool. The consistent relationship between SumIE and Capacity was also demonstrated; however this relationship could not be extended to shaft capacity or toe capacity. A study of the Total IE developed during pile penetration (SumIE vs. Depth) indicated that the SumIE was heavily weighted by dense and hard layers and subsequently underestimated the contribution to capacity of loose or soft layers while severely overestimating the contribution to capacity of hard or dense layers. This also resulted in difficulty when trying to use IE to predict the capacity of variable pile lengths.

Drilling data is recorded and IE is calculated at 1-second intervals. When the drilling tool encounters a hard or dense layer, the SumIE calculation is affected in two ways. First, the individual IE values calculated in that strata increase (as one would expect with an increase in density). Second, because drilling slows down in these layers and because these calculations are performed on a time interval, more IE values are recorded per unit length in these layers than in softer or looser layers. These additional recordings per unit length of penetration are what produce the exaggerated SumIE in dense and hard materials. An example of this calculation from an IE vs. Capacity profile is shown in Figure 4.

Cumulative IE was proposed as an alternative estimation of the total effort during pile penetration. Instead of a straight summation of recorded Installation Effort values, each value is weighted according to the length from the previous calculation depth, in effect an integration, rather than a summation, of the IE vs. Depth plot. The result is a much smoother Cumulative IE vs. Depth plot which does not exaggerate the influence of hard or dense layers (Figure 4).

Additionally, Cumulative IE shows a good correlation with shaft capacity, as one might expect considering that IE is calculated at 1-second intervals along the shaft of the pile.

Cumulative IE Database

In 2002, Berkel's database of Installation Effort vs. Capacity consisted of 15 test piles from 9 project sites. The current database consists of 111 load tests from 48 project sites (Figure 5). The mean relationship and plus/minus one standard deviation are also shown.

Figure 5 also includes ~~an~~ examples of load test results from two example projects and the resulting design Cumulative IE vs. Capacity line for Example A. This is typical of Berkel's current design process; the load test results from a project site are plotted on the entire database and the mean relationship is adjusted to fit the load test results for that particular site and to develop the relationship for use in final design of production piles on that project.

Typically, displacement piles in loose and medium dense sands have Cumulative IE and capacity relationships that fall within the plus/minus one standard deviation range of the database shown. As fines contents increase and density decreases, the relationship tends to move to below the minus one standard deviation line. This is due to the decrease in shaft resistance developed in these materials for the same amount of effort expended by the drilling platform AND the lower toe capacities developed by piles in these materials as well. An example of four load tests from one project is shown on Figure 5 with two load tests with the entire shaft and toe in a sandy silt; one load test with the shaft in this silt and the toe in a slightly cleaner sand; and one load test with the bottom of the shaft as well as the toe in cleaner sandy material. The movement of the Cumulative IE – Capacity relationship from below the minus one standard deviation line to about the mean relationship as soil type and density change is illustrated in this example. Piles installed in denser and cleaner sands tend to have an IE – Capacity relationship that falls towards the plus one standard deviation line. Piles that fall well above this line have typically been installed with the pile toe in dense cemented sands or gravels resulting in toe capacities in excess of what is developed in the majority of the displacement screw piles installed in North America.

Use of Cumulative IE

The development of the calculation of Cumulative IE vs. depth and the expansion of the IE – Capacity database are significant tools in the design of displacement screw piles. The database can be used to set final test pile depths based on the Cumulative IE developed by probe and reaction piles installed prior to test pile installation. IE – Capacity relationships from the test pile program can be used to set Cumulative IE values for pile termination during production. This is becoming a more common pile termination criteria as the database has expanded.

In addition, Berkel often uses the Cumulative IE vs. Depth curve (Figure 4) to evaluate the segmental capacity of pile shafts and to adjust production pile IE or depth requirements based on these segmental capacities. The most common application of this is on projects with deep excavations in some areas of the project site – for elevator pits or shear walls for example. Typically, an adjusted pile capacity is developed considering the loss of Cumulative IE from the material that will be excavated and the final Cumulative IE required for these piles is adjusted if necessary. This has often eliminated the need for production piles to be extended by a length equal to the depth of excavation, as is a common solution to the problem above. Instead, production piles need only be extended to compensate for the IE developed in the excavated material. As production piles often bear in denser materials than are in place nearer the ground surface, this typically results in shorter production piles than might be required if the Cumulative IE data was not available. In fact, Cumulative IE is much better suited to setting production pile lengths based on the conditions at each pile location than the historically used approach of using a required effective pile length for all production piles. The result is a more efficient and economical development of pile toe elevations across the project site.

Future Research

Currently Installation Effort is calculated as a function of KDK Pressure and Penetration Rate. When this relationship was developed, it produced a typically operator-independent IE calculation. However, there have been recent improvements in the efficiency with which hydraulic fluid pressure (KDK Pressure) is applied to the rotation head of the drilling tool. The result is that the manner in which an operator installs piles (aggressively vs. passively for example) can have a more pronounced effect on the IE calculated during pile installation. It is considered that revising the IE calculation to include rotation rate (a more recent) in conjunction with KDK Pressure, and thus using a more accurate reflection of torque than KDK pressure alone, may alleviate this issue. The addition of rotations as a parameter monitored and recorded by Berkel's data acquisition system will provide data to evaluate this matter.

Berkel also installs Partial Displacement Screw Piles that utilize a continuous flight auger with a large diameter drilling stem with the same installation platforms used to install Displacement Screw Piles. Typically, the IE – Capacity relationship for Partial Displacement Screw Piles plots significantly lower than the minus one standard deviation line shown on Figure 5. However, early research indicates that the overall IE - Capacity relationship of these piles conforms to the trend exhibited by the Displacement Pile database, but producing lower capacities at similar installation efforts. Currently, Berkel typically plots Partial Displacement test pile results on the Displacement Pile database and adjusts the mean line to the test pile results, similar to the example application for Displacement Piles discussed previously. As more Partial Displacement Pile load tests are performed, a new database will be developed specific to partial displacement piles for comparison to the current database.

Additionally, Berkel has recently installed ~~similar~~ automated monitoring equipment similar to that described in the forgoing on crane mounted (non-fixed mast) drilling platforms for continuous flight auger piles. Very little data is currently available for crane mounted drilling platforms but early results clearly indicate the need to incorporate rotation rate and total rotations (as one would probably expect) to any estimation of effort expended during penetration and the relating of this effort to pile capacity.
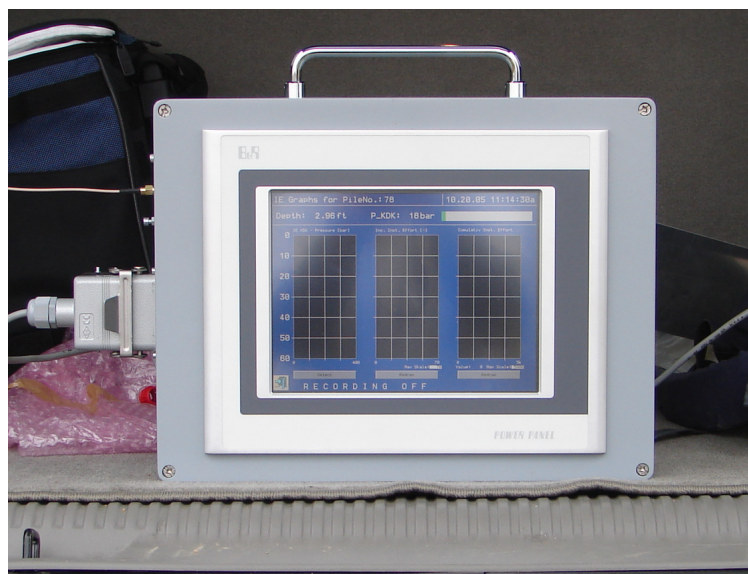
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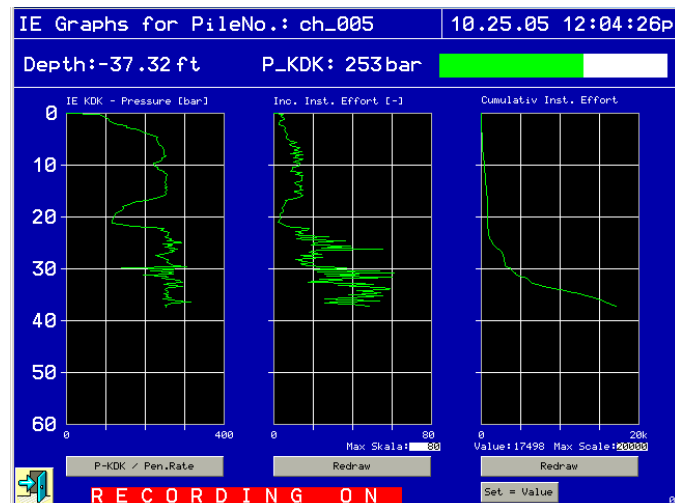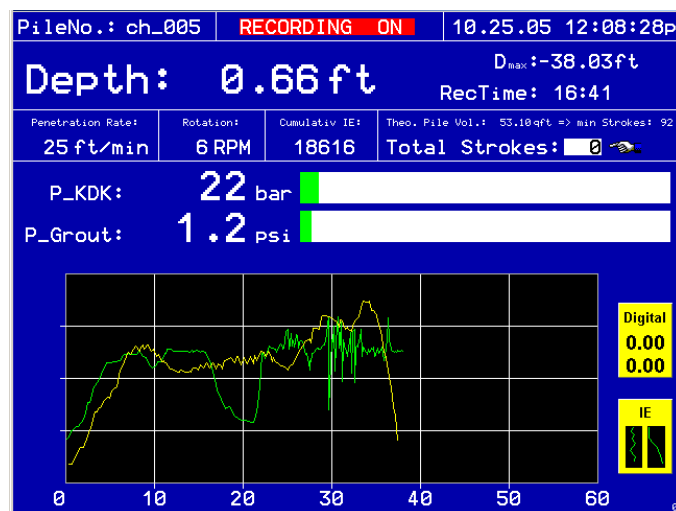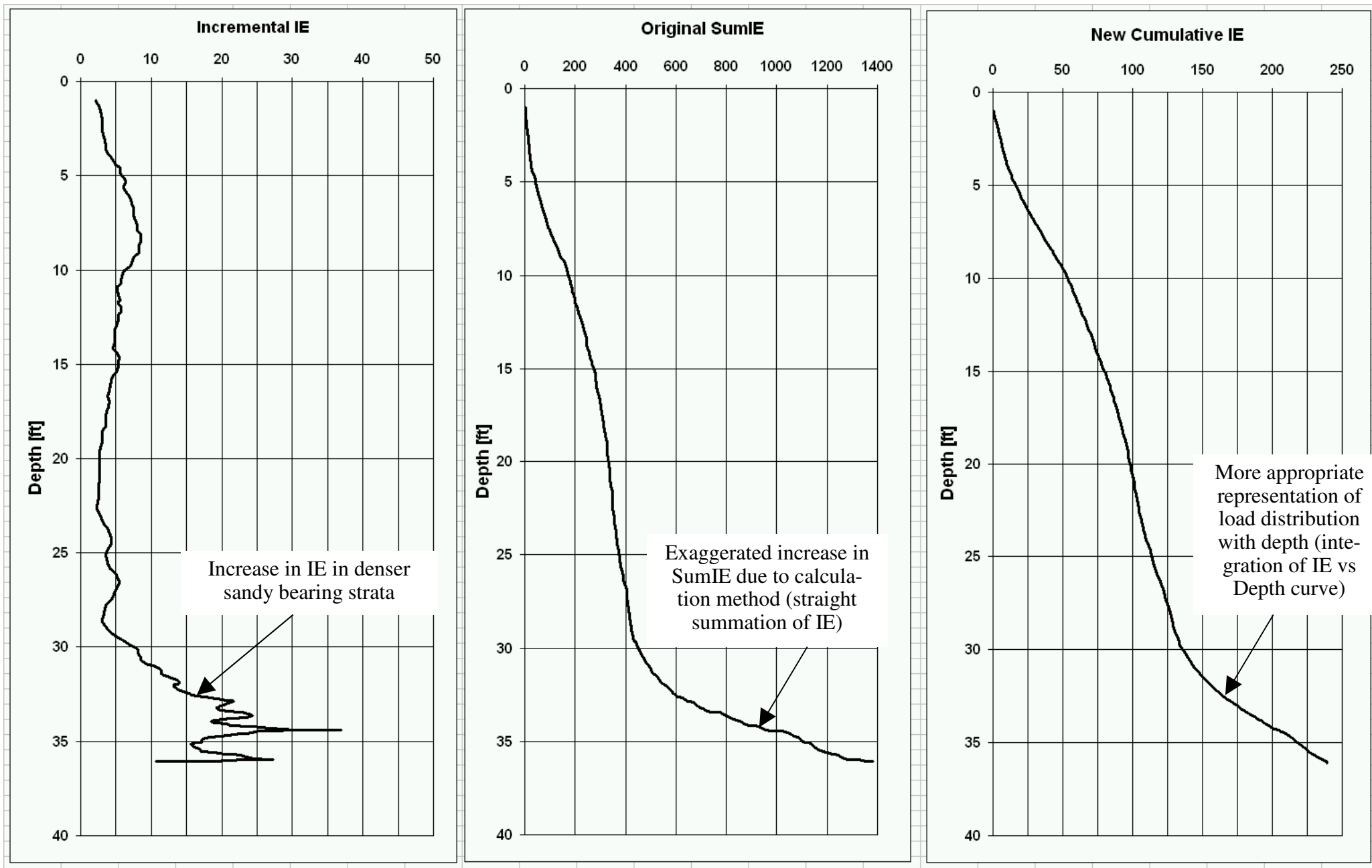NeSmith and NeSmith (2002) Anatomy of a DAS
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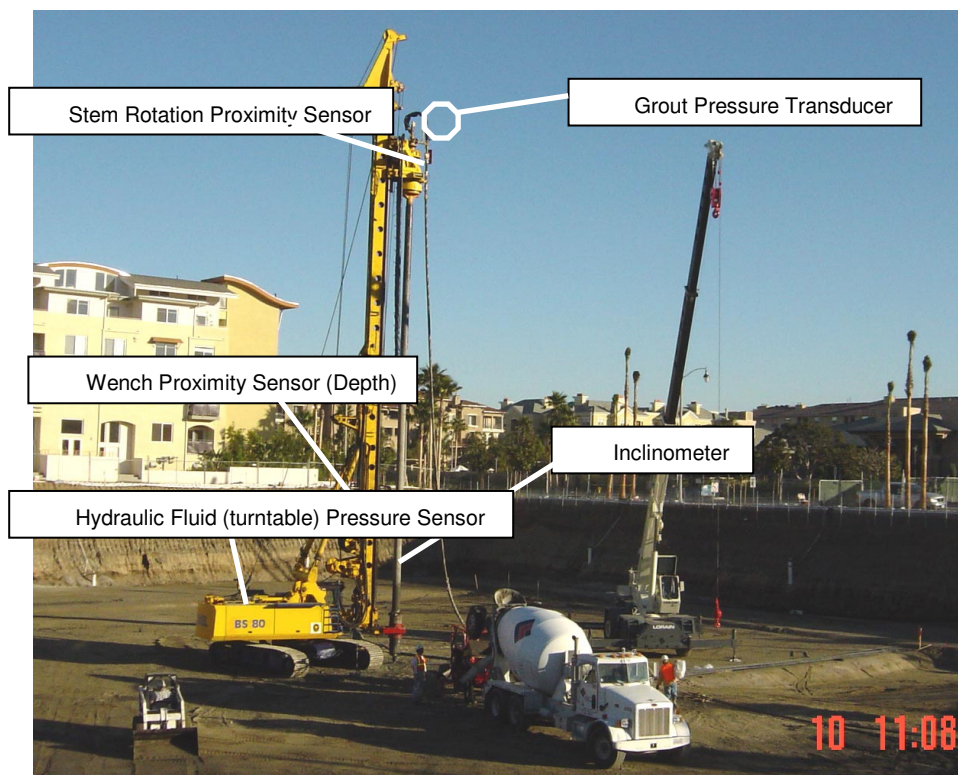
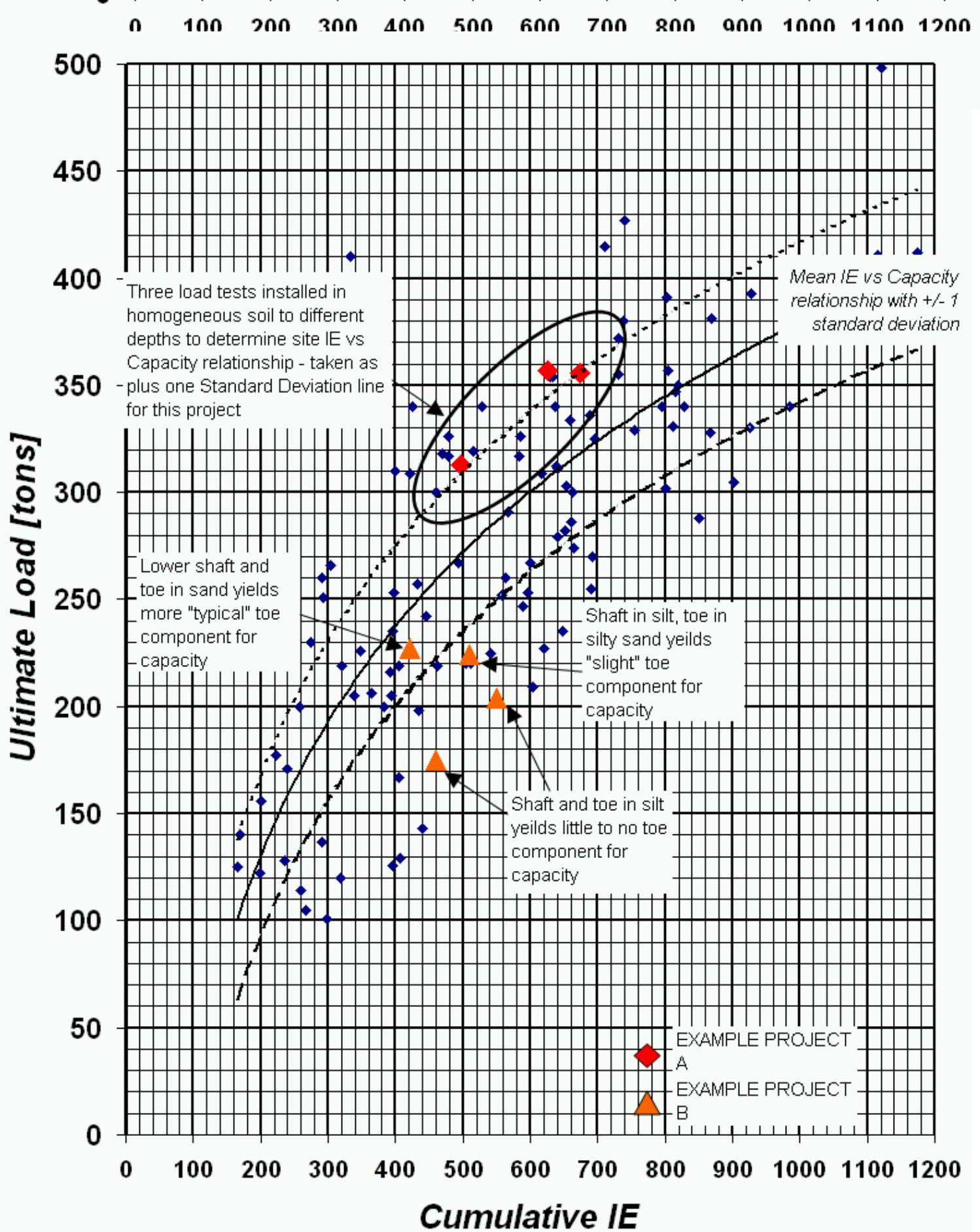**FIGURE 1**: Data Recorded on Drilling Platform

FIGURE 2: Wireless Remote Monitor

FIGURE 3: Main and Engineering Screen of Wireless Remote Monitor

FIGURE 4: Example Incremental IE Profile with Calculated SumIE and Cumulative IE Profiles

FIGURE 5: Database of Cumulative IE vs. Ultimate Load and 2 Example Projects