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PRACTICAL CONSIDERATIONS FOR DESIGN AND INSTALLATION OF DRILLED DISPLACEMENT PILES

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ABSTRACT

A design methodology for the capacity of Drilled Displacement (DD) piles was presented at the International Deep Foundation Congress in 2002. Advances in final design / installation developed since then were incorporated into a DD pile program for two large hotels in Orange County, Florida. The site consisted of granular soils to about 15-m (50-ft) depth underlain by inter-bedded coarse and fine-grained soils. The original design called for 457-mm (18-in) diameter by 29.3-m (96-ft) long conventional auger cast piles. It was estimated that 457-mm (18-in) DD piles installed in the granular materials within the upper 15 m (50 ft) would more efficiently support the proposed loads. The project team elected to utilize DD piles at a substantial cost savings. This paper focuses on one of the two hotel areas. The conditions and construction methods are applicable to both hotel sites.

PROJECT AND IN SITU DETAILS

The project consisted of two hotels with approximate design column loads of (1) Dead Load = 4450 kN (500 ton) to 6005 kN (675 ton) and (2) Live Load = 3115 kN (350 ton). Individual pile design compressive loads were estimated to be 1200 kN (135 ton). A factor of safety of 2 was applied to the design pile loads resulting in a required ultimate compressive load of 2400 kN (270 ton).

In-situ strength data consisted primarily of the results of Cone Penetration Tests (CPT) from a site characterization performed in January 2006. A composite plot of the CPT data in the example hotel area is shown on Figure 1.

DISPLACEMENT PILES – GENERAL METHOD

DD piles are constructed by advancing a displacement auger into the ground utilizing a track-mounted, fixed-mast, hydraulic drilling machine. As 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. The displacement tool and installation platform used for this project are shown in Figure 2. Further details regarding tooling and the installation method are available in NeSmith (2002).

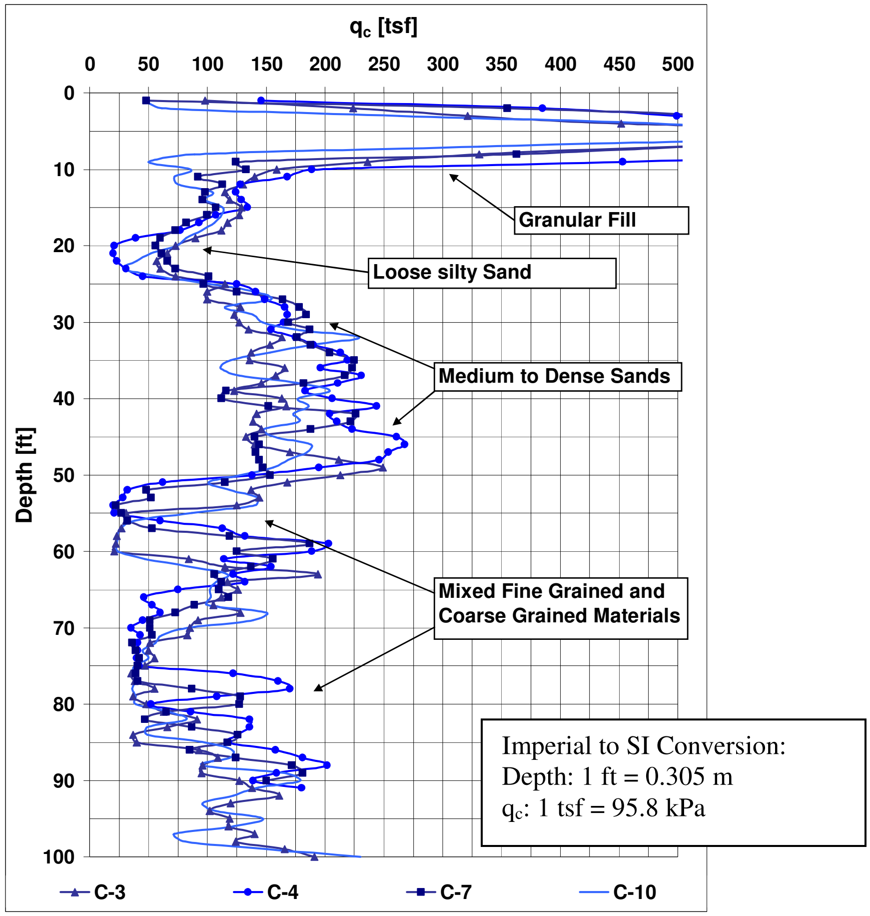


FIG. 1 – Composite CPT Results in Hotel Area

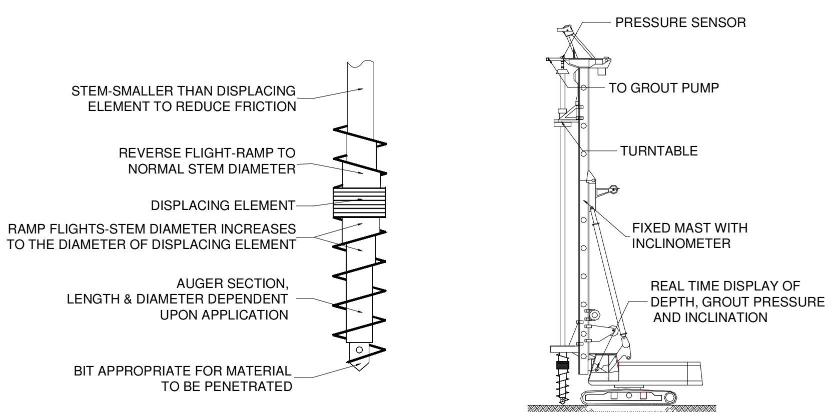


FIG. 2 – Schematic of DD Pile Tool and Installation Platform

ESTIMATION OF PILE RESISTANCE

The methodology for capacity of drilled displacement piles as installed by Berkel has been developed internally and is detailed in NeSmith (2002). Shaft and toe resistances were estimated from CPT tip resistance values with modifiers appropriate for the characteristics of the granular material penetrated. The calculation methodology is summarized in Tables 1 and 2.

Table 1: CPT-based Resistance Analysis Method

SHAFT RESISTANCE	**TOE RESISTANCE**
$f_{s,cpt} = 0.01 * q_c + w_s$	$q_{t,cpt} = 0.4 * q_{cm} + w_t$
$f_{s,cpt}$ = unit shaft resistance [tsf]; limited to 1.7 for rounded, uniform particles, fines>40%; limited to 2.2 for clean, angular, well-graded particles	$q_{t,cpt}$ = unit toe resistance [tsf]; limited to 75 for dirty, rounded, uniform particles; limited to 90 for clean, angular, well-graded particles
q_c = CPT tip resistance [tsf]; limited to $q_c \leq 200$ tsf	q_{cm} = CPT tip resistance [tsf] from 4 diameters above to 4 diameters below the pile toe; limited to $q_c \leq 200$ tsf
w_s = modifier for fines, angularity and uniformity	w_t = modifier for fines, angularity and uniformity
NOTE: 1 tsf = 95.8 kPa	

Table 2: Values for Resistance Modifiers

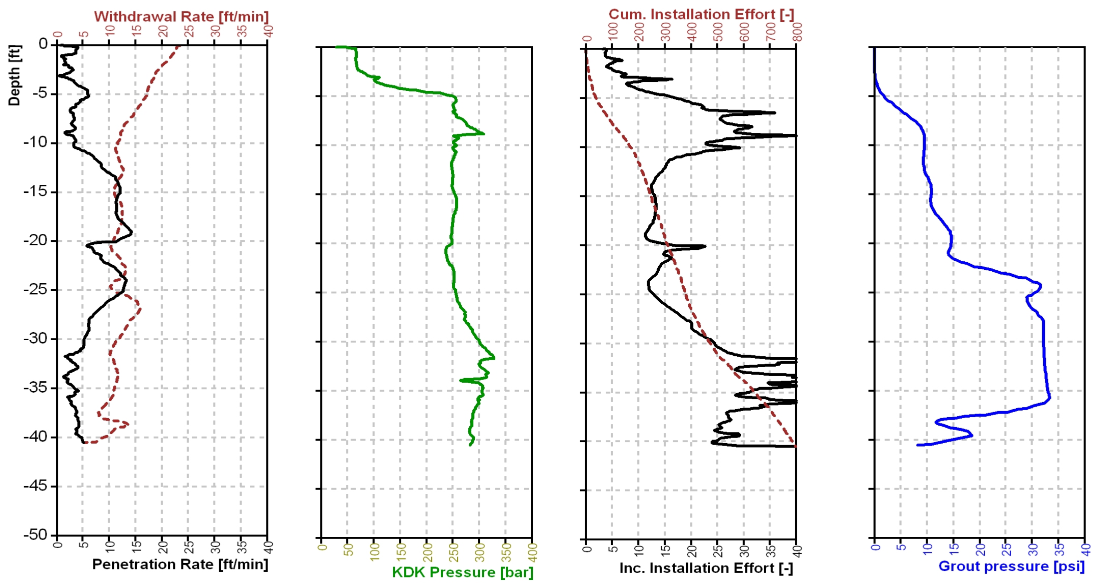
Soil Description	w_s	w_t
Rounded, ≥40% passing #200 sieve, Uniform coarse-grained particles	0.0 tsf	0 tsf
Increasingly cleaner, more angular and more well graded	interpolate	interpolate
Angular, ≤10% passing #200 sieve, Well Graded	0.5 tsf	15 tsf
NOTE: 1 tsf = 95.8 kPa		

The CPT results indicated that the predominantly sandy soils in the upper 15 m contained a range of fines quantities from ~ 30 percent to less than 5 percent. Capacity modifiers were selected based on these fines contents and considering the relative roundness and uniformity of the coarse grained materials in this area. Values used for analysis typically were 29 - 38 kPa (0.3 to 0.4 tsf) for the shaft modifier and 860 - 1150 kPa (9 to 12 tsf) for the toe modifier.

Analysis of the mixed fine- and coarse-grained material below 15-m (50-ft) depth indicated no group effects that would require a reduction in the allowable contribution of individual piles bearing in the sands in the upper 15 m (50 ft).

TEST PILE INSTALLATION DETAILS

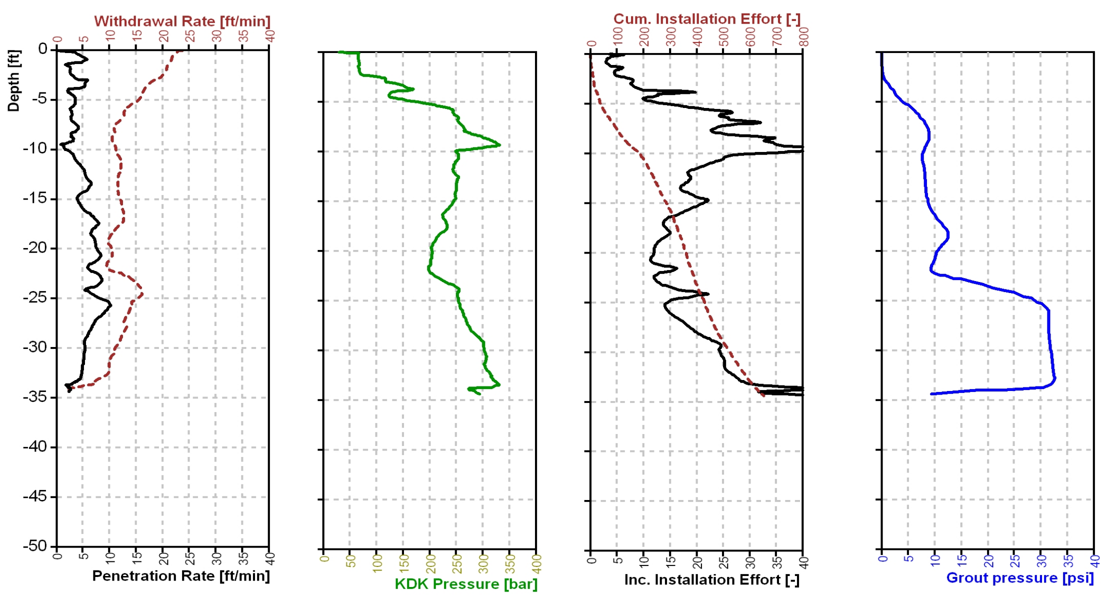
Density variations in the sands in the upper 15 m (50 ft) indicated that installation of production piles to one elevation across the site would not be the most economical use of DD piles. A test program was established to evaluate the energy required to install piles to provide the required resistance. Minor drilling difficulty was incurred while installing test piles which raised concern regarding production pile spacing (1.2 m (4 ft) center-to-center). However, the owner and representatives were reluctant to re-design pile caps or consider smaller diameter piles at this phase of the program. Two 457-mm (18-in) diameter test piles were installed for compression tests. Details recorded during these test pile installations are presented in Figures 3 and 4.



Solid Line – Penetration, Dashed Line – Withdrawal   Solid Line – Incremental IE, Dashed Line – Cumulative IE

Conversion: 1 ft = 0.305 m; 1 bar = 100 kPa; 1 psi = 6.9 kPa

FIG. 3 – Installation Details of Test Pile CT-1



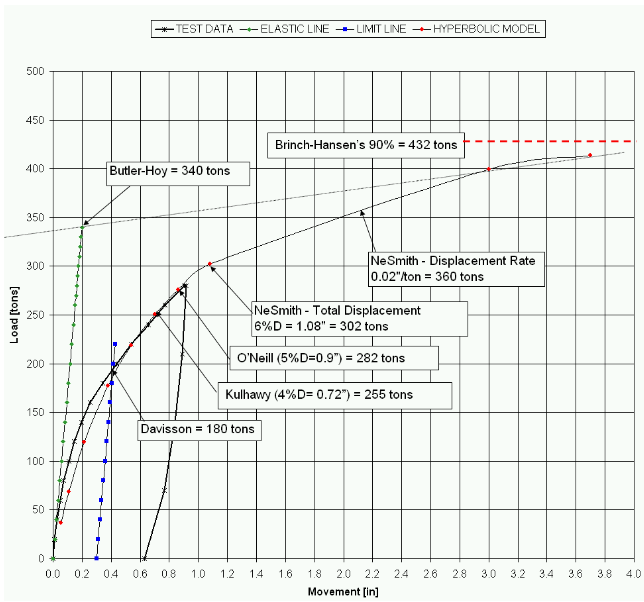
Solid Line – Penetration, Dashed Line – Withdrawal   Solid Line – Incremental IE, Dashed Line – Cumulative IE

Conversion: 1 ft = 0.305 m; 1 bar = 100 kPa; 1 psi = 6.9 kPa

FIG. 4 – Installation Details of Test Pile CT-2

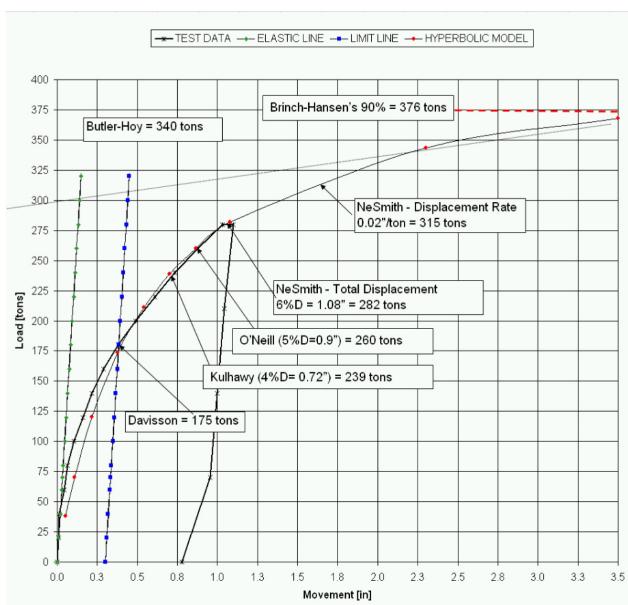
COMPRESSION LOAD TEST RESULTS AND ANALYSIS

Test piles were loaded in accordance with ASTM D1143 (Quick Test) in increments of 178 kN (20 ton) to a maximum load of 3380 kN (380 tons) and then fully unloaded. Plots of applied load versus pile head displacement are presented in Figures 5 and 6. Also presented in these plots are hyperbolic models of the load-displacement relationship.



Conversion: 1 in = 25.4 mm; 1 ton = 8.9 kN

FIG. 5 – Pile CT-1 Load Test Results and Estimates of Ultimate Load



Conversion: 1 in = 25.4 mm; 1 ton = 8.9 kN

FIG. 6 – Pile CT-2 Load Test Results and Estimates of Ultimate Load

The above extrapolations were obtained by applying the method described by Chin (1970). Ultimate compressive resistance was defined 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 0.06 mm/kN (0.02 inches/ton)
- The load at which the pile head deflection is equal to 6 percent of the pile diameter

Applying the above criteria, and estimating shaft and toe components from the equations for the hyperbolic models, the ultimate resistances of the test piles was estimated to be as follows:

- CT-1 – Total: 2687 kN (302 tons) Shaft: 2224 kN (250 tons) Toe: 463 kN (52 tons)
- CT-2 – Total: 2509 kN (282 tons) Shaft: 2118 kN (238 tons) Toe: 391 kN (44 tons)

It is noted that while the Davisson Offset Limit method is listed as an acceptable method for evaluating ultimate load for pile foundations in IBC 2006, the method was originally developed for driven piles and is inappropriately conservative for cast-in-place foundations. Davisson (1993) recommends a modifier of between 2 and 6 when calculating the offset for evaluating a cast-in-place pile, as research has shown that toe deflections of 2 to 5 percent of the diameter are required to reach ultimate load, compared to less than 1 percent for driven piles.

PRODUCTION PILE SPECIFICATION AND INSTALLATION EFFORT

It was proposed to establish production toe elevations by electronically collecting pile installation data (as shown in Figures 3 and 4) and relating this, in real-time, to pile resistance. Pile installation parameters including time, tip depth, auger torque and auger rotations were recorded and displayed on the installation platform used in this project (NeSmith and NeSmith, 2006a). Berkel proposed to use the parameters recorded during test pile installation to set production installation requirements as per the methodology described in NeSmith and NeSmith (2006b). This was to include using KDK Pressure and Penetration Rate to estimate the rig energy expended during test pile installation (Installation Effort, IE) and comparing the total energy (Cumulative Installation Effort) with an internal database of IE and compressive resistance. The Cumulative IE for the two test piles (shown in Figures 3 and 4) was as follows:

- CT-1 – IE = 801, Ultimate Resistance = 2687 kN (302 tons)
- CT-2 – IE = 651, Ultimate Resistance = 2509 kN (282 tons)

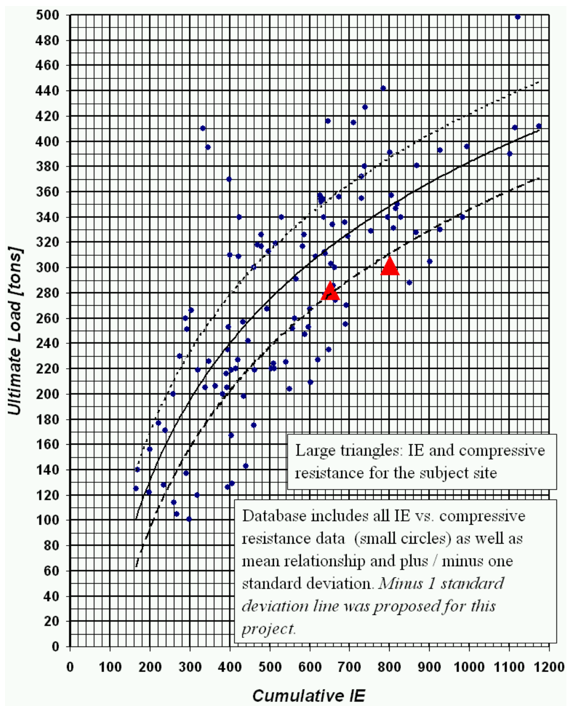
The entire database and details from the project test pile program are shown on Figure 7. For an ultimate compressive resistance of 2400 kN (270) tons, the Cumulative Installation Effort required was 635 [-].

Due to the variation in local conditions across this project site, the project team was advised that it would be inefficient to set pre-determined pile lengths according to pile cut-off elevations or required effective pile lengths. It was anticipated that production pile toe levels would vary by several feet across each of the features. However, initially the project team chose to adopt one effective pile length across each hotel, proposing to use the IE method as a check.

PRODUCTION INSTALLATION

Calibration of Installation Effort

Two drilling platforms were calibrated on site to address variations in their drilling parameters collected during installation. Calibration consisted of the rigs drilling ten probes simultaneously at closely spaced locations and plotting the calculated installation efforts for all of the probes from one rig against those from the other rig. It was determined that both platforms would calculate the same Installation Effort for a given soil condition.



Conversion: 1 ton = 8.9 kN, IE is dimensionless

FIG. 7 – Database of Installation Effort vs. Compressive Resistance

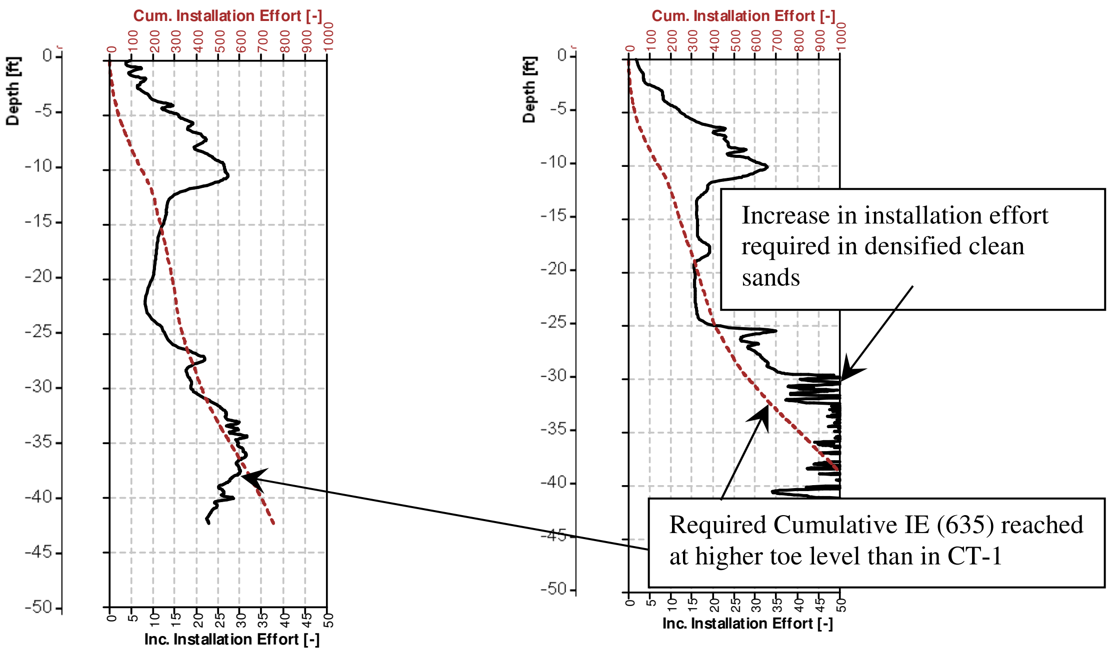
Changes to Production Specifications

During production, the granular materials immediately adjacent to installed piles became significantly denser. Production times for adjacent piles increased by factors up greater than four. This was also reflected in an increase in the hydraulic fluid pressure required to advance and rotate the displacement tool (KDK Pressure) and the Installation Effort, an example of which is shown in Figure 8.

The increase in required effort and corresponding increase in heat generated by the drilling tool resulted in increased production time, difficulty placing reinforcing steel and unexpected equipment wear. Eventually, the pile termination criteria was changed to the data-acquisition method based described above, based on the increase in density and resulting increase in effort shown by the pile records such as in Figure 8.

SUMMARY AND CONCLUSIONS

In coarse-grained soils, Drilled Displacement piles can often provide significantly higher shaft resistance than conventional APG piles. However, DD piles are more susceptible to soil density than APG piles. Where significant variations in soil density exists across a site, it will typically not be most efficient to install DD piles to a uniform "effective length" or toe elevation across the entire site. Systems exist to measure and display pile installation parameters including estimations of the energy required to install the piles. These measurements provide a rational basis for determining the required installation level at a given pile location. They also demonstrate the density increase of subsurface materials through the DD pile production phase of a project.



Dashed line – Cumulative IE; Solid Line – Incremental IE; 1 ft = 0.305 m

FIG. 8 – Comparison of IE of Test Pile CT-1 (left) and Production Pile (right)

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