Drilled Displacement Elements for Liquefaction Mitigation

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Abstract: Abstract The importance of seismic design considerations continues to increase in areas of the U.S. where, traditionally, they have not been considered. Liquefaction-induced settlement or structure movement due to lateral spread are two significant design challenges. In deep liquefiable sands (depths of 30 to 40 ft [9.1 to 12.2 m] and greater), traditional vibration or soil mixing techniques may prove to be financially and/or operationally inefficient. Drilled displacement (DD) systems that densify coarse-grained soils by mechanically displacing them laterally can be an efficient alternative in this scenario. This paper provides background on the development of DD tools in North America, the research and development of the ground improvement provided by DD tool installation, and the subsequent use of DD tools to install structural piles or ground improvement elements to mitigate potential liquefaction as a seismic hazard.

Introduction

The term "drilled displacement", for the purposes of this article, refers to the usage by the Deep Foundations Institute (DFI) Augered Cast-in-Place and Drilled Displacement (ACIP/DD) Pile Committee, which considers this a technique which results in a cast-in-place element or pile, installed by a single-pass, rotary drilling process. The term "pile" refers to structural deep foundations which are tied into the structure's foundation system and reinforced to resist the structure's compressive, tensile, and lateral loads. The term "elements" refers to non- or semi-structural elements which serve to improve the subsurface conditions to allow for the use of shallow foundation systems for support of the structure (and are not tied into the structure's shallow foundation system).

Several proprietary drilled displacement tools are available in North America (Figure 1) that use either pressure-grout placement or bottom-hole tremie concrete placement to form the pile once the tool has penetrated to the planned depth. The tool used in the examples of soil densification and at the example project presented in this article was an Augered Pressure Grouted Displacement (APGD) pile tool. A schematic of the pressure-grouted installed procedure for APGD piles and elements is shown in Figure 2.

The geotechnical benefits of these tools are most pronounced in coarse-grained soils where the mechanical (non-vibratory) displacement of these soils at or below the tool results in higher relatively densities of the soils around the tools than before installation. Most of the tools were developed in Europe and introduced to the North American market in the mid- to late-1990s to install higher capacity piles than non-displacement pile systems.

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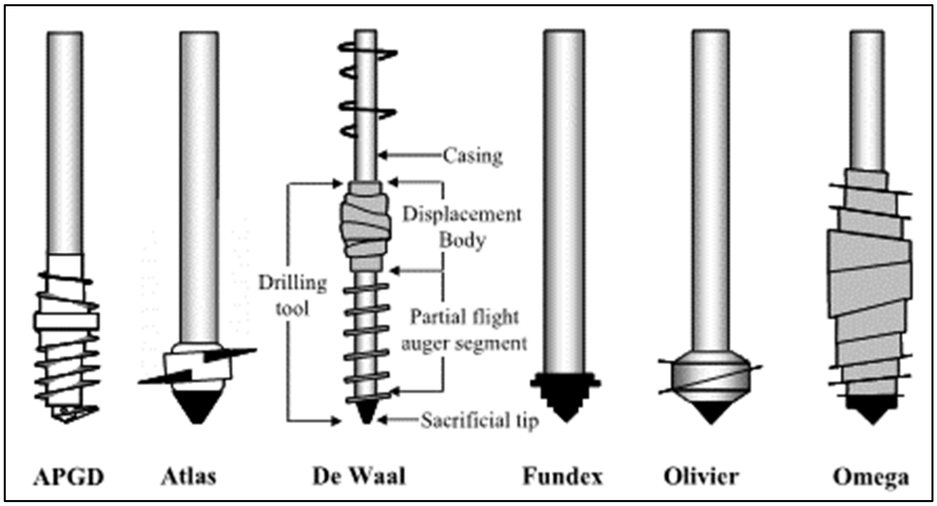

Fig. 1. Partial Example of DD Tools in North America (after Basu, et al, 2010)

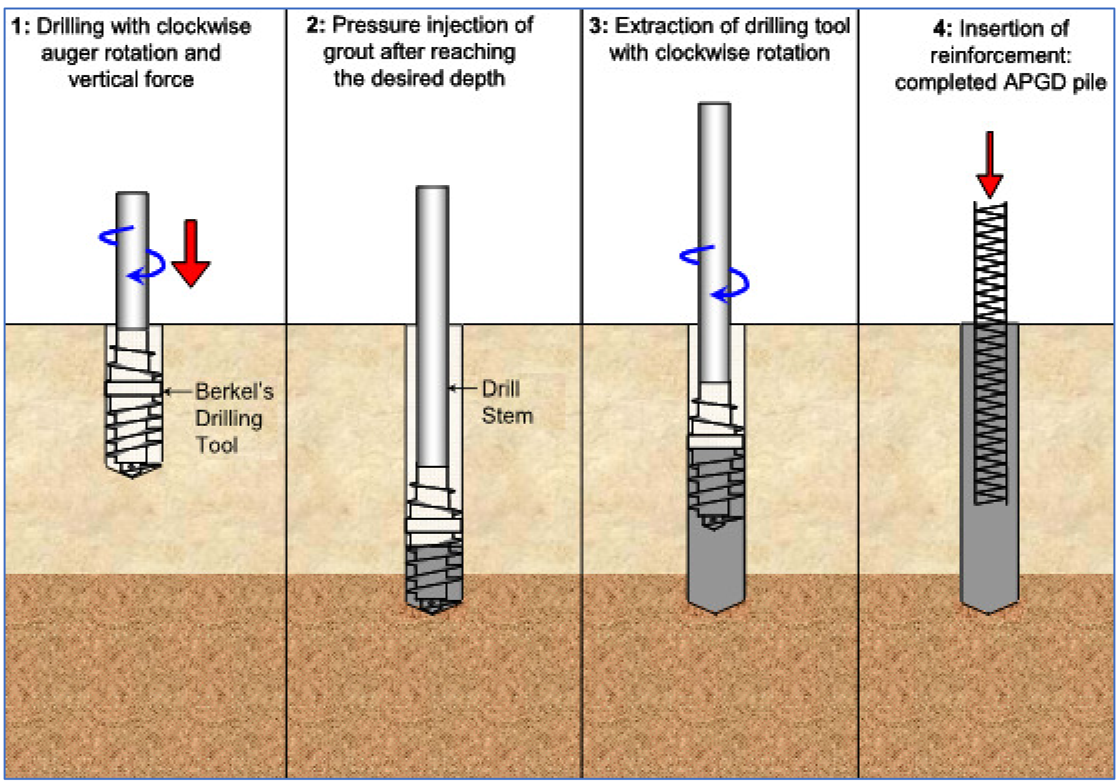

Fig. 2. Installation of DD Piles and CGEs (after Basu, et al, 2010)

Liquefaction Mitigation

DD piles/elements can mitigate the risk of liquefaction due to a seismic event by densifying coarse-grained subsurface soils at a project site. This is achieved due to the mechanical lateral displacement of the soils as described herein.

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An example of the amount of densification, as represented by the results of Cone Penetration Tests (CPTs) is presented in this section. Figure 3 is a schematic of the location of a set of CPTs that were performed near and then in-between a group of four 18-in diameter DD piles. Figure 4 shows the tip resistances measured by the CPTs performed between the DD piles and about 4.5-ft away from the group. The increase in CPT tip resistance after the installation of the four-element group is apparent in these plots.

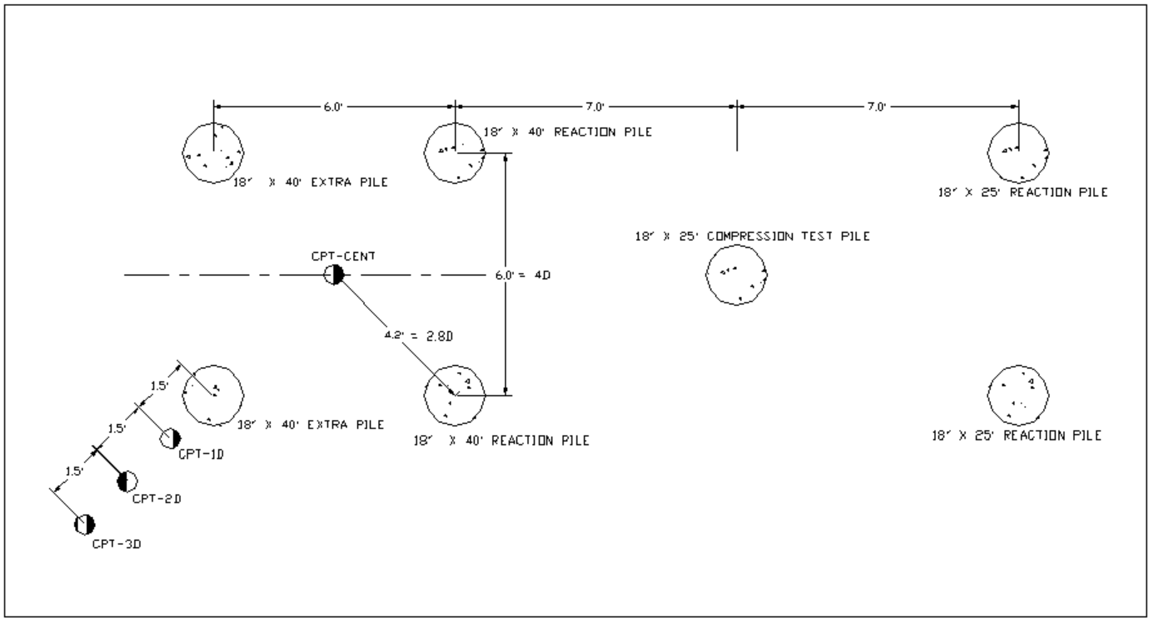

Fig. 3. Cone Penetration Tests Near/Between Installed DD Elements

Siegel, et al (2007a, 2007b and 2008) demonstrated how to develop databases of the level of increase in measured CPT tip resistance due to the installation of DD elements of various sizes and configurations by collecting pre- and post-installation CPT results. An example of the relationship between Area Replacement Ratio (the size and quantity of DD elements installed within a given area) and the expected increase in CPT tip resistance is shown in Figure 5.

Please note that this example is specific to results of CPTs performed after the installation of an APGD tool and may not accurately reflect the level of increase in CPT tip resistance for other displacement technologies (e.g. driven piles). Such a database can then be used to estimate the required size and spacing of DD elements to increase a soil's density, as indicated by CPT results, to the level necessary to resist liquefaction for a given design seismic event.

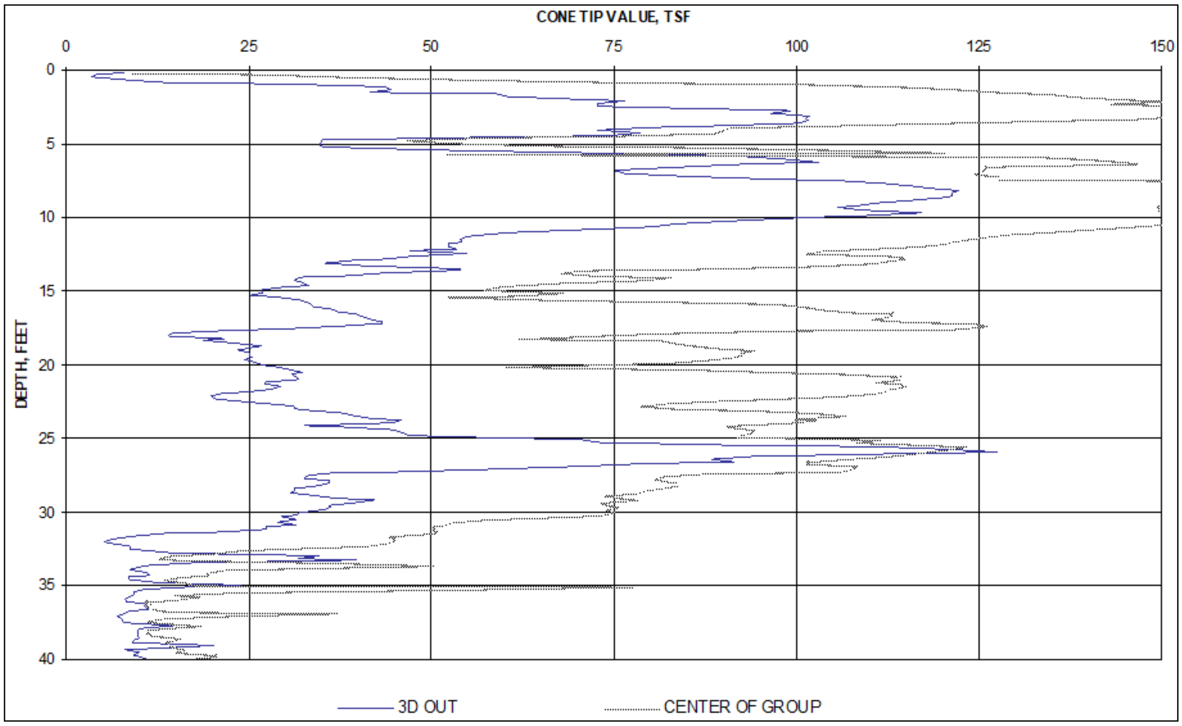

Fig. 4. CPT Results Outside and Inside of DD Element Group

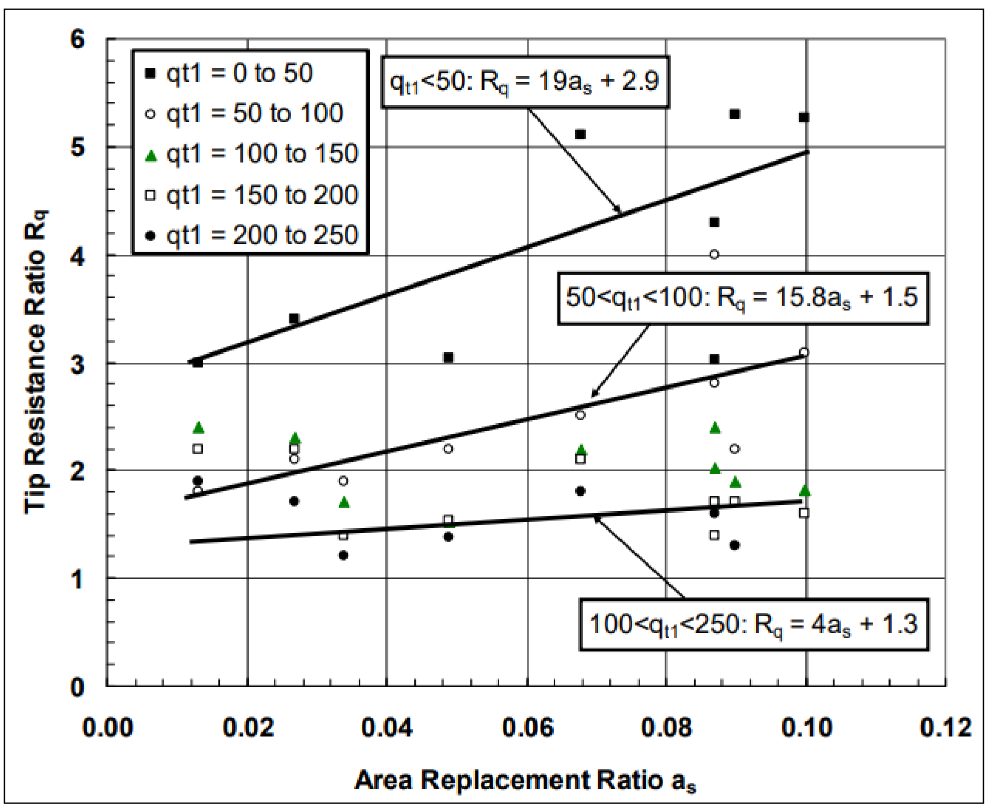

Fig. 5. CPT Tip Resistance Ratio vs DD Element Area Replacement Ratio

Installation Effort and Real Time Installation Data

The drilling platforms used to install DD piles/elements are typically configured with automated monitoring equipment (AME) to record, calculate and display various parameters during DD pile/element installation. During installation (advancing the tool into the ground), typical parameters recorded/calculated include time, depth, tool rotation rate and torque (as measured by the hydraulic fluid pressure driving the rotation of the turntables (NeSmith and NeSmith, 2006a). It is also possible to calculate additional parameters from those recorded, including an estimation of the energy expended by the drilling platform as the drilling too is advanced (aka Installation Effort (IE), NeSmith and NeSmith, 2006b).

Figure 6 shows an example plot of DD tool penetration rate, rotational fluid pressure (KDK pressure) and resulting calculated IE. These IE values are calculated at every 1-sec interval based on the KDK pressure and penetration rate recorded at that interval and provide a representation of soil stratigraphy, including density, like CPT tip resistance. This data can be displayed in the installation platform operator's cabin and transmitted wirelessly for monitoring by an inspector. The real-time display allows the inspector to observe soil stratigraphy during element installation and adjust the required DD element installation (i.e., densification) level as appropriate. indicated by CPT results, to the level necessary to resist liquefaction for a given design seismic event.

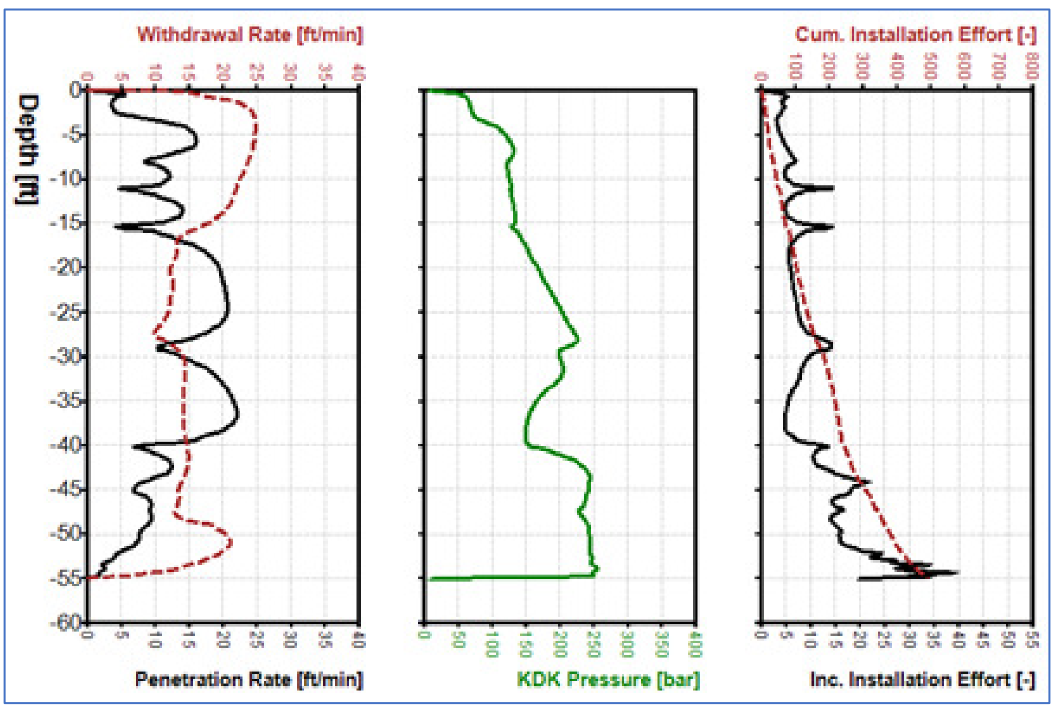

Fig. 6. Recorded and Calculated Parameters During DD Element Installation

TVA Power Facility – Memphis TN

The subject site was a new power generation facility in Memphis TN, near the New Madrid Seismic Zone. A separate liquefaction study for the site indicated that a magnitude 7.7 earthquake with a peak ground acceleration (PGA) of 0.55g should be considered in the final facility design. This PGA was obtained considering a 2% probability of exceedance in 50 years, considering the facility to be critical (i.e., must be operation post-seismic event).

Facilities included a large water-cooling facility and multiple stacks, generators, tanks, and ancillary facilities. Design bearing pressures ranged from 2500 to 4500 psf in the primary facilities and 1500 to 2000 psf in the ancillary facilities (Figure 7). In the stack and HRSG areas, there were also large lateral and uplift (overturning) loads that dictated structural pile support to resist these loads. The facilities were generally supported by mat foundations. Tanks were typically supported by ring footings with geogrid reinforced structural fill under the tank in the space between the footing.

An example preliminary CPT result is shown in Figure 8. Challenges to supporting the desired loads included settlement of the soft to firm clay in the upper 20-ft (along with small zones of similar soils from 20-ft to 50-ft depth) and settlement due to liquefaction (considering the design seismic event) of medium dense sands between 20-ft and 55-ft depth.

It was estimated that 14-in diameter DD elements could be installed as semi-structural elements on a 7-ft x 7-ft center-to-center triangular spacing under the majority of the foundations to (a) create a soil-grout block to transfer the design bearing load through the soft clay soils down to the lower sandy soils and (b) increase the density, as measured by post-installation CPTs, in any liquefiable sands to mitigate that risk. Under the stacks and HRSGs, it was estimated that 16-in diameter DD piles could be installed on a similar spacing to mitigate liquefaction but also to fully resist the design per-pile loads of up to 125 tons compression, 30 tons tension and 10 tons lateral.

During the early stages of CGE installation, a post-installation CPT program was conducted to verify an “improved” condition of the liquefiable sands using the 14-in elements as described above. A noted increase in the tip resistance can be seen in the post-installation CPT results (Figure 9). An analysis of the results, considering the seismic design parameters for the project, indicated that the liquefiable sands had been improved to a point where liquefaction was mitigated using this size element and spacing, resulting in CPT refusal levels of densification in the lower sands (early-stage elements were installed to a depth of about 55-ft below grade).

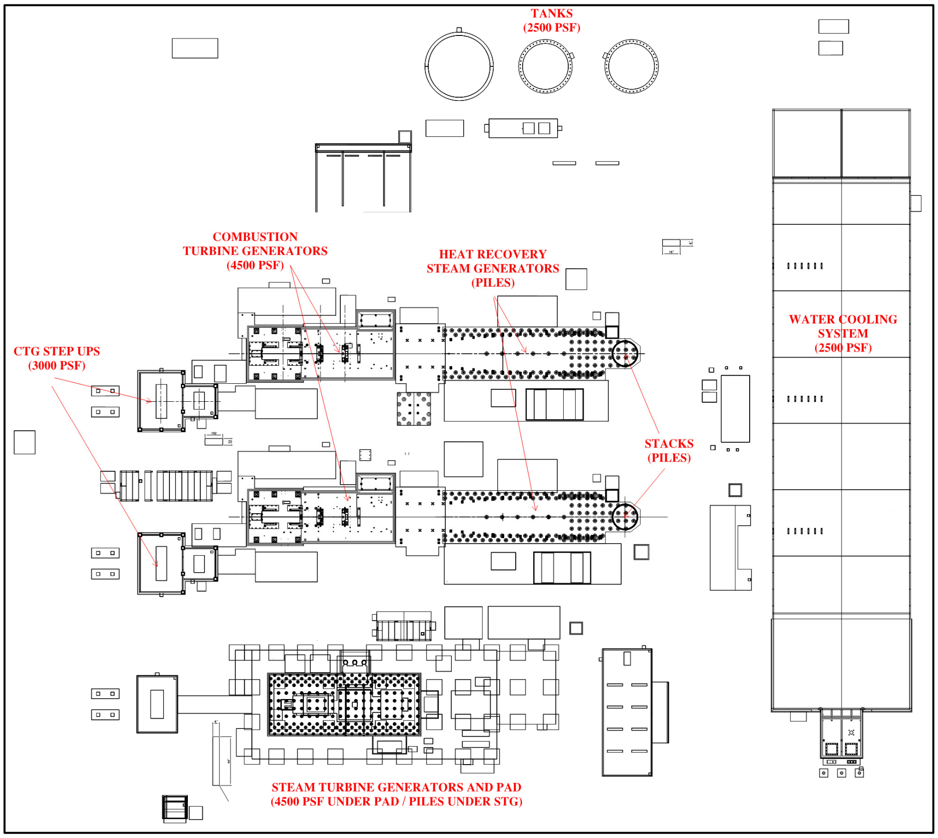

Fig. 7. General Facilities Layout with Bearing Pressures

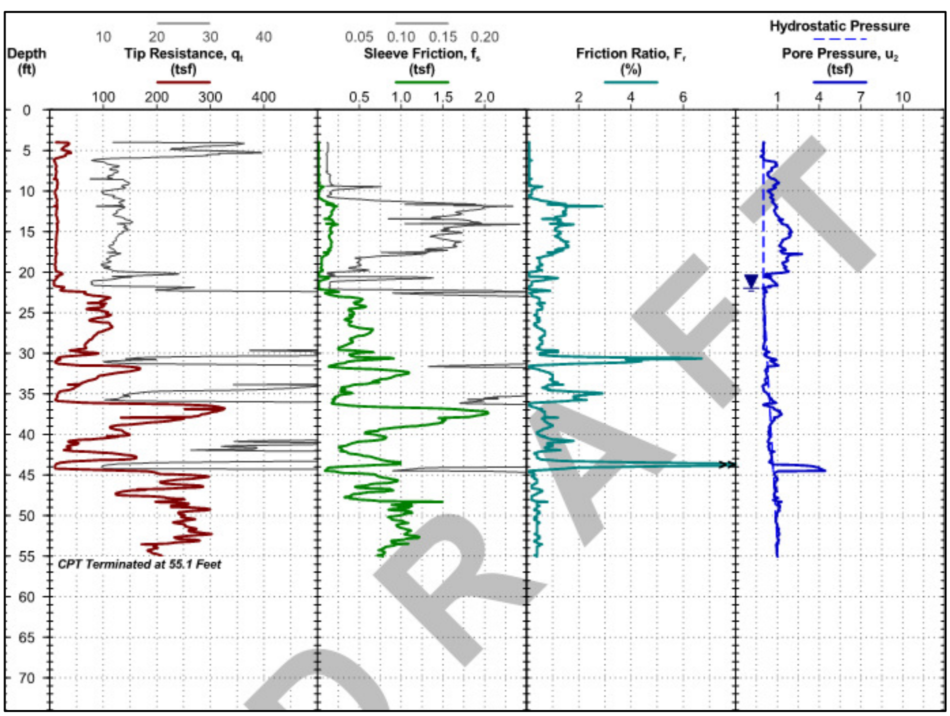

Fig. 8. Example CPT Result – Pre-installation Site Condition

Elements were typically installed to a minimum of 55-ft below grade under most structures. They were extended up to 65-ft when drilling resistances (as demonstrated by Installation Effort, IE) were encountered that indicated that the zone of medium dense, potentially liquefiable soils extended below 55-ft depth. Elements were typically cut-off 6-in below foundation level and covered with structural fill to the bottom of the mat level for each structure. However, the elements were reinforced with steel center-bars to increase ductility because of the lateral forces in the soil during the design seismic event. To obtain appropriate factors of safety for individual piles, the 16-in diameter DD piles were installed to depths of approximately 65-ft below grade in the HRSG and Stack areas and 70-ft below grade in the STG area, based on the results of the pile load test program for the project. These structural piles were reinforced to adequately resist the tension and uplift loads described above.

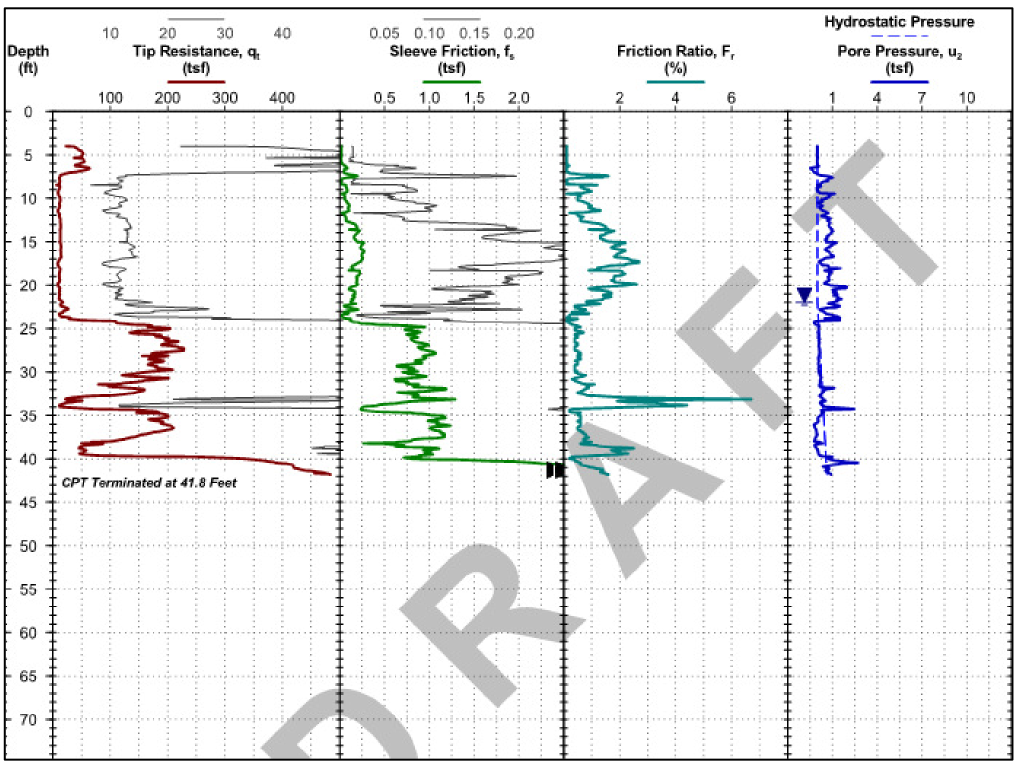

Fig. 9. Example CPT Result – Post-Improvement Site Condition

Conclusions and Moving Forward

The results of this project indicated that there is a measurable increase in the density of coarse-grained soils due to the installation of elements using drilled displacement tools and that this can be estimated by pre- and post-installation CPTs. It should be noted that post-installation testing is typically performed in the center of the element group, i.e., the point where improvement will be the lowest. There is some preliminary evidence that, over time, the density increase between elements becomes an average of this lowest measured density and the higher increases measured closer to the individual elements in the group.

As more information in this regard becomes available, designs should become more efficient, as lower target post-installation CPT results could be for immediate post-installation testing, with consideration for the averaging of soil density between elements over time. The required depth of installation of DD piles and elements to mitigate liquefaction can be varied, in real-time, across a project site, by monitoring the energy expended by the installation platform during element/pile installations.

References

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