LARGE-SCALE PLATE LOAD TESTING OF GROUND IMPROVED USING DISPLACEMENT GROUT COLUMNS

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ABSTRACT

The site of a warehouse expansion in Tampa, Florida was underlain by sand overlying limestone. The performance criteria required ground improvement to densify the upper sand in order to maintain a maximum total settlement of 25 mm (1 inch) for an applied subgrade pressure of 110 kPa (2300 psf). Considering the objectives, displacement grout columns were selected as the ground improvement technique. The efficacy of the displacement grout columns for densifying the upper sands was verified by a pre-production test program that included cone penetration tests and a large-scale plate load test. The cone penetration test results showed a significant increase in tip resistance after ground improvement. The plate load test results showed that improved ground performed consistent with the design requirements. It is concluded that the design methodology proposed by the authors provides a very good estimate of the behavior of ground improved by displacement grout columns beneath shallow foundations.

INTRODUCTION

As described by NeSmith (2002), drilled displacement piles are installed by the displacement of the soil within the pile volume and subsequent placement of fluid cement grout within the evacuated volume. With similar equipment, the drilled displacement process may also be used in ground improvement applications (Siegel *et al.*, 2007a; Siegel *et al.*, 2007b). That is, the evacuated volume may be replaced with *inclusions* (rather than piles) composed of unreinforced grout or an alternate material. The application of the drilled displacement process can include both soil improvement (as a result of displacement) and reinforcement (as a result of the addition of higher strength material to the soil matrix). The displacement process has construction advantages including: (1) negligible spoil generation, (2) full support of adjacent (in-place) soil during installation, and (3) readily installable below the water level. This paper describes the technical aspects involved in the application of displacement grout columns, commercially known as *CGE* (Berkel & Company Contractors, Inc., 2009) to a site in Tampa, Florida

Drilled Displacement Process

The Berkel tool (Figure 1) used to install displacement grout columns consists of a bottom auger section with a length of 0.9 m (3 feet), a displacement section that is equal to the nominal diameter of the pile, and a few flights of reverse auger above the displacement section. The installation platform (Figure 2) is typical of those used in European continuous flight auger (CFA) applications. It includes a vertical mast with an attached turntable capable of producing 25 meter-tons (180,000 ft-lbs) of torque and a cabling system that allows a downward force (or crowd) of 356 kN (40 tons). The system is adaptable to larger equipment, which would increase the maximum depth and the largest diameter that could be installed.

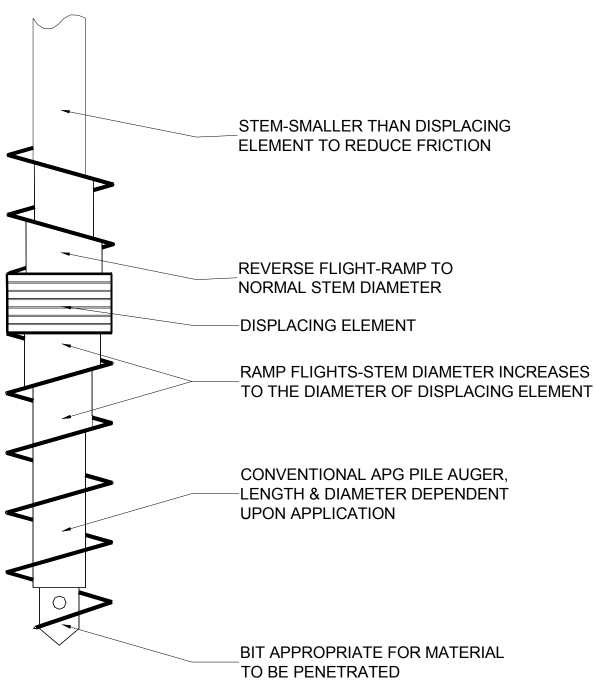

FIG. 1. Berkel Displacement Tool

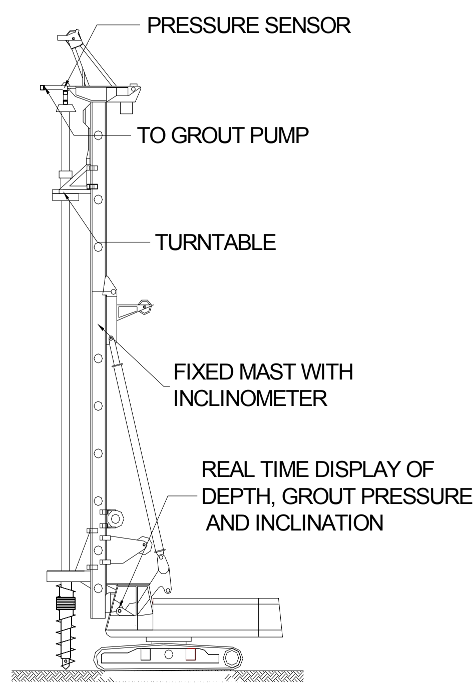

FIG. 2. Installation Platform

The drilling platform allows the Berkel tool to be advanced by displacing the soil horizontally, either at its original vertical position (in loose to medium soils) or after transport to the displacement element (in denser soils). Material in the auger flights is compressed by being forced to the displacement element. The noise and vibration levels generated by the displacement process are comparable to conventional CFA pile installation. The spoil generation is reduced to approximately the tool volume within 1.5 m (5 ft) of the ground surface, where the confining stress is very low. Because the soil displacement is fully horizontal only below this depth, this process may not be practical where very shallow soils require densification. In general, advancement and withdrawal become difficult in continuous layers exhibiting corrected cone tip resistances (q_t) of about 14.4 MPa (150 tsf) and very difficult at tip resistances of 19.2 MPa (200 tsf). Thin lenses of about 2 m (6.6 ft) or less can usually be readily penetrated, but thicker layers of very dense material should be avoided due to the difficulty with timely installation through these layers.

Warehouse Facility Expansion Site in Tampa, Florida

The warehouse facility expansion site is in Tampa, Florida, which is located within the Coastal Plain Physiographic Province. The upper 6.1 m (20 feet) of the subsurface profile consist of alluvial and beach sands that are Pleistocene/Holocene age deposits. Locally, these sands are underlain by the Hawthorn Group, a soft limestone. Figure 3 presents a CPT profile of the upper subsurface profile at the warehouse facility expansion site prior to installation of any displacement grout columns. Note that the majority of the profile classifies as essentially continuous sands [Soil Behavior Type (SBT) of 8 or 9] according to the sleeve friction method (Robertson *et al.*, 1986).

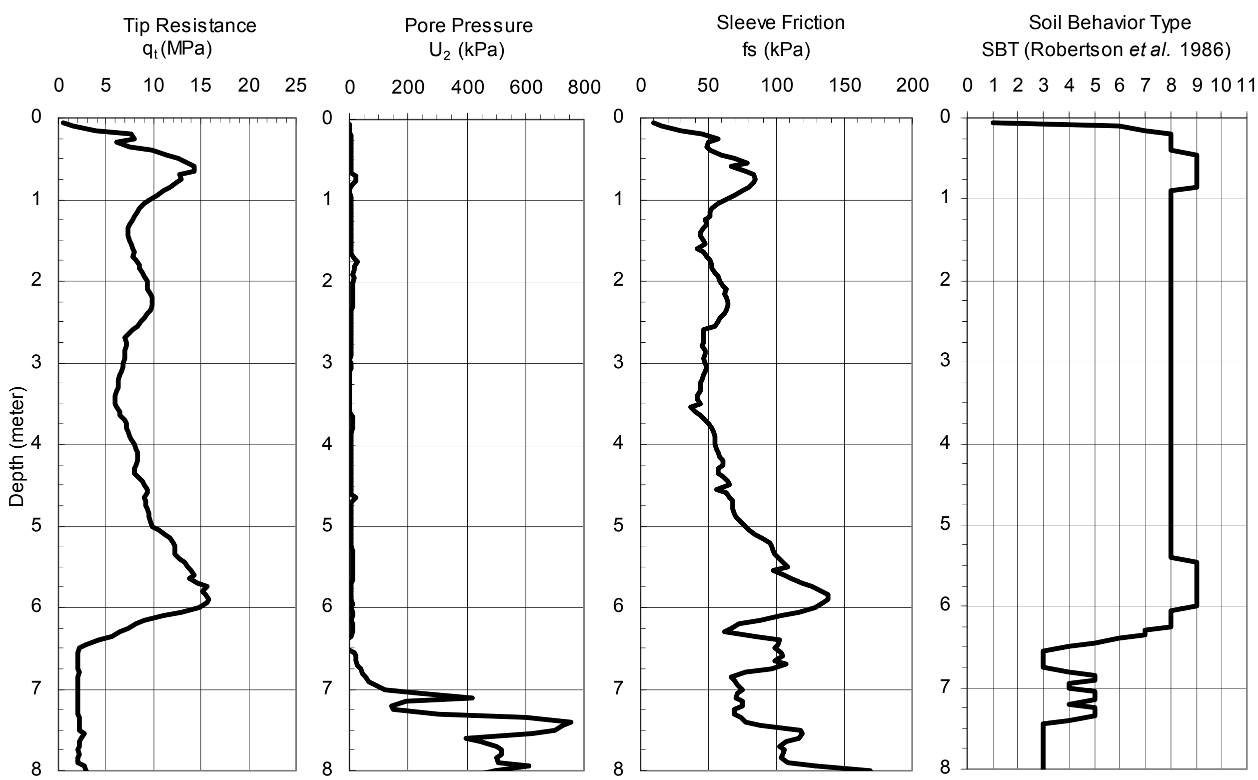

FIG. 3. CPT Profile for Original Site Conditions

GROUND IMPROVEMENT DESIGN

The authors designed the ground improvement using the following combination of methodologies. The original conditions were characterized in terms of cone tip resistance. A spreadsheet that estimates settlement beneath shallow foundations, based on cone tip resistance, according to the Schmertmann method (1970) and improved strain influence factor diagrams (Schmertmann *et al.*, 1978) was used to determine the increase in tip resistance necessary to maintain a maximum total settlement of 25 mm (1 inch) beneath an applied subgrade pressure of 110 kPa (2300 psf). The ratio of the improved tip resistance (*i.e.,* the post-installation tip resistance) to the pre-installation tip resistance has been defined by Siegel *et al.* (2007a) as the *tip resistance ratio* R_q:

Tip resistance ratio:

$$R_q = \frac{q_{t\_post\_installation}}{q_{t\_pre\_installation}} \quad (1)$$

After determining the required value of R_q from the preceding equation, then the relationship between area replacement ratio (a_s) – *i.e.*, the cross-sectional area of the displacement grout column divided by contributory area between displacement grout columns - and R_q, as proposed by Siegel *et al.* (2007b), was applied to determine that an area replacement ratio of 0.033 would achieve the degree of improvement necessary for this project. The relationship between a_s and R_q is illustrated in Figure 4. Note that the degree of improvement, as represented by the value R_q, is typically lower for soils having a relatively higher pre-installation normalized tip resistance (q_{t1}).

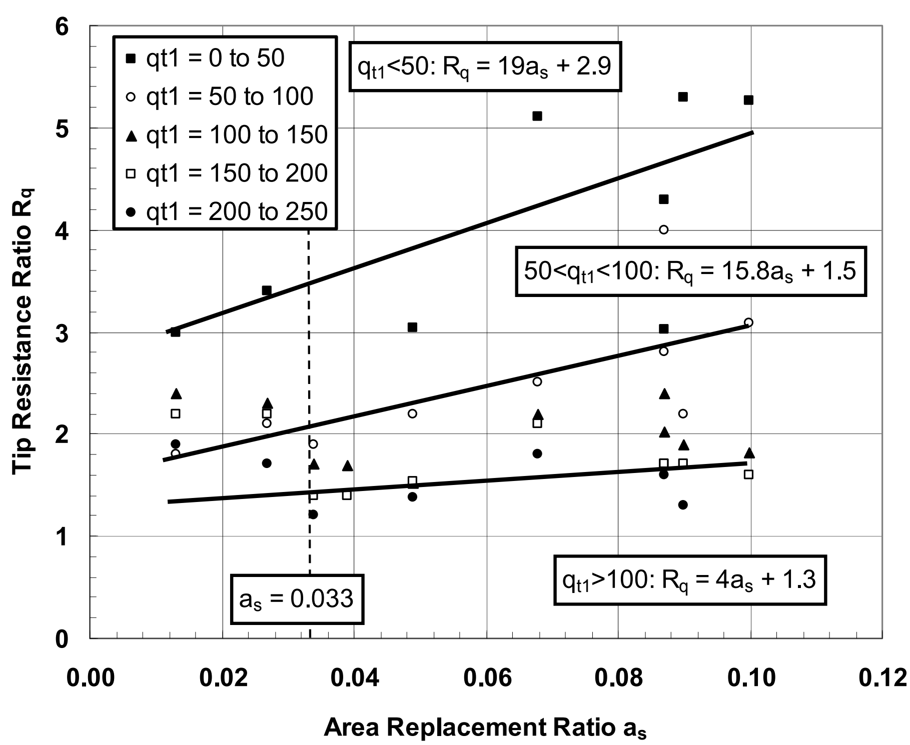

FIG. 4. Relationship Between R_q and a_s (after Siegel *et al.*, 2007b)

Post-improvement CPT

In order to confirm the ground improvement design, the authors executed a test program for the purpose of quantifying the degree of ground improvement, in terms of cone tip resistance, on a site-specific basis. A series of CPT soundings were initially performed in conditions representing the site prior to ground improvement. Subsequently, 406 mm (16 inch) diameter displacement grout columns were installed in square patterns at spacings of 1.8 m (6 ft), 2.1 m (7 ft), and 2.4 m (8 ft) to a depth of 6.1 m (20 ft) below the ground surface. The grout column spacings correspond to a_s values of 0.045, 0.033, and 0.025, respectively, and bracket the a_s that was determined to be required during the initial design. After installation of the grout columns, another series of CPT soundings were performed within the groups of grout columns. Figure 5 shows the layout of the CPT program. The post-installation CPT results should be a conservative representation of the ground improvement given that the testing was performed at the midpoint of adjacent displacement grout columns. Previous testing has shown that R_q decreases as the distance away from the displacement grout column increases.

Note that the grout factor (*i.e.,* the ratio of actual grout volume to the theoretical displacement volume) shown in brackets in Figure 5 ranges from slightly below 100 percent to much greater than 150 percent. Typical grout factors for displacement grout columns are expected to range from 100 percent to 120 percent. The higher grout factors were the result of difficulties encountered when using a variety of pump types without first establishing a withdrawal rate consistent with the target grout factor.

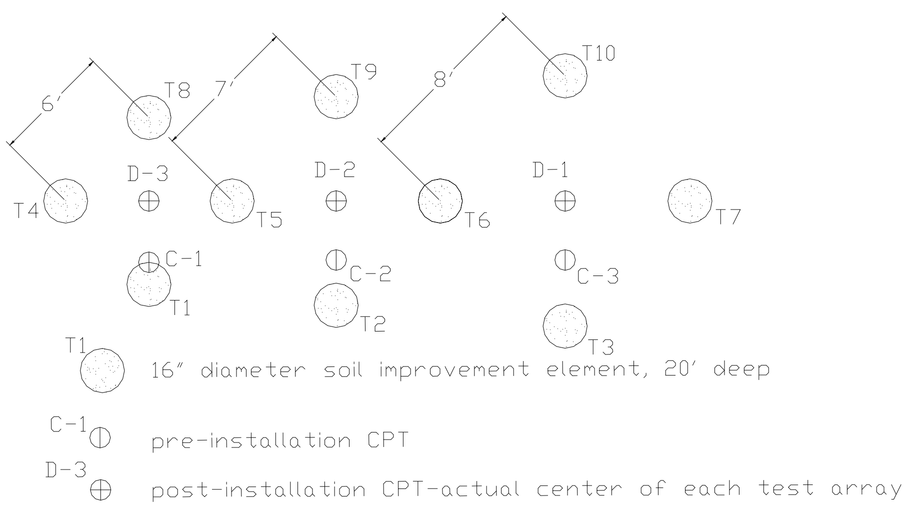

FIG. 5. CPT Program Layout (1 ft = 0.305 m)

The degree of ground improvement for the design spacing of 2.1 m (7 ft) is illustrated in the tip resistances in Figure 6. It is the authors' experience that the ground improvement illustrated in Figure 6 is typical of the improved conditions surrounding displacement grout columns. The improvement, in terms of cone tip resistance, is not observed from the ground surface to a depth of 2 m (6.6 ft) but is significant through the sand extending to a depth of 6.1 m (20 ft).

The post-installation CPT soundings were performed approximately one week after installation of the displacement grout columns. While there is data to support that cone tip resistance will continue to increase at least a few weeks after installation (Charlie *et al*, 1992; Schmertmann, 1991), this beneficial increase was conservatively ignored in the design calculations.

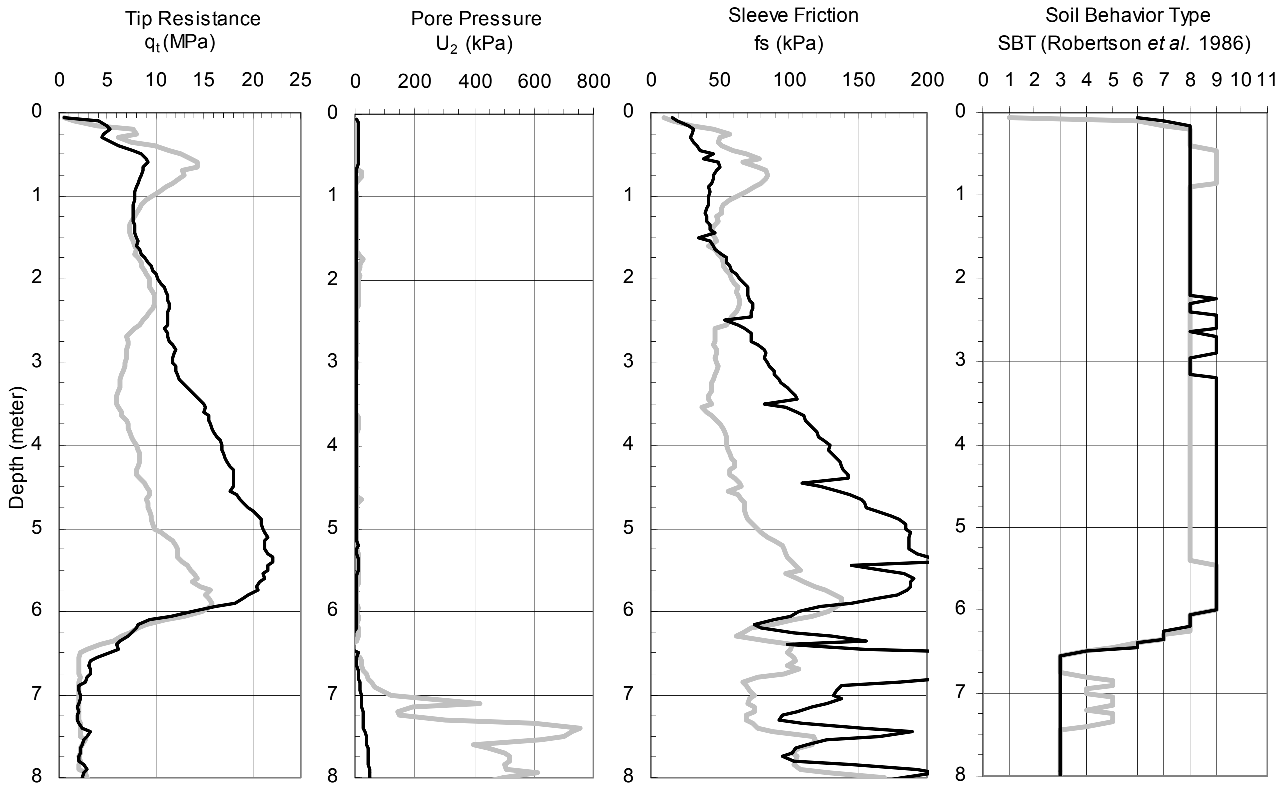

FIG. 6. CPT Profiles of Original Conditions (light gray) and Improved Ground (black)

Large-Scale Plate Load Test

The performance of the improved ground was confirmed by a large-scale plate load test performed in the layout shown in Figure 7. The grout columns extending from approximately 0.45 m (1.5 ft) +/- below the ground surface to a depth of 6.1 m (20 ft). The grout columns were installed in a rectangular spacing with a center-to-center spacing of 2.1 m (7 ft).

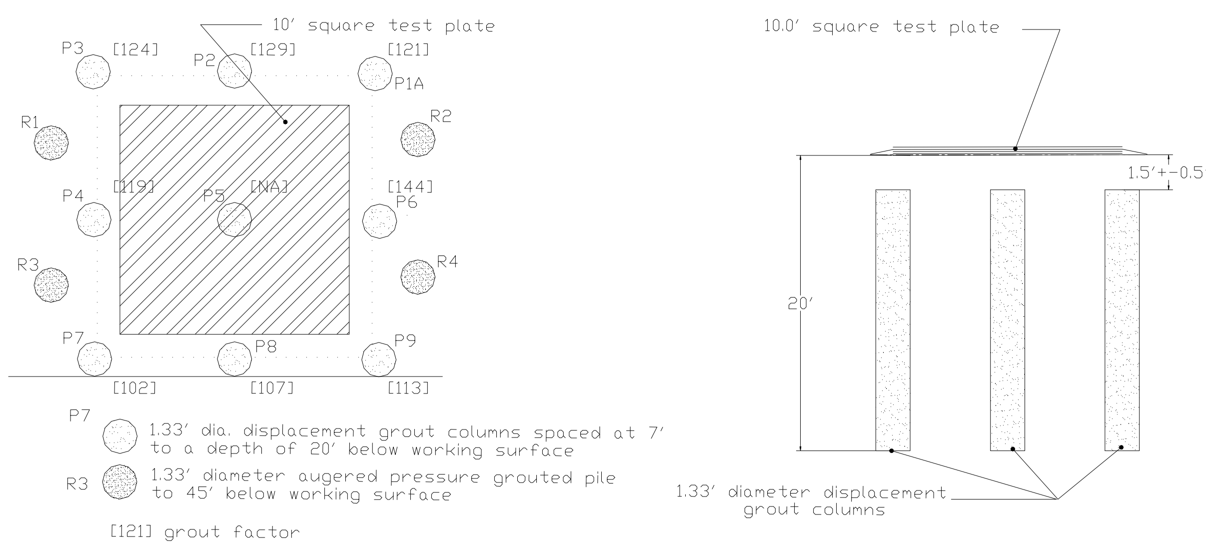

FIG. 7. Plate Load Test Layout (1 ft = 0.305 m)

The compressive load was applied to the plate in increments of 222 kN (50 kips) to a maximum load of 2670 kN (600 kips). The load increment and maximum load correspond to pressures of 24 kPa (0.5 ksf) and 287 kPa (6 ksf), respectively. The plate movement was monitored with a set of two dial gages. Each load increment was held for 15 minutes before proceeding to the next load increment. Note that the dial gages were observed to stabilize within this timeframe which would indicate that the settlement of the sand was essentially immediate upon application of the load.

The results of the plate load test are graphically illustrated in Figure 8 along with the load-displacement curves predicted according to the methodology proposed by the authors using the pre-installation CPT results. The CPT-based predictions are for three different ratios of modulus (E) to tip resistance (q_c) – $E/q_c = 3$, $E/q_c = 4$, and $E/q_c = 5$. These ratios are in the range of values presented by Robertson (1991) for dense sands at load levels well below ultimate capacity (*i.e.,* $q/q_{ult} < 0.1$).

From the results, it may be concluded that the design methodology discussed in this paper provides a very good estimate of the behavior of ground improved by displacement grout columns beneath shallow foundations. It is noted that the slopes of the respective load-deflection curves for the plate load test data and the CPT-based estimates tend to diverge at higher applied pressures. This may be explained by limitations in the Schmertmann method that uses a constant modulus selected based on the *in situ* conditions while in reality the modulus will vary with strain and stress.

The presence of the grout columns is expected to further reduce the observed settlement as they provide some reinforcement by attracting stresses induced by the applied surface load and transmitting these stresses to a deeper, less compressible stratum. Given the modest area replacement ratio, it is not anticipated that the reinforcement provided grout columns significantly influenced the performance of the improved ground at this site. Further study is required to better define the reinforcement provided by displacement ground columns as rigid inclusions.

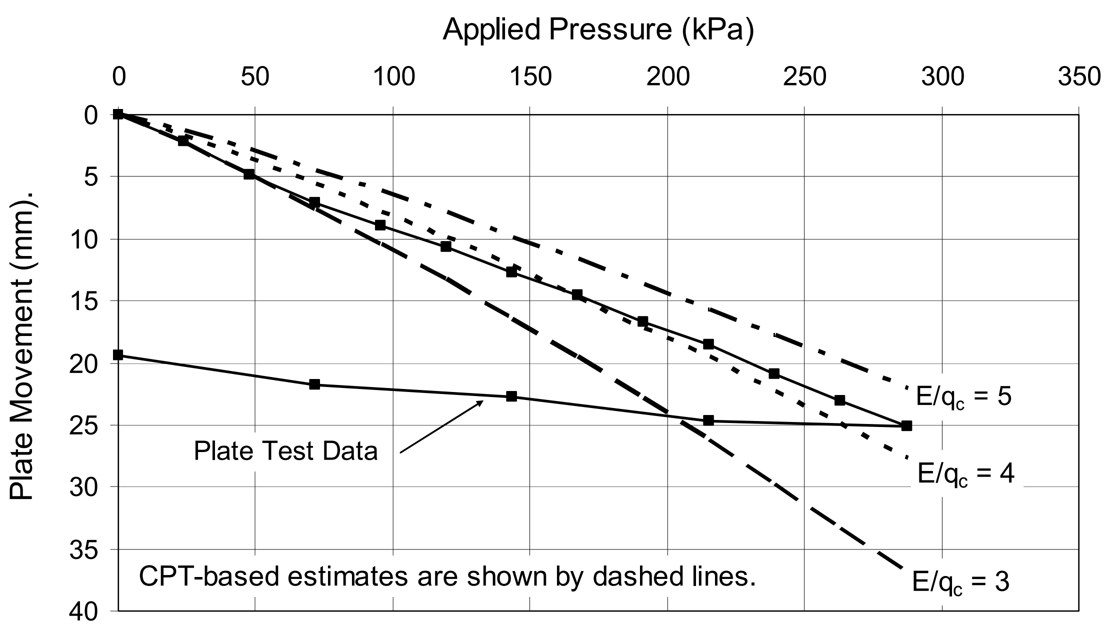

FIG. 8. Plate Movement versus Applied Pressure

CONCLUDING REMARKS

The ground beneath a proposed warehouse expansion in Tampa, Florida was successfully improved using grout displacement columns, which are installed by the lateral displacement of soil within the tool volume and subsequent placement of fluid cement grout within the evacuated volume. The preliminary design for displacement grout columns was prepared based on an approach developed by the authors (and described herein) that involves the combination of established methods for computing settlement in sand and an empirical relationship between column geometry and increase in cone tip resistance. The efficacy of the displacement grout columns for densifying the upper sands at the subject site was verified by a pre-production test program that included cone penetration tests and a large-scale plate load test. The authors foresee that grout displacement columns can be a cost-effective ground improvement technique in suitable soil conditions, especially when other advantages of the displacement process are applicable.

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