CONFIRMATION OF COMPOSITE GROUND DESIGN USING FIELD PLATE TESTS

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In response to a solicitation for ground improvement for the construction of a new hospital in Owensboro, Kentucky, the team of Berkel & Company Contractors and Dan Brown and Associates PC designed and installed lightly reinforced cast-in-place piles (known commercially as Cast-in place Ground improvement Elements or CGEs) as part of a composite ground system. The concept of the design is that the structure load is shared between the piles and the soil subgrade. The load sharing is controlled (to some degree) by the placement of a cushion between the pile head and the bottom of the overlying spread foundation. In an effort to confirm the design principles and to better understand the behavior of composite ground, the design-build team performed plate load tests on ground with a single CGE and with a group of CGEs. The small plate test (on ground with a single CGE) characterized the stiffness of the cushion. The large plate tests showed that the cushion will distribute the applied load to the CGEs and to the soil subgrade between the CGEs. On the basis of the plate tests, it was concluded that the plate stiffness can influence the test results. The use of a concrete layer was effective at supplementing the plate stiffness. The cushion was shown to be an important component of a composite ground system by allowing mobilization of the soil subgrade resistance and avoiding a stress concentration at the tops of the CGEs that would otherwise be present if the spread foundation and piles were rigidly connected. Because the composite ground system engages the resistance of the soil subgrade, the structural demand is reduced and consequently there is a potential for savings when compared to a conventional pile foundation. Several foundations for the new Owensboro hospital are being monitored for vertical movement during construction of the superstructure that will extend through 2011. At the time of this paper (mid 2011) the settlement of the foundations due to only part of the structural load (primarily the structural steel) has been negligible.

Introduction

The project team for a new hospital in Owensboro, Kentucky solicited design-build proposals for ground improvement for the support of spread foundations. The team of Berkel & Company Contractors and Dan Brown and Associates PC designed and installed lightly reinforced cast-in-place piles (known as *CGE*s in Berkel's marketing literature) as part of a composite ground system. The design, which is illustrated in Figure 1, has a 6-inch layer of compacted gravel cushion between the bottom of the shallow foundation and the tops of the CGEs. The CGEs were installed using a Bauer BG-28 platform and Berkel's displacement pile tools. The compacted gravel cushion and the spread foundations were placed by Baker Concrete. The design-build team performed plate load tests on ground with a single CGE and with multiple CGEs arranged in a pattern. The results of the plate load tests were used to better understand the behavior of the composite ground and to confirm the design principles. The final composite ground design consisted of a typical spread foundation underlain by a layer of compacted gravel above a group of CGEs.

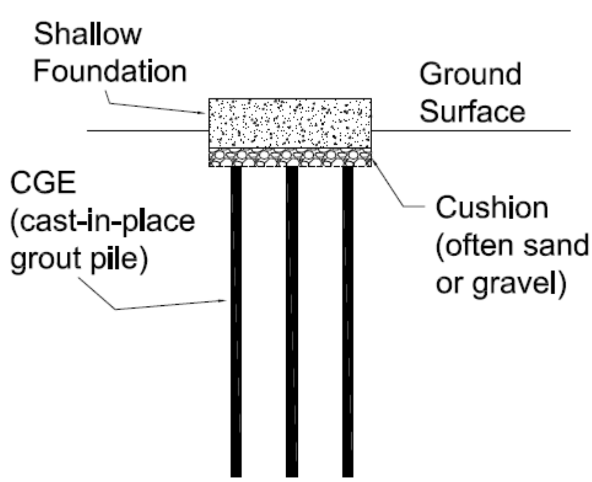

Figure 1. Composite Ground with CGEs

Literature Review

As part of the continuing evolution of foundation engineering and construction, the use of piles beneath spread foundations to partially resist the structural load and/or reduce the settlement has received increasing interest. The terms piled raft, pile enhanced raft and settlement reducing piles have been applied when the structural load is shared between a shallow foundation and piles that are structurally connected (Poulos, 2001). The terms composite ground, column-type reinforcement, rigid inclusions, and disconnected piles have been applied when the piles are not structurally connected to the overlying shallow foundation and there is either a gap or a cushion present between the piles and the overlying spread foundation (Zheng *et al.*, 2009; Paniagua *et al.*, 2008; Eslami *et al.*, 2008).

Both piled rafts and composite ground are designed to share the structure load between the piles and the soil between the piles. An advantage of composite ground is that the stiffness of the pile-cushion system can be designed to distribute the load away from the top of the piles to the spread foundation subgrade thus avoiding the stress concentrations that would normally be expected at a rigid pile-cap connection (Wong *et al*., 2000; Liu *et al.*, 2009). Another advantage is that it is not necessary to design the composite ground with a factor-of-safety near unity for the axial pile resistance which is typically part of piled raft design. A rigidly connected pile, that has a factor-of-safety significantly greater than unity, will not be sufficiently compliant to allow a significant portion of the structure load to be distributed to the soil between the piles. Rather a gap is assumed to develop between the bottom of the pile cap and the soil surface.

The Chinese have been very prominent in the advancement of the composite ground technology and have applied it to the soft soils located in western or northwest China (Han *et al.*, 2009). The Chinese literature typically distinguishes between flexible piles, such as sand or stone columns, and rigid piles, such as concrete or steel piles. This paper uses the term pile rather than rigid piles and there no consideration of flexible columns composed of unbounded gravel or sand.

Liang *et al.* (2003) performed numerical analysis for composite ground with both rigid and flexible piles and concluded that the cushion properties and/or cushion thickness can be adjusted to control the distribution of the structure load in the piles and the subgrade soil. This conclusion received further support by a numerical analysis by Liu *et al*. (2009). Cao *et al.* (2004) performed laboratory model plate tests that showed that the presence of the “disconnected piles” (model piles separated from the plate by a sand layer) stiffens the subgrade. Zheng *et al.* (2007) performed field plate tests on ground containing a single pile and concluded that the soil beneath the plate can resist a considerable portion of the total load due a cushion or a gap located between the pile head and the plate.

Plate Test Setup

Four plate tests were performed for this study. One test (illustrated in Figure 2) was performed using a 24-inch diameter, 1-inch thick steel plate on a 6-inch thick cushion of compacted gravel and a single 16-inch diameter, 50-foot long CGE. The purpose of this small diameter plate test was to estimate the compressibility of the gravel cushion.

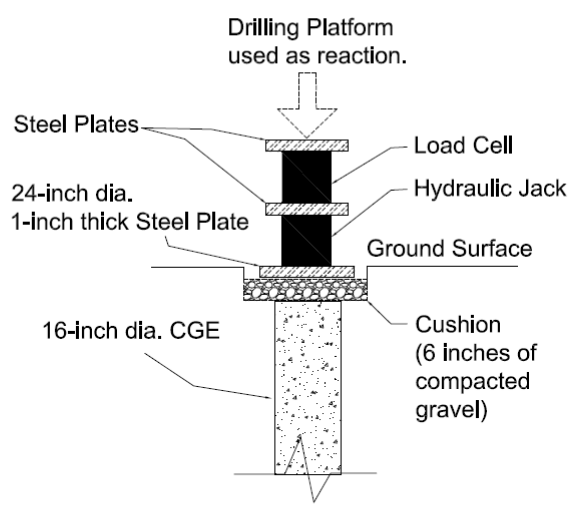

Figure 2. Small Plate Test Setup

Three large plate tests were performed on composite ground. The test setups for these tests designated Large Plate Tests 1, 2 and 3 are illustrated in figures 3, 4 and 5, respectively.

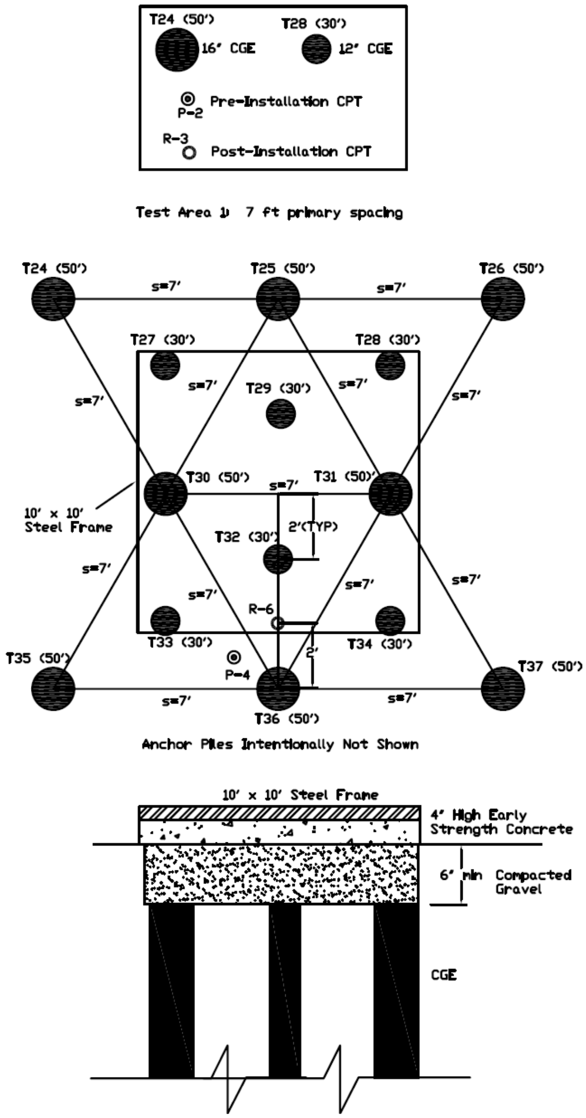

Figure 3. Set Up of Large Plate Test 1

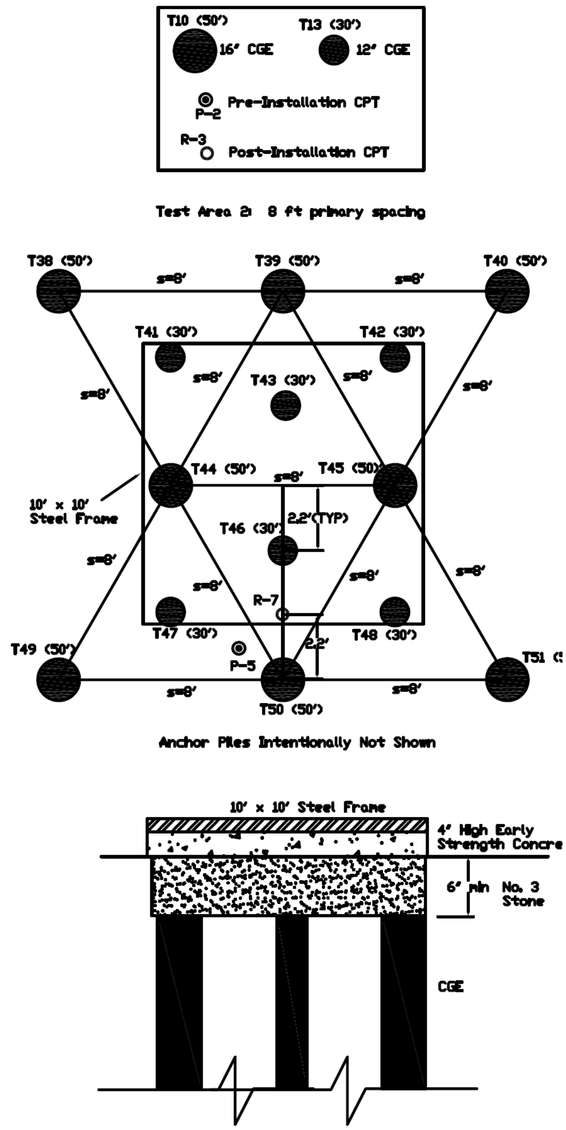

Figure 4. Set Up of Large Plate Test 2

The general setup for the large plate tests consisted of the installation of a pattern of CGEs. The primary CGEs were 16 inches in diameter and had a length of 50 ft. The intermediate CGEs were 12 inches in diameter and had a length of 30 ft. The CGEs for the plate testing were unreinforced and consisted of Portland cement grout with a 28-day compressive strength of 1000 psi. The CGEs were installed with Berkel's displacement pile tools using a Bauer BG-28 fixed mast platform. The cast-in-place displacement pile installation process is described by Bassu *et al.* (2010). A 6-inch thick layer of compacted gravel was placed immediately above the CGEs.

A 4-inch layer of high early strength concrete was placed on the compacted gravel and the test plate was embedded into the fresh concrete. The purpose of the concrete was to provide more rigidity to the system. The load was applied with a hydraulic jack and monitored using a load cell. Two additional load cells were used to measure the resistance mobilized in the two 16-inch diameter CGEs beneath the plate. The plate was incrementally loaded to the safe capacity of the reaction frame. Each load increment was held for 15 minutes. The reference beams were monitored throughout the test with a surveyor's level to identify any movement.

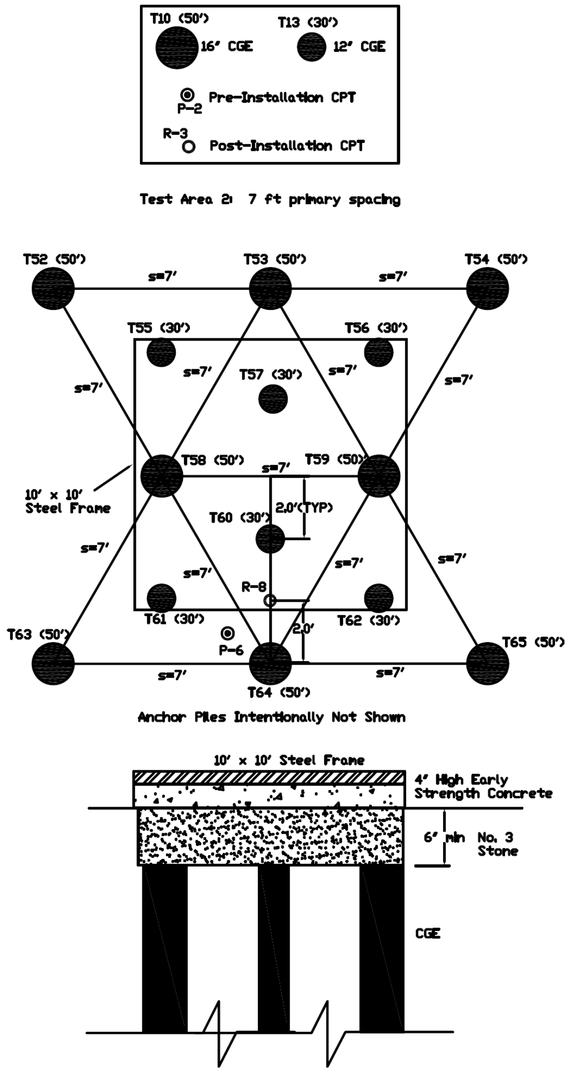

Figure 5. Set Up of Large Plate Test 3

Site Characterization

As illustrated in Figure 6, the project site is located in the city of Owensboro which is along the Ohio River in western Kentucky.

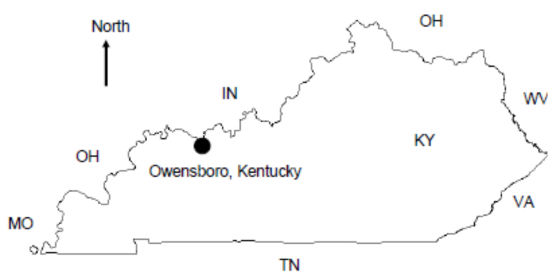

Figure 6. Site Vicinity Map

The relevant subsurface conditions at the site consist of alluvium deposited by the Ohio River and its precursors. The deeper alluvium is predominantly sand and gravel and the upper alluvium is clay and silt (Walker, 1957). Figure 7 graphically presents the results of a cone penetration test performed in the area of the plate tests prior to installation of the CGEs. According to the soil behavior type (SBT) according to the sleeve friction method (Robertson *et al.*, 1986), the upper 27 ft of soil is interbedded and predominately behaves as clay and silt (SBT between 4 and 6). Below 27 ft the soils primarily behave as sand and silty sand (SBT of 8). The corrected cone tip resistance (q_t) in the upper fine-grained soils is generally between 10 and 25 tsf. The q_t in the sand is between 50 and 75 tsf. Dissipation tests showed perched water in the upper interbedded soils and a static ground water groundwater level at a depth of approximately 50 ft.

Geotechnical analyses performed using the CPT data showed that the ultimate bearing capacity for conventional spread foundations averages between 4 and 5 tsf. The soil compressibility in terms of constrained modulus was estimated based on a correlation with q_t and soil behavior type index (I_c) proposed by Robertson (2007). The constrained modulus for the upper fine-grained soil was estimated to typically range between 200 to 250 tsf and was as low as 25 tsf in the very soft zones or pockets.

Plate Test Results

The results of the plate tests are graphically presented in figures 8 thru 11. The results of the small plate test, shown in Figure 8, are expected to illustrate the compressibility of the compacted gravel layer or the cushion. The test was terminated at an applied load of 19 tons which was the practical limit of the system. The Bauer platform was used as a reaction and this equipment began to experience significant tilt at an applied load of 19 tons. The stiffness of the cushion is nearly linear with a value of 45 tons/inch (or a modulus of approximately 385 tsf) within the load range of the test.

In figures 9, 10, and 11 which show the results of the large plate tests that are designated 1,2, and 3, respectively, the uppermost graph is the average plate movement is plotted versus the average stress on the bottom of the plate. The middle graph is load measured in the 16-inch diameter CGEs versus the average stress. The lower graph is the interpreted load distribution

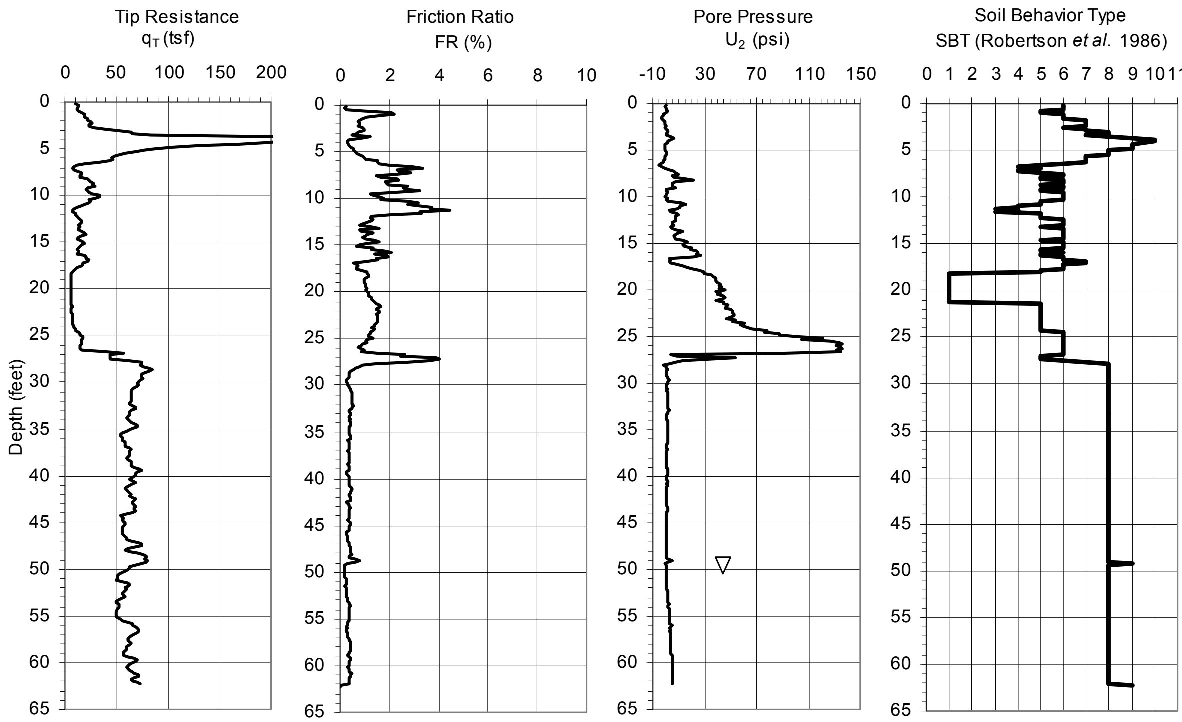

Figure 7. Cone Penetration Test Data for Project Site

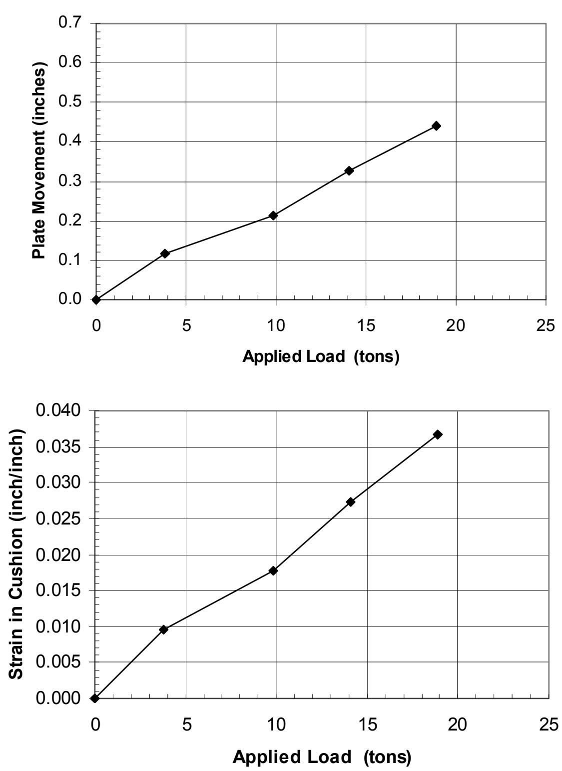

Figure 8. Small Plate Test Results

between the CGEs and the soil subgrade in between CGEs. For the load distribution, it was assumed that the 12-inch diameter CGEs located beneath the plate provided a resistance equal to the average measured load for the two 16-inch diameter CGEs. This assumption was not validated during the testing. There are several factors that determine the actual load distribution including the relative stiffness between the CGE with a cushion and the adjacent soil, the stiffness of the plate, and the stiffness of the soil subgrade that is between the CGEs.

Discussion

The large plate load test results show that a cushion will distribute to the applied load to the CGEs and to the soil subgrade between the CGEs. Therefore, the use of a cushion can reduce the demand on the spread foundation reinforcement and make it less critical that the ultimate axial resistance of the CGE (or any pile element in composite ground) be maintained near a factor-of-safety near unity.

It was apparent during the testing that the plate stiffness had a significant influence on load shared between the CGEs and the soil

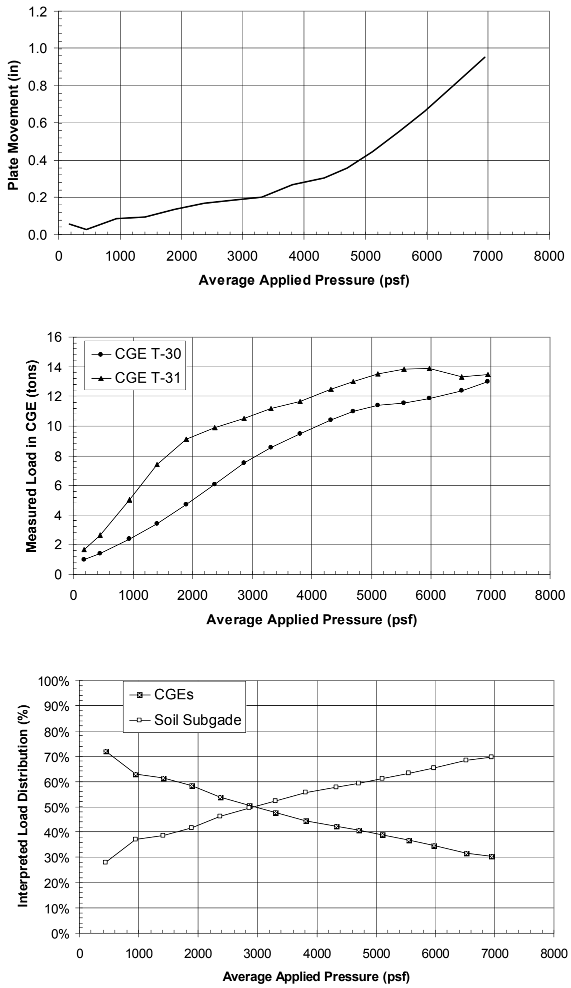

Figure 9. Results for Large Plate Test 1

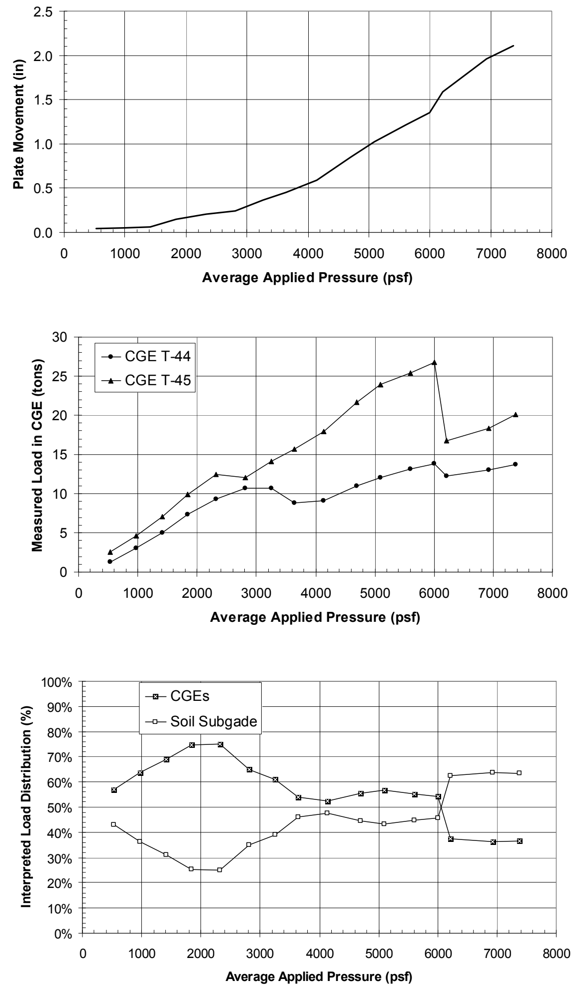

Figure 10. Results for Large Plate Test 2

subgrade. Initial test attempts used only the steel plate without the layer of high early strength concrete. However, the bending of the plate was significant, particularly at higher loads, and the mobilized resistance of the CGEs was much less than expected. The plate embedded into the concrete layer provided a substantially stiffer system and allowed greater mobilization of the available CGE resistance.

Another initial test attempt used a short cylinder-shaped cushion only directly above the CGE rather than a continuous layer beneath the concrete and plate. Again, the mobilized resistance in the CGE was very small. It was not clear during the testing whether the reason for this was the flexing of the plate or excessive bulging of the cushion. Due to time restraints associated with the project schedule, it was decided to eliminate as many testing variables as practical including the potential for excessive lateral bulging of the cushion. Therefore, the subsequent plate tests included a cushion composed of a layer of compacted gravel to provide greater lateral confinement. The plate load tests were very useful in confirming the effectiveness of the compacted gravel layer as a cushion.

It is noted that the measured plate movement for average applied pressure is for the loading conditions (i.e., a typical hold time of 15 minutes). While it may be correctly stated that plate movement had usually stabilized after 15 minutes during testing, it is almost a certainty that soil subgrade contains thick silt zones that would have continue to experience some consolidation settlement under a long term load.

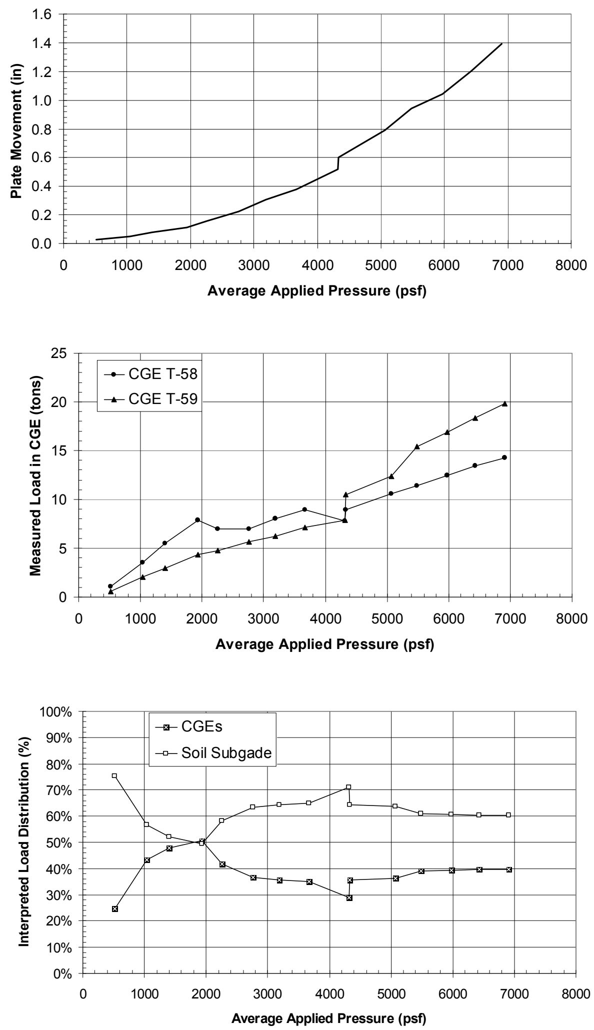

Figure 11. Results for Large Plate Test 3

Application to Design

The distribution of the load between the CGEs and the soil subgrade was determined using the settlement model proposed by Siegel (2011) and the results of the plate tests. As illustrated conceptually in Figure 12, the cushion is designed to compress to an extent compatible with the relative settlement between the CGEs (which are assumed to be rigid) and the soil subgrade. The spread foundation settlement (S_f) is the sum of the compression of the cushion (S_Δ) and the settlement of the CGEs (S_p).

The specified maximum settlement for the project was 1 inch. For design, an S_Δ of 0.5 inches was selected which corresponded to the axial compressive load in each CGE of 25 tons. The sustained pressure on the subgrade of 1000 psf at a settlement of 0.5 inches was calculated

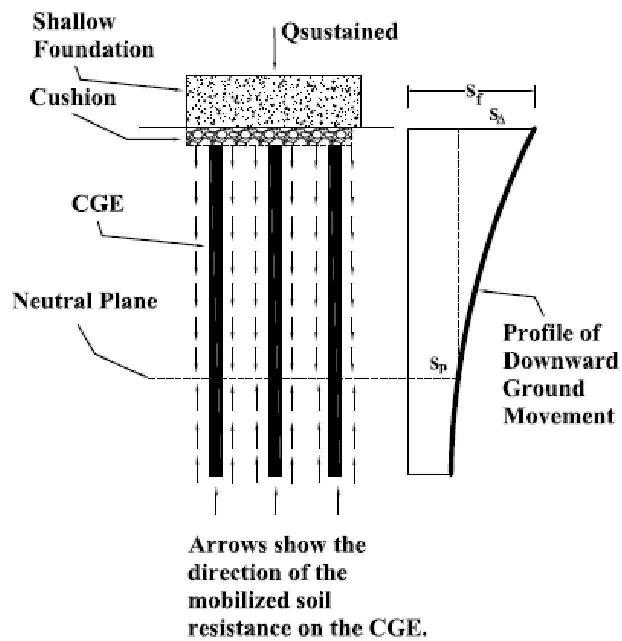

Figure 12. Conceptual Settlement Model of Composite Ground

using conventional settlement analysis and the CPT results. The neutral plane (which is the depth where the direction of the mobilized side resistances reverses from negative to positive) was estimated to be within the sand below a depth of 27 ft. The settlement of the CGEs (S_p) was calculated using the equivalent pier method (Meyerhoff, 1976) where the pier is located at the depth of the neutral plane. The total settlement ($S_f = S_\Delta + S_p$) was estimated for each foundation and checked against the specified maximum settlement.

Note that the settlement analysis for the design conservatively ignored any densification of the upper silt that may have been caused by the CGE installation (i.e., the displacement process). The consolidation settlement of the soil subgrade was estimated based on the Boussinesq stress distribution for an elastic half-space. This is recognized as a simplification as the relatively stiff CGEs will tend to attract stress and lead to a different stress distribution.

Conclusions

This study performed plate tests on composite ground to confirm the design for a new hospital in Owensboro, Kentucky. The composite ground system consisted of groups of cast-in-place grout piles (commercially known as Berkel

CGEs) and compacted gravel as a cushion immediately beneath the bottom of the spread foundation.

The following conclusions are made based on the results of the plate tests:

1. The plate stiffness can influence the results of plate tests on ground with groups of piles (i.e., CGEs in this study). A flexible plate will bend and make it difficult for the system to mobilize the resistance provided by the piles. The use of a concrete layer during plate testing was effective at providing additional stiffness.
2. A cushion consisting of a continuous layer of gravel is believed to provide a greater reliability than a cylinder-shaped cushion above the piles. It is hypothesized that the silt between the piles provided a reduced confinement and allowed the cylinder-shaped cushion to bulge laterally.
3. The cushion is an important component of a composite ground system by allowing mobilization of the soil subgrade resistance and avoiding a stress concentration at the top of the piles that would otherwise be present if the spread foundation and piles were rigidly connected. Thus, there is a reduced structural demand and potentially a decrease in the cost of the foundation reinforcement.

Final Remarks

Several foundations for the new Owensboro hospital are being monitored for vertical movement during construction of the superstructure that will extend through 2011. At the preparation time of this paper (mid 2011) the settlement of the foundations due to only part of the structural load (primarily the structural steel) has been negligible.

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