SUPPORT OF HIGH RISE BUILDING ON ORGANIC AND ALLUVIAL DEPOSITS USING RIGID INCLUSIONS

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Abstract: Densified Aggregate Piers have been used extensively for support of low to high rise structures since the late 1990's. These systems are constructed by backfilling cylindrical cavities with densified stone, whereby the columns exhibit a higher axial stiffness than the matrix soil resulting in a composite mass of soil that has less compressibility and higher shear strength characteristics. Densified aggregate piers systems are confining stress dependent, thereby tending to have lower capacities in organic and very weak soils because of their propensity to bulge and expand into very weak confining soil materials. Therefore, as the application of ground improvement has continued to expand further into high rise structures, typically 30 stories or less, over the last 10 years, densified aggregate piers have become less applicable to sites with highly compressible organics or thick compressible alluvial deposits; particularly for more heavily loaded structures. Rigid inclusions can be a type of densified aggregate pier or ground improvement element that typically has cementitious properties to provide bulging resistance of the ground improvement element resulting in providing increased bearing and settlement control in poor soil environments.

This paper presents the results from the installation of GeoConcrete® elements, a type of rigid inclusion, for support of a 14-story office building with adjacent 8.5 story pre-cast parking garage in New Haven, Connecticut. The rigid inclusions were installed through soft organic silt and loose sand deposits bearing in medium dense sands 30 feet below grade. This paper presents the design considerations through the ground improvement solution, the innovative quality control program used during construction and the results of the full-scale load testing program. Ultimately, the rigid inclusion elements exceeded the performance requirements for the project and provided suitable support and settlement control for the proposed structure. This project is of particular importance because it demonstrates that the quality control method used for rigid inclusion installation is a key consideration in verifying the element quality and capacity.

I INTRODUCTION

The Downtown Crossing project is a multiphase residential and office-space development intended to revitalize a critical area of Downtown New Haven, Connecticut (Figure 1). The first phase of the project included construction of the 100 College Street building, a 450,000 square foot pharmaceutical research facility. Phases II and III would include the addition of an adjacent parking structure to the office building and the replacement of an existing expressway with walking and bicycle paths to reconnect Downtown New Haven, the Hill neighborhood, the Medical District, and Union Station and will provide additional opportunity for mixed use developments including residential, office space, public areas, and ground level retail.

Figure 1: Site location map

The first phase of the project, specifically the 14-story "100 College Street Building", is the subject of this paper. The structure is at the terminus of the existing Route 34 highway which enters and exits the building at a depressed level (Figure 2). As such, the foundation scheme for the structure resulted in a heavily loaded central core and two "outrigger" strip mats on each side of the roadway. The design resulted in isolated spread footings with loads more than 4,100 kips, wall loads ranging from 10 to 62 kips per linear foot, and mat pressures ranging from 5 ksf to 7.8 ksf. Wind loads governed the transient loading, increasing mat pressures by up to 3.8 ksf.

Figure 2: Photo of completed structure, illustrating Route 34 below the building, central core loading and "outrigger footings'

II SOIL CONDITIONS

A total of 38 soil borings were performed in the immediate vicinity of the office building and garage. Boring depths ranged from 21 to 121 feet below grade. Subsurface explorations generally encountered granular fill extending to depths of 4 to 20 feet, overlying a 2 to 4 ft thick layer of highly compressible peat, followed by a thick deposit of natural sand and silt extending to depths of 68 to 110 feet, where dense glacial till or sandstone bedrock was encountered. The sand and silt layer is loose to medium dense through nearly the entire thickness, with SPT N-Values of approximately 10 to 20 blows per foot in the upper 50 feet of the layer. Blow counts increased between 20 and 30 in the bottom portion of the sand & ilt layer. Groundwater was encountered at depths of 6 to 12 feet below grade. Figure 3 below illustrates a simplified soil profile for the project site.

Of interest is the elevation of the peat layer, generally located at the bottom of footing elevation, as well as the very thick deposit of medium dense sand. These led to geotechnical challenges for the design team.

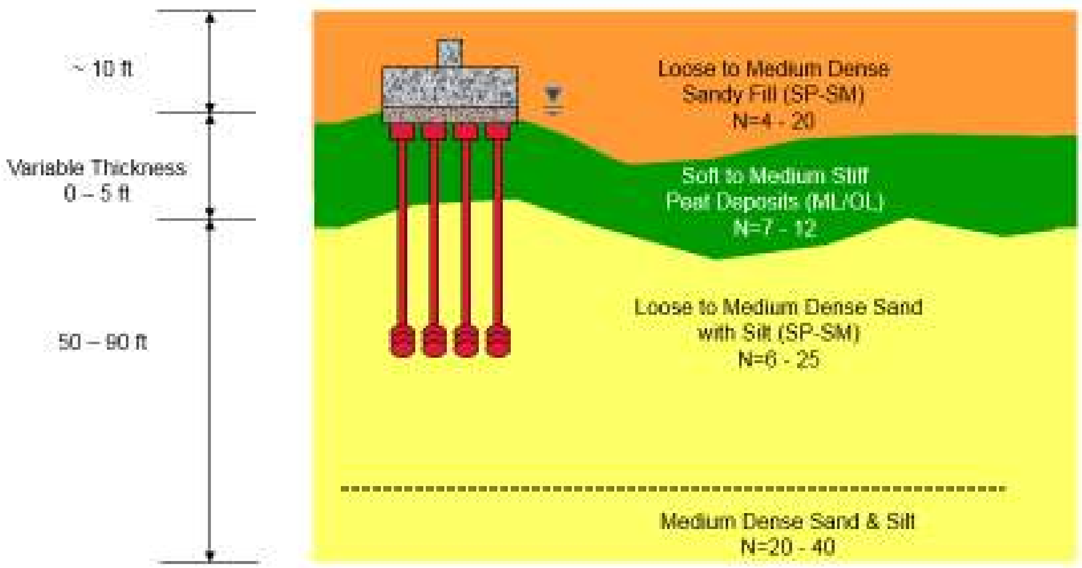

Figure 3: Simplified soil profile

III PROJECT CHALLENGES

The primary geotechnical challenge identified by the geotechnical engineer of record, (*McPhail Associates)*, was developing a foundation solution that would meet the project budget, schedule, and total and differential settlement performance requirements considering the heavy loads of the structure and the shallow compressible organic layers and loose to medium dense sand deposits. Several foundation support options were considered as viable options and consisted of the following

- Shallow Foundations: Traditional mat foundations and shallow spread footings were considered for technical and commercial viability. This option was ruled out because of construction risks associated with high groundwater and high costs associated with removal and replacement of the of the shallow sand and organics with better suited structural fill. This option also resulted in settlement that exceeded the project requirements.

- Deep Foundations: Augercast piles and driven piles have been used successfully in the project vicinity. The pile options would provide reliable performance although more costly than desired by the design team because of the long pile length requirements.

- Aggregate Pier Ground Improvement: Aggregate piers have the advantage that a higher allowable bearing pressure can often be provided than native soil or structural fill can afford and eliminate the need to remove undocumented fill or other unsuitable soil. This often lends to savings in the total foundation costs. Aggregate piers are confining stress dependent, however, and this option was not selected because of the high settlement and long-term performance risk with not removing the organic layer near the foundation elevations for the heavily loaded structure.

IV PROPOSED FOUNDATION SOLUTION

Given the subsurface conditions, structural loading, and performance requirements, McPhail Associates recommended the structure be supported by rigid inclusions. GeoConcrete Column® (GCC) elements were selected because of their high stiffness, superior load transfer characteristics, and ability to provide high allowable design bearing pressures. The GCC elements provided significant costs savings over other foundation options and the high production rates provided an expedited project schedule.

The rigid inclusions GCC elements support the structure on traditional spread footings which extend through the fill, organics, and very loose soil to achieve superior load transfer through shaft friction and ending bearing resistance in the medium dense native sands. The footing and top of the rigid inclusions are separated by an engineered footing pad to provide structural separation between the ground improvement elements to reduce the potential for transferring lateral loads to the tops of the rigid inclusions. A typical footing detail is shown in Figure 4. Support of floor slabs and flexible pavement for the Route 34 roadway was not required. The ground improvement design is discussed in more detail below.

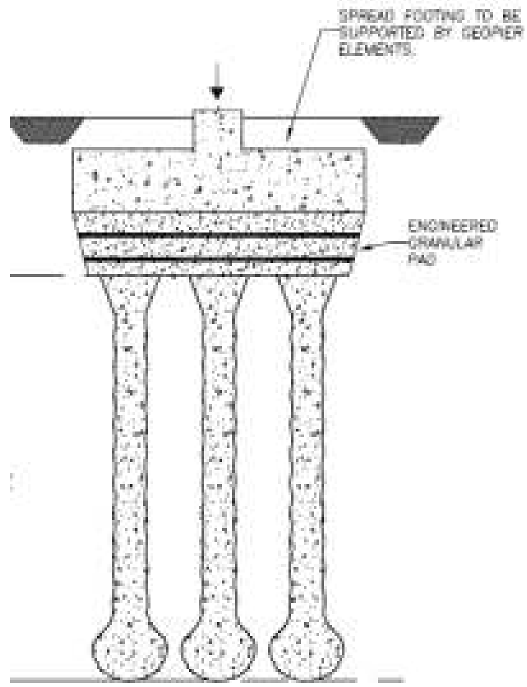

Figure 4: Typical Footing Detail

V DESIGN APPROACH

Rigid Inclusions are grouted or concreted columns that have superior strength and stiffness over traditional aggregate pier elements. They are used to transfer stress from the foundation through very soft or loose soil deposits to stiffer and less compressible soil layers. The elements have relatively high structural capacity and stiffness, with design unconfined compressive strengths of the grouted or concrete elements ranging from 1,000 to 5,000 psi depending on the diameter of the elements and required load capacity.

The result of the high structural capacity and high stiffness is that the foundation stresses are attracted to the rigid inclusions, transferring the stress deeper into the soil profile where more confinement and stiffness is present. The base of the GCC elements are constructed by vertically ramming concrete to form an expanded base, the system exhibits outstanding bearing capacity performance with great coupling with the densified matrix soil.

The geotechnical and axial structural capacity are evaluated using traditional methods and the design capacity selected based on the governing working capacity. The design for this project included 150-kip design capacity elements that were installed through the fill, organics, and loose sand to achieve geotechnical capacity in the medium dense sand. Footings were designed for an allowable bearing pressure of up to 9.5 ksf. Figure 5 illustrates the GCC element layout under the office building footprint with pressure contours highlighted under the central core and “outrigger footings” supported on each site of the Route 34 alignment.

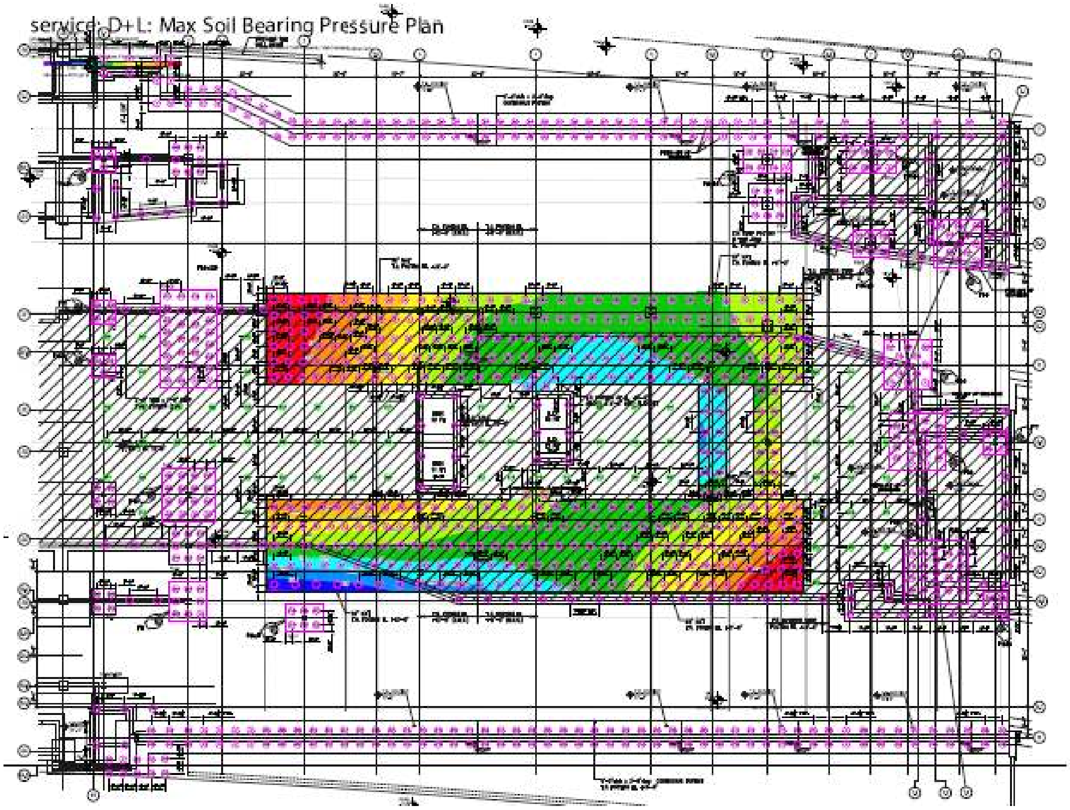

Figure 5: GCC Layout for Office Building

The GCCs are typically overlain by a separation layer or layers that may consist of a mud mat or expanded tops for providing more efficient load transfer from the footing to the top of the piers and / or with an engineered footing pad that can consist of compacted select granular material, cement treated aggregate, or sand. Design of the separation layer and footing pad can vary depending on pier diameter, element capacity, bearing stress, and soil conditions at the bottom of footing.

The engineered footing pad serves three primary purposes:

(1) Creates a shear break between the rigid inclusion and the spread footing,

(2) Adds vertical "ductility" to the system, and

(3) Helps distribute the spread footing load to the rigid inclusions, which limits the potential for punching and prevents large stress concentrations at the bottom of the footing.

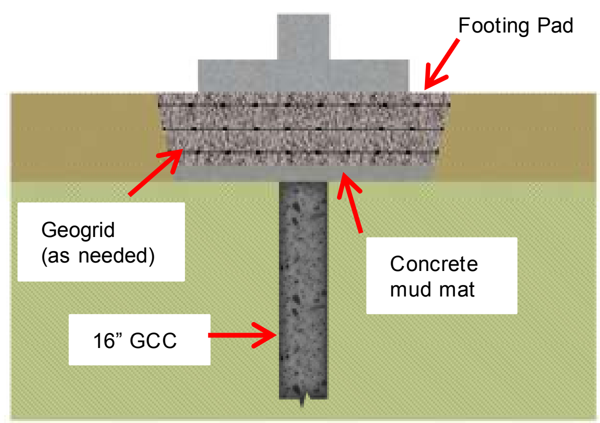

Figure 6 – Footing Pad Detail

Most of the footings on this project consisted of a combination of a mud mat or cement treated aggregate and crushed aggregate (Figure 6). The thickness of the mud mat was up to 10 inches, and the footing pad was generally 12-inches. The rigid inclusion system, including the GCCs and the footing pads, were designed to limit the post-construction settlements for the 14-story office building to 1.5-inch total and 1-inch differentially. Since the engineered footing pad will compress from the high bearing pressure applied by the footings, one layer of Tensar geogrid was also used to help facilitate compaction of the footing pad and reduce the compressibility of the pad. GCCs were generally installed to depths of 25 feet below the bottom of the mud mat.

VI INSTALLATION AND QUALITY CONTROL

The rigid inclusions used on this project were constructed by driving a closed-system displacement mandrel charged with concrete down to the competent bearing layer. The mandrel is outfitted with a valve at the tip that prevents soil from advancing up into the mandrel. Once the design depth is achieved, the mandrel is stroked up and down to build an expanded concrete base to optimize load transfer into the bearing layer. Following base construction, the mandrel is withdrawn while maintaining a positive internal pressure so that concrete is extruded into the columnar soil cavity created by the mandrel. Figure 7 shows a photograph of the construction equipment.

Once constructed, the top of the rigid inclusion is excavated down to the bottom of the footing pad/mudmat elevation (i.e., while the concrete is still fluid). This practice helps avoid damaging the element after the concrete cures and eliminates the need for chipping down the top of the element.

Figure 7: GCC Construction Equipment, including ABI mast rig, concrete pump, concrete truck

One of the benefits of the particular rigid inclusion system used is that it allows for robust quality control monitoring during construction. Being a closed system, the air that remains in the mandrel is subject to the Ideal Gas Law (PV=nRT), where "P" is the mandrel air pressure, "V" is the mandrel air volume, "n" is the number of moles of air in the mandrel (constant), "R" is a constant, and "T" is the temperature in degrees Kelvin (assumed to be constant). Each mandrel, having a fixed internal volume, has a specific air pressure-volume relationship that can be calibrated on the job site. Once the calibration has been established, the volume of concrete placed during construction can easily be determined.

By monitoring the change in air pressure during specific times during the construction process, the precise quantity of concrete delivered at each stage can be measured. This process provides unmatched quality control compared to other rigid inclusion systems. At all times during the build process, the air pressure can be predicted. Conversely, by confirming that the construction pressures are being maintained at various stages during the process, the geotechnical engineer observing construction has high confidence in the product being delivered.

The pressure-volume relationship and build process are closely tied and are described below. Italicized words correspond to stages of construction as illustrated below in Figure 8.

- As the *initial* concrete is pumped into the sealed mandrel, the concrete displaces/compresses the air in the mandrel, increasing the internal air pressure of the system.

- As the mandrel is advanced to the design depth in the *drive* stage of construction, concrete is added to the system. The air pressure continues to rise. When the calibrated pump strokes have delivered the prescribed volume of concrete, the predicted air pressure can be confirmed by the quality control personnel.

- During the *bulb* construction phase, the mandrel is raised and the air pressure extrudes the concrete into the cavity. The pressure is observed to drop corresponding to the precise volume of concrete extruded. To create the rammed bottom bulb, the mandrel is raised and driven down a prescribed number of times to deliver a selected quantity of concrete at the bearing elevation. A one-way valve only allows concrete to escape the mandrel but is forced closed on the downstroke to force the concrete aggregate outward into the matrix soil.

- When bulb construction is complete, the volume of concrete expelled from the mandrel can be measured and calculated from the air pressure dial gauge. The shaft is constructed as the mandrel is *withdrawn* from the pier, continually expelling concrete through the one-way valve, under pressure, to fill the cavity created by the mandrel. The air pressure at all depths within the shaft construction can be predicted by the air-volume relationship (PV-nRT) and confirmed by quality control personnel during construction.

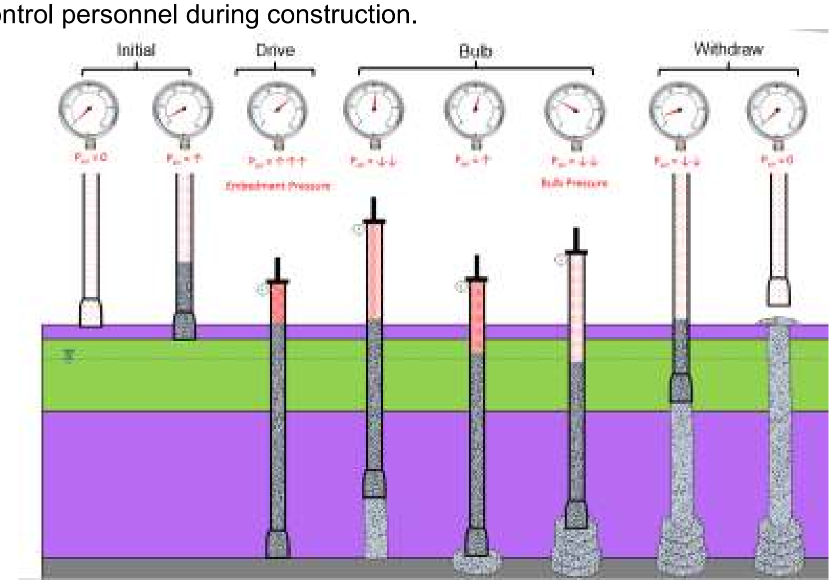

Figure 8: GCC construction sequence, indicating air pressure and volume relationship with each stage of pier construction

VII TEST PROGRAM

To demonstrate performance on this project, an elaborate test program was conducted to exhibit performance of the GeoConcrete columns and the engineered footing pad.

A. Test Setup

The test program included installing a group of 3 GCC elements, constructing a thickened mud mat and engineered footing pad, and performing a load test. Instrumentation included telltales and total pressure cells to measure deflections of the footing pad and GCC elements and to determine load transfer behavior through the system. The test program was installed with the bottom of footing bearing within the very soft peat layer, with the entire footing pad and tops of GCC elements within the very soft peat. Elements were installed as indicated in Figure 9.

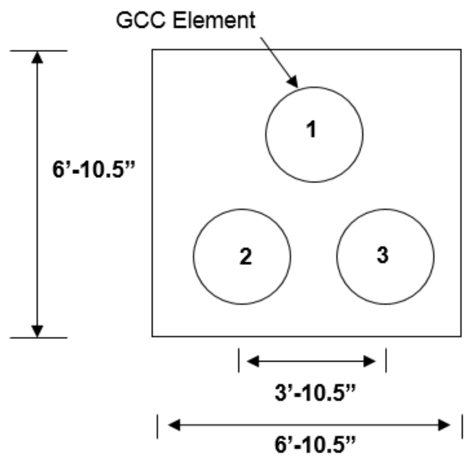

Figure 9: GCC Test Setup

B. Instrumentation

The test incorporated Geokon Model 4800-7.5MPa pressure cells on the top of each GCC elements, and Geokon Model 4815-7.5MPa pressure cells directly in contact with the bottom of footing and at the bottom of the engineered footing pad (both in the center of the footing, directly over each other). Pressure cells were bedded in a thin layer of sand for leveling. Telltales were placed at the top and bottom of each GCC element. Telltales were also attached to the Model 4815 pressure cells, enabling a direct measurement of the compression of the footing pad. Telltales were sleeved in PVC and the footing was cast up to the working grade. Deflection of the footing and telltales were measured with dial gauges to a precision of 0.001 inches. Figure 10 illustrates pressure plate installation over piers and between piers on the matrix soil, located below the mud mat layer.

Figure 10 – Pressure Cells Bedded in Sand

C. Load Test Result

The load test was performed in 2 cycles and followed appropriate portions of ASTM D 1143 (Pile Load Test Procedures) and ASTM D 1194 (Spread Footing Load Tests). The first footing load achieved 675 kips in approximate 75-kip increments. The second load cycle stepped in 150 kip increments to achieve a maximum footing load of 900 kips. The test protocol also included 60-minute creep testing at the 117% design load and an 8-hour hold at 200% design load. Deflections during these load increments are illustrated in Figure 11. At the design load (150 kips per pier, 450-kip footing load), the GCCs deflected approximately 0.1 inches, and the footing deflected approximately 0.2 inches at a footing stress of 9.5 ksf. The footing pad compression measured was approximately 0.1 inches. It can also be seen that at approximately 700 kips (233 kips per element) and 15 ksf footing stress the GCC elements deflected ½ inch while the gravel pad compressed about 0.4 inches, thereby indicating that the design and compaction of the gravel pad is a key design component that must be accounted for; particularly at high bearing stresses, as noted in the following section.

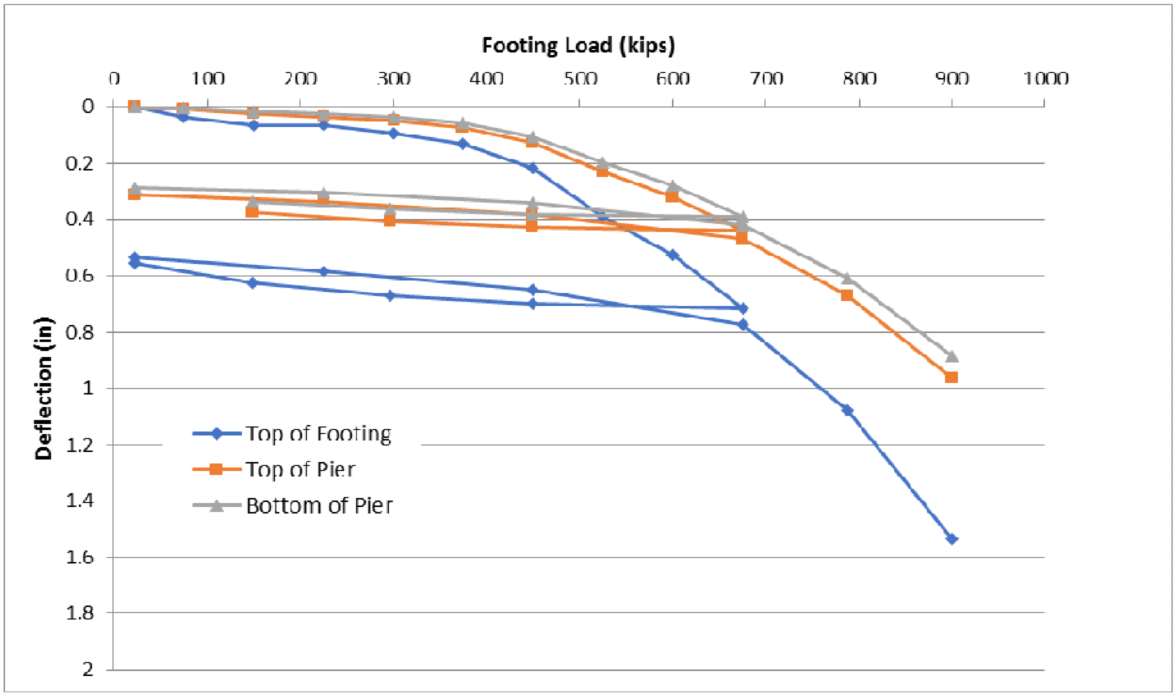

Figure 11 – Load Test Results - Measured Deflections

In addition to the outstanding performance of the GCC elements and engineered footing pad, useful insight to the performance of the footing pad is gained from the pressure plate measurements in conjunction with the telltale measurements. First, the pressure plates confirm that the footing pad serves to arch the footing load to the rigid inclusions. The pressure plate at the bottom of footing measured the bottom of footing contact stress between the GCC columns. We note that the measured bottom of footing stress is less than the average footing stress expected for a uniform bearing pressure of 9 ksf at design load. This is likely because of stress re-distribution in the footing and stress concentration to the GCC elements. The pressure plate between the piers at the bottom of the footing pad measured essentially no increase in stress, and the pressure plates on the tops of the piers measured transfer of the bottom of footing stress to the tops of the piers. Figure 12 below illustrates the averaged pressure plate results.

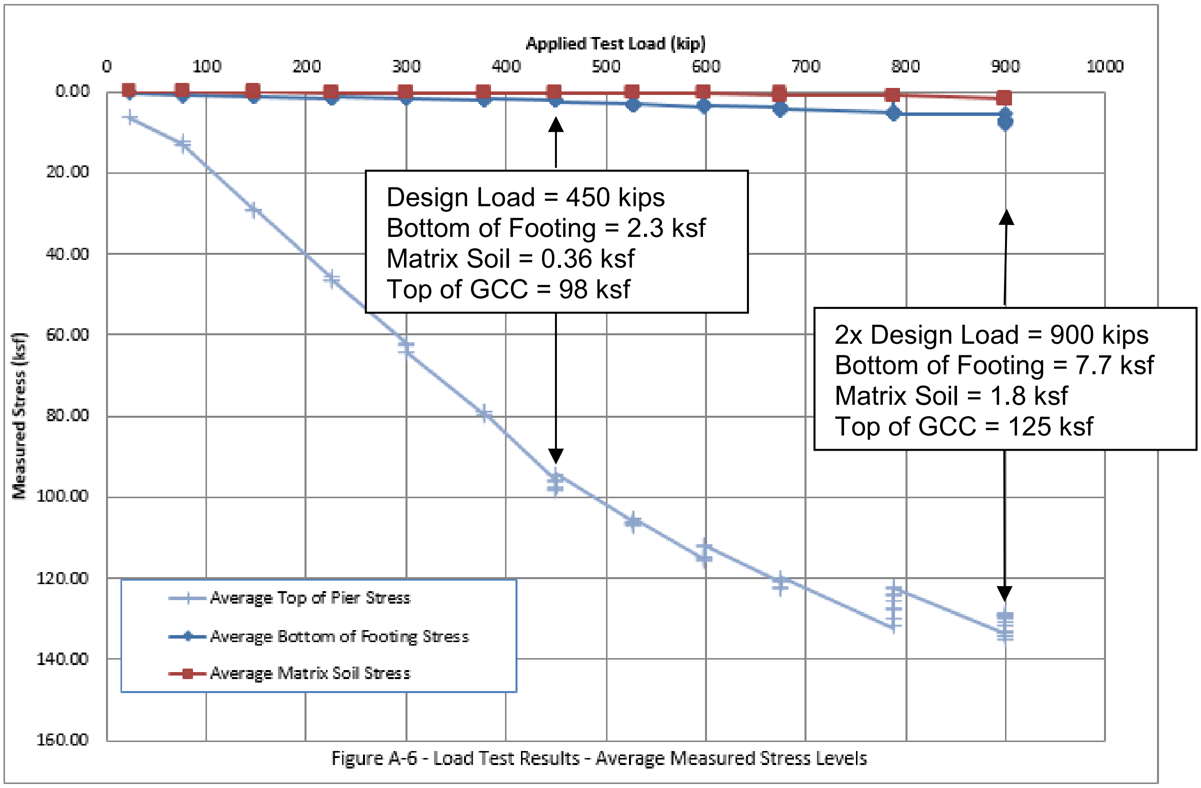

Figure 12 – Load Test Results – Averaged Measured Stress Levels

Second, the test illustrates that the footing pad contributes a substantial portion to the total settlements. Table 1 below summarizes results. At moderate stress levels on the top of the rigid inclusion (60 to 100 ksf), fairly small contribution results from the 12-inch thick footing pad. However, top of pier stress levels in excess of 100 ksf quickly add substantial settlement to the rigid inclusion system. Independent testing by the authors (not included in this study) indicate similar results, with pad compression on the order of 1-inch for stress levels near 150 ksf on 12-inch thick footing pads. As a result of this, and other test programs, GCC elements are typically installed with 4 to 6-inch thick footing pads to minimize settlement and maximize building performance.

Applied Axial Load (kips)	Top of Pier Stress (ksf)	Footing Pad Deflection (in)
150	29	0.04
300	62	0.04
450	98	0.1
600	115	0.21
900	125	0.6

Table 1: Footing Pad Compression

VII CONCLUSIONS

Ground improvement has been used with increasing frequency in the last 25 years in the US to manage challenging soil conditions. For this project, compressible peat at the bottom of footing and loose to medium dense sand extending far below the proposed structure made conventional foundations ineffective. GeoConcrete elements (GCCs) proved to be a cost effective, high performing foundation system by exhibiting superior load transfer in the medium dense sands with a unique footing pad solution to manage soft organics at the bottom of footing.

A full-scale footing test was performed at the project site, demonstrating that the GCC system would support the design loads within project settlement tolerances. The pressure-volume relationship that is inherent in the GCC installation method provided a high degree of quality control accuracy with precision predictions and measurements of concrete delivery during installation. The test program also illustrated that the footing pad system works to effectively transfer footing loads to the GCC elements, and that highly stressed footing pads can add an appreciable amount of total settlement to the project that must be incorporated in to total settlement predictions.

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