Ground Improvement for Foundation Support in Organic Soils

Brian C. Metcalfe, P.E[1]., Kord J. Wissmann, Ph.D, P.E.[2], Stephen S. Weyda, P.E.[3], Bruce Bush, G.I.T.[4]

1. Geopier Foundation Company, Inc., 130 Harbour Place Drive, Suite 280, Davidson, North Carolina, 28036; e-mail bmetcalfe@geopier.com
2. Geopier Foundation Company, Inc., 130 Harbour Place Drive, Suite 280, Davidson, North Carolina, 28036; e-mail kwissmann@geopier.com
3. Ground Improvement Engineering, 3950 Woodridge Court, Colgate, Wisconsin, 53017; e-mail sweyda@groundimprovementeng.com
4. Geopier Foundation Company, Inc., 130 Harbour Place Drive, Suite 280, Davidson, North Carolina, 28036; e-mail bbush@geopier.com

ABSTRACT

Twenty years ago, most buildings in the United States were supported by either shallow spread footings or deep foundations. Since then, "intermediate" ground improvement options have increased in use, providing building owners, contractors, and engineers with a host of options each with its own unique design and construction characteristics. Loose sands are now often densified, and soft cohesive soils are reinforced with displacement or replacement aggregate piers prior to shallow foundation construction. For heavier loads and softer soils, the subsurface materials are often now reinforced with "rigid inclusions", typically consisting of cementitious columnar elements installed by either driven-displacement or drilling methods. Organic soils, such as those typically found in New England, the upper Midwest, and the Pacific Northwest almost always require "improvement" prior to shallow foundation construction because of their inherent compressibility under even small loads. In certain conditions, the organic materials can be reinforced by non-cemented aggregate piers, provided care is used in the appropriate selection of pier stresses to avoid the pier "bulging" and long-term settlement performance issues. In other conditions, such as when the thickness of the organic soils is large, when the loads are heavy, or when the consequences of settlement are severe, more robust solutions, such as those provided by rigid inclusions are necessary. This paper provides the results of multiple case histories in which organic soils have been reinforced by both confined aggregate and cemented ground improvement elements.

INTRODUCTION

Ground improvement has been utilized to provide practical and economical solutions to challenging geotechnical projects for decades (Mitchell 1981) with most of the historical applications consisting of densification or drainage of the native ground to support area fills. Increasingly over the last 20 years, ground improvement has seen rapid expansion as one of the many tools available to geotechnical and structural engineers, general contractors, owners and developers, for the support of conventional loads.

Over this time aggregate piers have increasingly been implemented as an alternative to over-excavation and replacement and deep foundation systems. Aggregate piers are often suitable for a wide range of soil conditions from soft clay to loose sand and to a lesser extent, relatively thin organic soil deposits, depending on organic content, compressibility and loading conditions. The overall applicability of aggregate piers depends on the soil conditions, loading conditions and sound geotechnical engineering analyses to verify that project performance specifications will be achieved.

Fox and Edil (2000) present several case histories of projects where uncemented aggregate pier elements were implemented in organics soil deposits. Over the last 10 years, columnar elements that are not confining-stress-dependent, such as rigid inclusions or confined aggregate piers, have been increasingly implemented to control settlement of structures in very soft or organic soil deposits. Rigid inclusions typically consist of aggregate columns with cementitious binder, or batched quantities of sand-cement, and concrete. Confined aggregate piers typically consist of compacted aggregate within a pre-installed extensible shell. The primary purpose of these types of ground improvement elements is to either prevent bulging of the aggregate or to completely bypass the compressible layer and transfer foundation loads to a less compressible soil layer. This paper presents three case histories where rigid inclusions and confined aggregate piers were utilized in organics soil deposits to control foundation settlements to tolerable levels.

SEVEN04 PLACE APARTMENTS, MILWAUKEE, WISCONSIN

The first case history presents foundation and floor slab support for a four-story apartment building in Milwaukee, Wisconsin. The site is located east of Interstate 43/94 at the northwest corner of W. National Avenue and South 7th Street. The project loading conditions consisted of maximum column loads of 310 kilonewtons (kN), wall loads of 120 kilonewtons per meter (kN/m), and floor slab pressures of 7 kilopascals (kPa). Grade-raise fill of up to 1 meter of was required to reached finished floor elevations.

The generalized soil profile interpreted from the project soil boring logs is shown in Figure 1 with soil conditions consisting of as much as 1.5 meters of loose to dense sand fill overlying 2.5 to 3 meters of very soft peat and organic silt underlain by layers of stiff clay and medium dense sand extending to depths of 23 meters. Groundwater was encountered within the organic layers at depths of 2.5 to 3 meters.

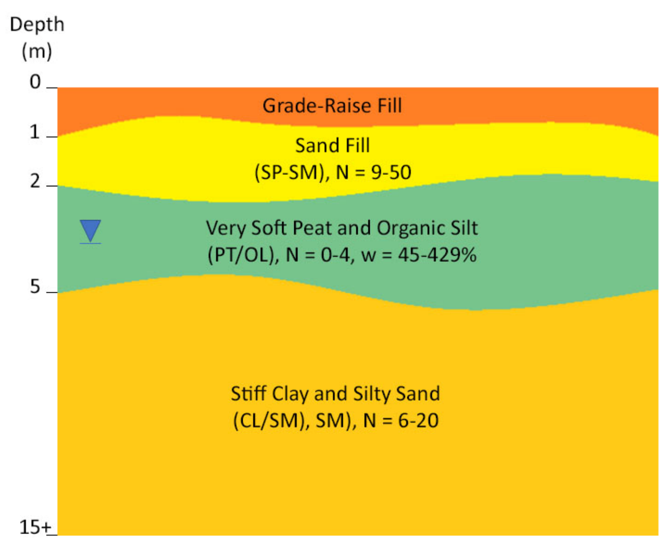

Figure 1. Seven04 Place Apartment subsurface conditions.

Project challenges and foundation support options

The primary foundation option was to install H-piles to depths of 23 meters below grade because of the risk of long-term settlement associated with grade-raise fill and building loads. The floor slab was also planned to be supported by H-piles. Wick drains and surcharging were also considered for slab support to accelerate primary and secondary settlement of the floor slab area.

Ground improvement was provided to the design team as an alternate to the options mentioned above. Although unconfined/uncemented aggregate piers were considered, the preferred ground improvement option for foundation support was to install confined aggregate piers below the foundations to limit bulging potential and provide long-term settlement performance of aggregate pier supported foundations. Using this method, floor slab support could then be supported with aggregate piers, as described by Fox and Edil (2000). The ground improvement option was ultimately selected and constructed because it compared favorably to the more costly deep foundation structural slab option. A 50 to 100 cm surcharge was utilized above the finished floor elevation to accelerate settlement and reduce the potential for secondary compression of the organics resulting from the grade raise fill and slab pressure.

Confined aggregate pier foundation design and construction approach

Confined aggregate piers consist of the use of a high density polyethylene (HDPE) closed-ended sleeve that provides lateral confinement of the pier through the soft and organics soil, creating a very stiff element. The elements are constructed using a displacement method by inserting a hollow mandrel within 475 to 600 mm diameter and 10 mm thick conical HDPE sleeves and driving them to the design depths using static crowd force augmented by a high frequency vibratory hammer delivering vertical driving energy.

The HDPE sleeve remains in place after driving to the design depth. Aggregate is then placed inside the hopper propagating to the bottom of the mandrel and into sleeve. The aggregate is compacted in lifts by incrementally raising and lowering of the mandrel using hydraulic crowd force and vertical ramming from the high frequency vibratory hammer. The process densifies the aggregate vertically and causes the sleeve to expand slightly outward against the soft native soil. The top of the HDPE shell is situated slightly above the organic layer and once the mandrel is raised above the sleeve a conventional compacted aggregate pier element is constructed above the shell to the bottom of footing elevation. A photograph of the typical confined aggregate pier installation is shown in Figure 2a and a general schematic construction of the finished product in Figure 2b.

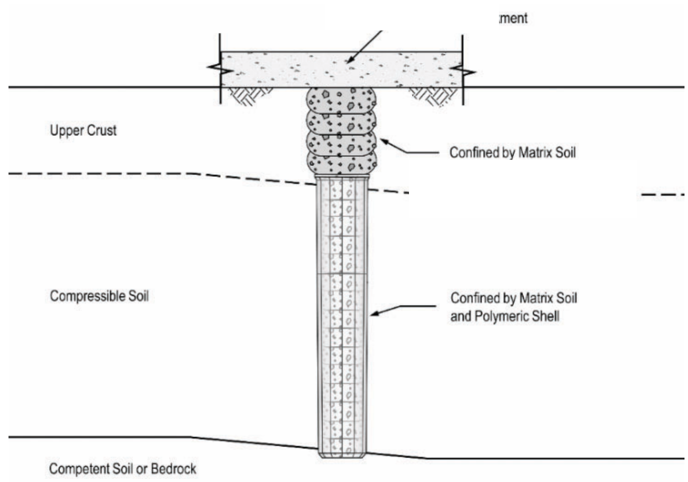

Figure 2(a). Installation of confined aggregate pier with outer HDPE sleeve;
(b) Confined aggregate pier schematic

The confined aggregate piers were installed below column and strip footings with an allowable confined aggregate pier load of 200 kN, resulting in 1 to 2 elements per column and additional elements were installed at 2.3 to 2.9 meters on center below strip footings for wall support. A minimum 30 cm compacted aggregate pier was constructed between the HDPE sleeve and the footing bottom where pier confinement was not required and to reduce potential for damage to the HDPE from footing excavation.

A modulus load test was performed in general conformance with ASTM D-1143 to verify the stiffness and behavior of the elements. A telltale was installed at the top of the confining sleeve to measure the deformation of the aggregate stem and at the bottom of the confining sleeve to measure the tip movement of the element. The modulus test results are presented in Figure 3 and show total deformations of about 13 mm at the design load. The telltales show that the compression of the aggregate stem is about 2 mm with 11 mm of the composite confining sleeve and aggregate deformation. The bottom telltale showed no movement indicating all the compression was within the ground improvement element.

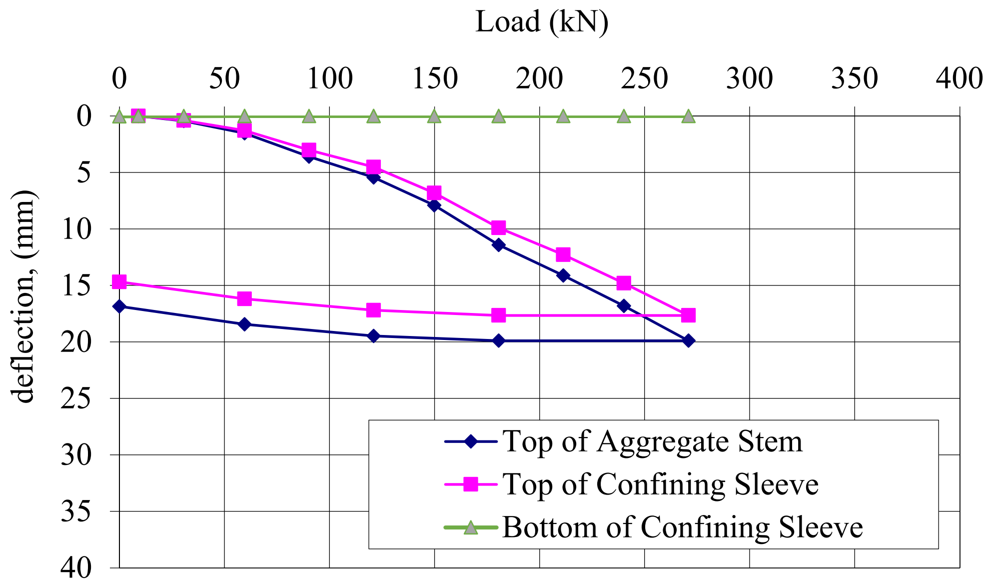

Figure 3. Confined aggregate pier modulus test

The floor slab was supported by displacement aggregate piers without confining sleeves (Wissmann, et al., 2015). The piers were spaced at 2.5 to 3.0 meters on center and installed prior to raising site grades to provide an increase in composite stiffness and provide radial drainage to help accelerate consolidation of the organic soil. This unique ground improvement system saved the project owner hundreds of thousands of dollars compared to support provided by traditional deep foundations.

MIXED USE BUILDING, FONTANA-ON-GENEVA LAKE, WISCONSIN

The second case history presents foundation and floor slab support for a two-story mixed-use building in Fontana-On-Geneva Lake, Wisconsin. The site is in southeastern Wisconsin near Geneva Lake. Foundation support was needed for relatively light column loads of 225 kN, wall loads of 35 kN/m, and floor slab pressure of 7 kPa. Grade raise fill of up to 1.2 meters was required to finished floor elevation.

The generalized soil profile is shown in Figure 4 and consist of 1.5 meters of loose to medium dense sand fill overlying 4 to 6 meters of very soft organic silt and peat seams underlain by medium stiff to stiff clay to a depth of 15 meters. Groundwater was encountered within the organic layers at depths of 2.5 to 3 meters.

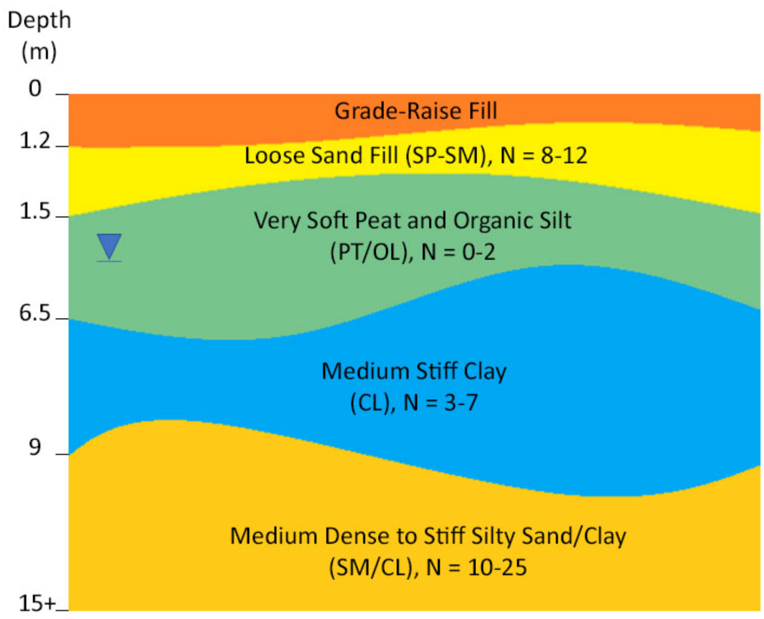

Figure 4. Mixed-use building soil profile.

Project challenges and foundation support options

It was recognized by the project geotechnical engineer that significant long-term settlements would occur for footings and slabs bearing on untreated subgrades. The grade raise fill would further compound the settlement issues. For this reason, the primary foundation option consisted of helical piers or driven piles and structurally supported slab.

Ground improvement was proposed as a value engineering alternative to replace the deep foundation and structural slab option. A similar design approach was taken for this site as the Seven04 Apartments site. Grouted aggregate piers were selected for foundation support to provide cementitious elements that will convey the foundation loads through the organic soil and develop support and settlement control from the underlying very stiff soil deposits. Conventional displacement aggregate piers were then utilized to support the grade raise fill and floor slab including a 1-meter surcharge.

Grouted aggregate pier foundation design and construction

Grouted aggregate piers are a type of rigid inclusions element that consists of constructing displacement aggregate piers with a neat cement slurry added to the aggregate mix during construction. The grouted aggregate pier is constructed using a hollow-pipe mandrel that has typical pipe diameters of 300 to 400 mm. Open-graded aggregate, such as #57 stone, is added to the pipe mandrel by a top mounted hopper and neat cement slurry is dosed into the mandrel to create a gravel and cement slurry mix. The mandrel and hopper are attached to a fixed leader mast and high frequency vibratory hammer mounted to a base excavator. The mandrel is driven to the design depth using the hydraulic crowd pressure and vertical vibratory action of the hammer as the gravel and grout mixture is added. Once the piers reach the planned tip elevation, the aggregate and grout mix are compacted in lifts to the ground surface. The cement slurry can be either batched on site, typically using colloidal mixers and holding tanks, or can be delivered in ready mix trucks.

Typical grout and aggregate mixes result in an unconfined compressive strength of 10 to 17 MPa. Figure 5 show typical installation of the grouted aggregate pier.

Figure 5. Grouted aggregate pier construction

The ground improvement system was installed prior to raising site grades to take advantage of the radial drainage of the floor slab piers. The grouted aggregate piers were installed below the foundations to depths of 7.5 to 9 meters below grade penetrating into the very stiff clay and medium dense sand deposits. The grout was discontinued at depths of 30 to 60 cm below the bottom of footing elevation to provide uncemented aggregate pier elements through the sand fill to reduce the potential for "hard spots' below the foundations. Floor slab support was provided using uncemented aggregate piers at spacing of 2.5 to 2.75 m on-center and fully penetrating through the organic soil. Following installation of foundation and slab piers, the grade raise fill was constructed and a 1-meter thick surcharge was added to help accelerate the grade raise fill settlement and reduce the potential for long-term settlement of the organic soil below the floor slab. Settlement of 30 to 60 mm were measured from the approximate 2 meters of grade-raise and surcharge fill heights occurring over a three- to four-week monitoring period.

DOWNTOWN CROSSING PROJECT, NEW HAVEN CONNECTICUT

The Downtown Crossing project is a multiphase residential and office-space development intended to revitalize a critical area of New Haven, Connecticut. This case history presents the geotechnical design, construction, and testing program for a 14-story office building. The structure is at the terminus of the existing Route 34 highway which enters and exits the building at a lower elevation than surrounding grades (Figure 6a). 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 greater than 18,250 kilonewtons, wall loads ranging from 145 to 905 kilonewtons per meter, and mat pressures ranging from 240 to 375 kilopascals. Wind loads governed the transient loading, increasing mat pressures by up to an additional 180 kilopascals.

Subsurface explorations (Figure 6b) generally encountered granular fill extending to depths of 1.5 to 5 meters overlying a 1.5-meter-thick layer of highly compressible peat, underlain by a thick deposit of natural sand and silt extending to depths of 20 to 30 meters, where dense glacial till or sandstone bedrock was encountered. Groundwater was encountered at depths of about 2.5 meters below grade.

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.

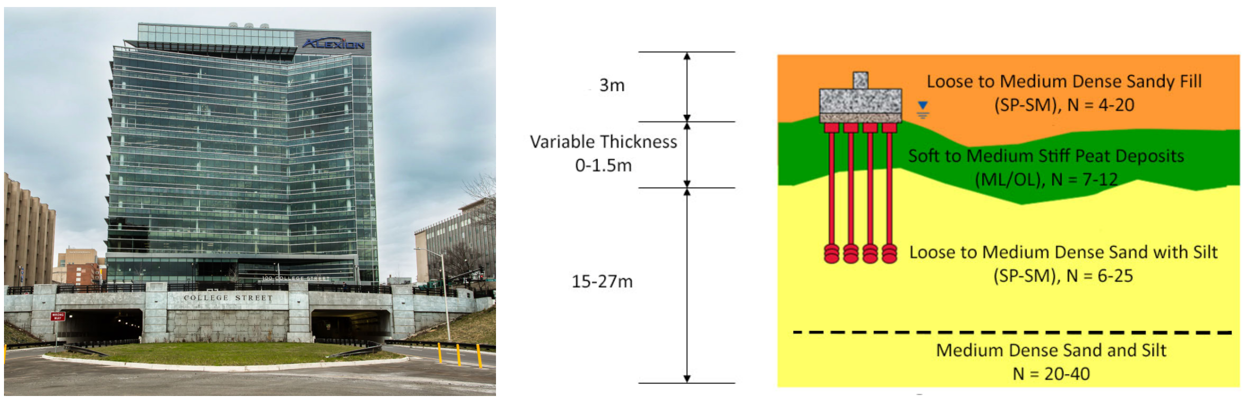

Figure 6. (a) Photo of completed structure with Route 34 below the building; (b) generalized soil profile

Project challenges and foundation support options

Several foundation support options were considered as viable options and included the removal and replacement of the organic soil layer followed by mat foundation or deep foundations. The mat foundation option was not preferred because of the requirements to remove the organic soil layer and associated substantial shoring and dewatering. The piled foundation option was considered a viable option to provide relatively conventional design and construction procedures. As an alternative to traditional methods, the design team selected a rigid inclusion ground improvement system consisting of displacement concrete columns known as GeoConcrete Columns® (Kraemer, et al., 2018). The specific rigid inclusion system was selected because of the high stiffness, superior load transfer characteristics, and ability to provide high allowable design bearing pressures. The concrete rigid inclusions elements provided significant costs savings over other foundation options and the high production rates provided an expedited project schedule.

Rigid inclusion foundation design and construction

The type of rigid inclusion ground improvement system for this project is installed by driving an open-ended displacement mandrel with a closed top (Fig. 7a) to the design depth, partially filling the mandrel with concrete, (thereby increasing the air pressure in the closed system) and extruding the concrete as the mandrel is raised. A specially designed valve is used in the driving head to compact the concrete at the bottom of the pier to provide for an expanded base head used for efficient transfer. 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.

One of the benefits of the particular rigid inclusion system used is that, being a closed system, it allows for recording of internal air pressure within the mandrel and the Ideal Gas Law can be used as a quality control measurement of concrete extruded at the tip of the mandrel. The Ideal Gas Law is expressed as 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. The pressure-volume relationship and build process are closely tied and illustrated in Figure 7b.

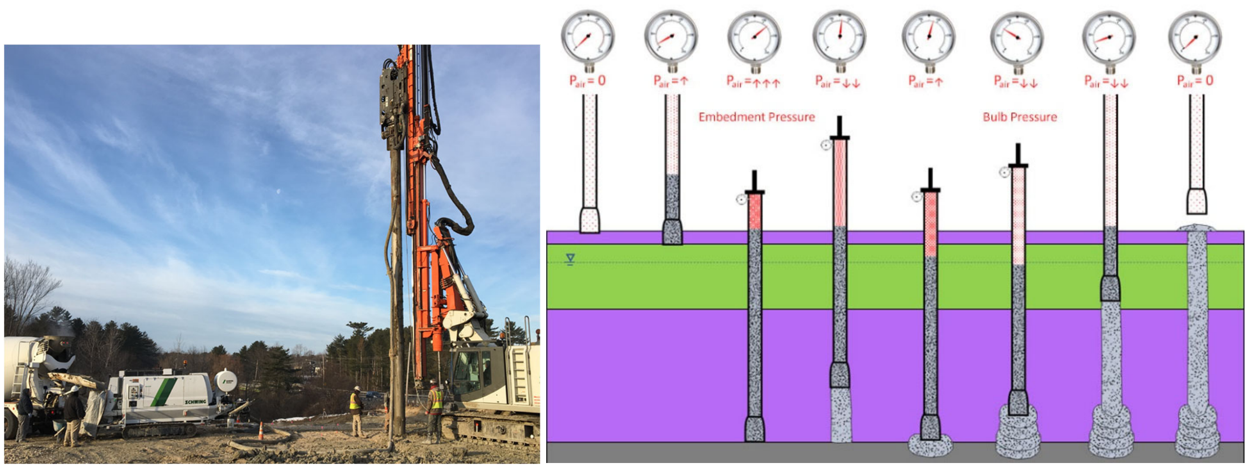

Figure 7: (a) Rigid inclusion construction; (b) Construction sequence, indicating air pressure – volume relationship with each stage construction

The rigid inclusions were each designed for an allowable capacity of 667 kN. Footings were designed for a maximum bearing pressure of 455 kPa. Figure 8a illustrates the rigid inclusion element layout under the office building footprint with bearing pressure contours highlighted below the central core and "outrigger footings" supported on each side of the Route 34 alignment. The footings are designed to have an engineered granular pad (footing pad) as structural separation between the rigid inclusions and footings to reduce the potential for transferring lateral loads to the tops of the rigid inclusions. Once constructed, the top of the rigid inclusion is typically excavated down or drilled out to the bottom of the footing pad 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. A typical footing detail is shown in Figure 8b.

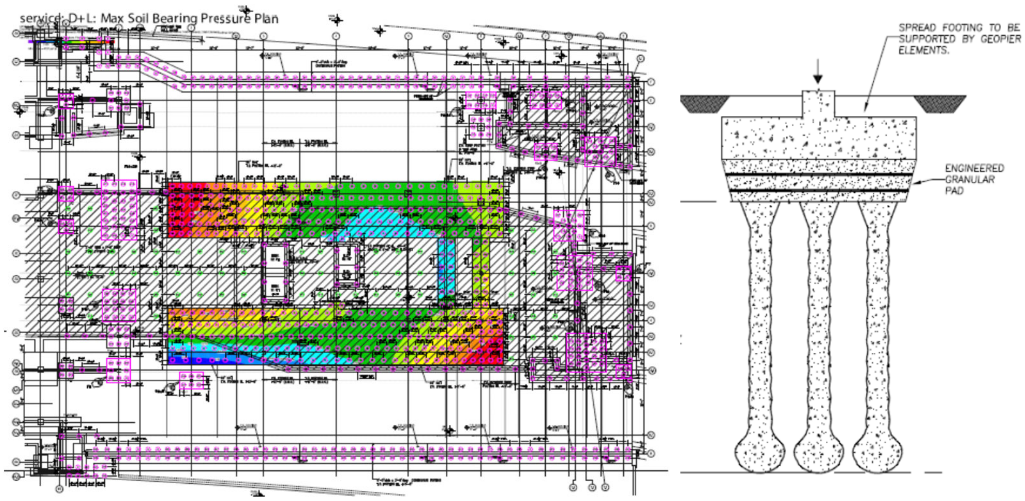

Figure 8: (a) Rigid inclusion layout; (b) Typical footing pad detail

Testing Program

The test program included installing a group of 3 rigid inclusion elements (Fig. 9a), constructing a thickened mud mat and engineered footing pad as per the project specifications for footing construction on the project. A group footing load test was performed on the 3 pier group to demonstrate performance on this project. Instrumentation included telltales and total pressure cells to measure deflections of the top of the cast-in-place concrete footing, footing pad, the rigid inclusion elements, and to determine load transfer behavior through the system. The test program was installed with the bottom of footing bearing within the peat layer and with the entire footing pad and tops of GCC elements within the peat.

The test incorporated Geokon Model 4800-7.5MPa pressure cells on the top of each rigid inclusion, 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. Figure 9b illustrates pressure plate installation over piers and between piers on the matrix soil, located below the mud mat layer.

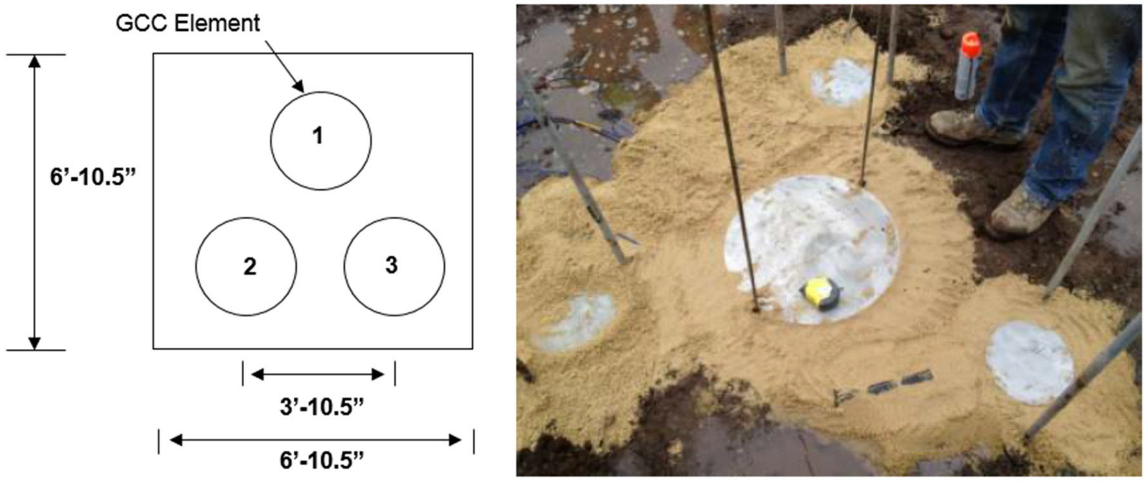

Figure 9: (a) Rigid inclusion test layout; (b) Test instrumentation showing telltales and total stress pressure plates.

The load test results are shown in Figure 10. The first footing load cycle was performed up to 3,000 kN (150% of design) in approximate 333-kN increments. The second load cycle stepped in 667 kN increments to achieve a maximum footing load of 4,000 kN (200% of design). At the design load of 2,000 kN (667 kN kips per element), the footing deflected 5 mm and the rigid inclusions deflected 2.5 mm, thereby indicating that the footing pad compression was one-half of the total deflection. It is important to note that the footing pad compression at higher footing stresses is a key design component to the total footing settlement that must be accounted for in design.

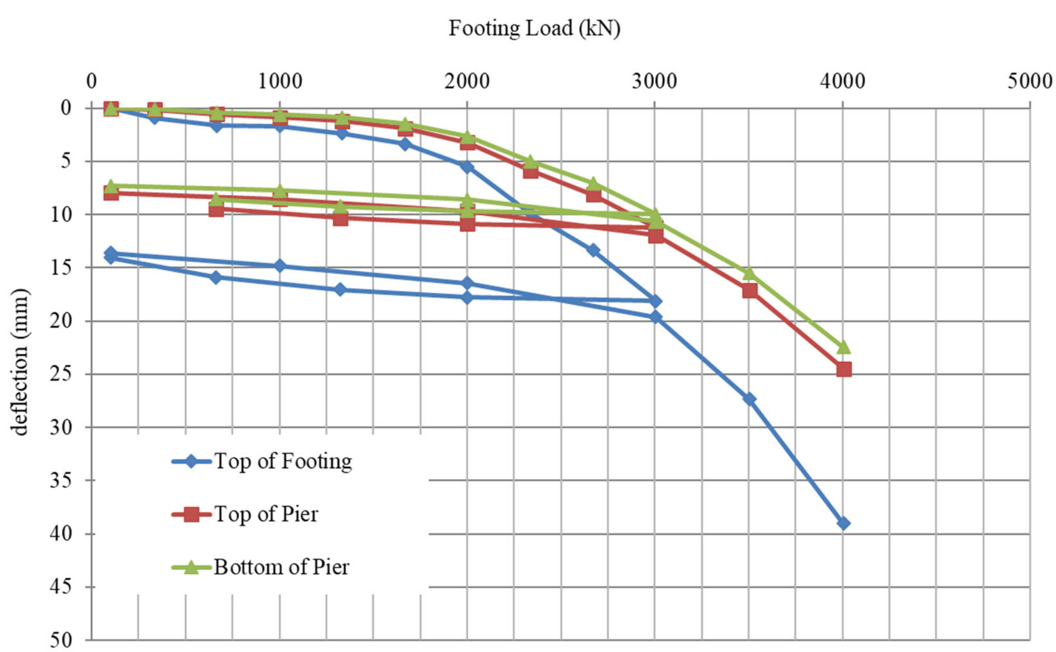

Figure 10. Load Test Results - Measured Deflections

The pressure plates provided good insight and confirm that the footing pad arches 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. 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 11 below illustrates the averaged pressure plate results.

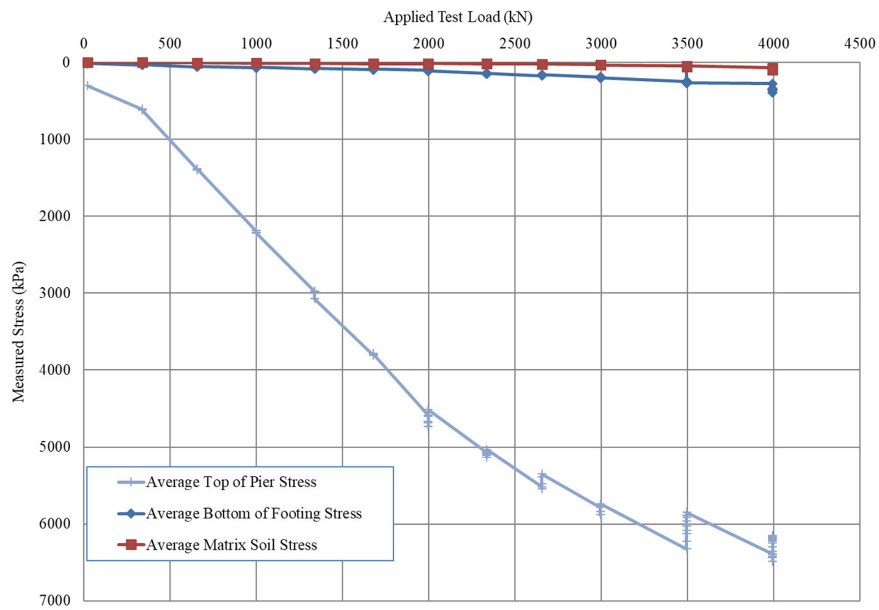

Figure 11. Averaged measured stresses at top of rigid inclusions and matrix soil

The footing load test demonstrated outstanding performance of the rigid inclusion system with the footing bearing within the soft peat layer. Settlement of 5 mm was recorded at the design load of 2,000 kN and 20 mm at 3,000 kN (150% of design load). The granular footing pad is an important design component, resulting in about one-half of the total top-of-footing settlement measured.

CONCLUSIONS

Ground improvement for foundation support in organic soils has been implemented for decades. Uncemented or unconfined aggregate piers can be used, when appropriate, and with careful attention to the thickness and compressibility of the organic soil layer, and the consequences of long-term behavior of the organics and the soil and aggregate pier behavior. More commonly, rigid inclusions or confined aggregate piers with polymeric sleeves are being utilized for organic soil sites to reduce the risks of poor long-term performance in these soil types. This paper presented three case histories where three different types of ground improvement systems were utilized to provide control of foundation settlement using confined and grouted / cemented aggregate elements that resulted in significant savings compared to traditional foundation support methods.

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