RIGID INCLUSION SYSTEM SUPPORTS MULTI-STORY RESIDENTIAL AND PARKING GARAGE STRUCTURES IN ORGANIC SOIL PROFILE

Steven R. Kraemer, P.E., [1] **Robert B. Condon, P.E.,**[2] **and Kord Wissmann, Ph.D., P.E., D.GE**[3]

[1] Haley & Aldrich, Inc., 465 Medford Street, Suite 2200, Boston, MA, 02129; email: skraemer@haleyaldrich.com
[2] Geopier Foundation Company, 130 Harbour Place Drive, Suite 280, Davidson, North Carolina, 28036; email: rcondon@geopier.com
[3] Geopier Foundation Company, 130 Harbour Place Drive, Suite 280, Davidson, North Carolina, 28036; email: kwissmann@geopier.com

ABSTRACT

Boston is notorious for challenging soils. The highly organic peat and variable fill soils littered throughout the City commonly result in risk of unfavorable settlements of buildings if supported on shallow foundations or the need for expensive deep foundation solutions. However, due to advancements in ground improvement, aggregate piers and rigid inclusions are rapidly becoming a preferred foundation solution at such challenging sites. This paper discusses one such site, for which both rigid inclusions and aggregate piers were used to reinforce urban fill and organic soils for support of a 5-story parking garage and the surrounding mixed-use structures. The paper walks through the ground improvement solution, the innovative quality control program used during construction, and the results of the 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 QC method used for rigid inclusion installation is a key consideration in verifying the element quality and capacity.

PROJECT BACKGROUND

The 5.5-acre project site, located at 600 Rivers Edge Drive in Medford, Massachusetts, is approximately 500 feet west of the Malden River (Figure 1). The development consists of two 4- to 5-story residential structures abutting a 5-story parking structure. Typical column loads are in the range of 175 to 1,940 kips, and typical wall loads are in the range of 7 to 38 kips per linear foot. The occupied ground floors are concrete slabs-on-grade. Existing site grade at the time of foundation installation in 2015 was el. +19 feet (+/- 1 foot), and the ground floors were finished at el. +21.

Figure 1: Site Location

SUBSURFACE INVESTIGATIONS AND CONDITIONS

Multiple phases of geotechnical subsurface explorations were performed at the project site over the years for various purposes. The most recent program, performed in 2014 by Haley & Aldrich, consisted of 15 test borings and geoprobes supplemented by six groundwater observation wells.

In general, site subsurface conditions consist of 7 to 17 feet of miscellaneous, typically granular fill underlain by 4 to 10 feet of organic soils. The total thickness of the fill and organic deposits range between about 11 to 17 feet. A complex and highly variable stratigraphy is present directly beneath the organic soils, consisting locally of estuarine sand; medium dense poorly graded fluvial/marine sand; medium dense silty sand; or medium stiff to stiff marine silt and/or clay. The remaining profile beneath these variable upper deposits consists of up to 70 feet of marine deposits (medium dense silt and very soft to stiff silty clay) which are underlain by dense glacial deposits and ultimately bedrock. Groundwater is typically at depths of about 10 to 13 feet below grade (el. +9 to el. +6). Figure 2 shows an example generalized profile of the upper soils at the site.

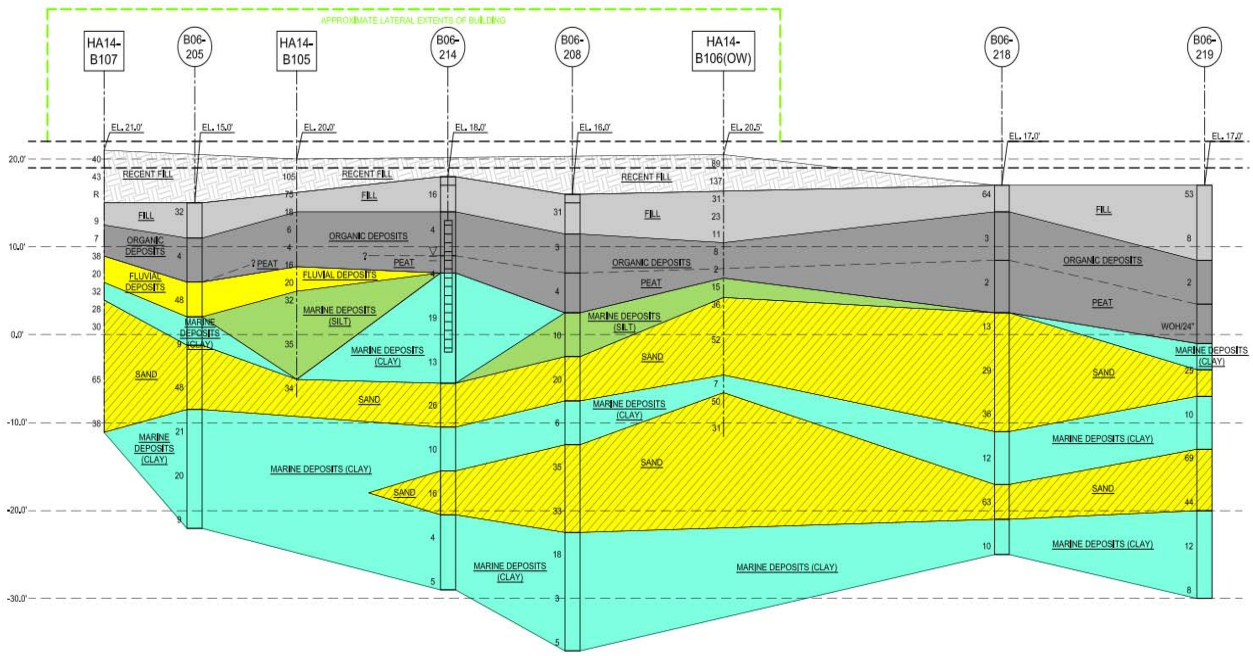

Figure 2: Typical Subsurface Profile (Figure created by Haley & Aldrich)

PROJECT CHALLENGE

The primary geotechnical challenge for the project was developing a cost-effective foundation system that would limit total and differential settlements of the structures. Haley & Aldrich evaluated the following foundation systems that ultimately were deemed inappropriate for the site conditions and proposed construction:

- Shallow Foundations: Conventional shallow spread footing foundations bearing in the unaltered existing fill and organic soils were deemed infeasible due to the uncertainties of foundation performance, likelihood of excessive settlements, inadequate factors of safety against bearing capacity failure due to the shallow depth of the weak organic soils below footing bearing levels, as well as Building Code issues.

- Removal and Replacement: Removal and replacement of the unsuitable soils was deemed both impractical and cost-prohibitive given the thickness of the fill and organic soils and the relatively shallow depth to groundwater.
- Pressure-Injected Footings (PIFs, also known as Expanded Base Piles): PIFs were used to support an adjacent structure; however, the cost if implemented at the subject buildings was determined to be significantly greater than the final engineered solution.
- Belled Caissons: The Marine Deposits were not stiff or consistent enough to provide sufficient end bearing for a cost-effective belled caisson solution. Further, the belling strata contained lenses and zones of cohesionless soils that could make belling difficult or unsafe.
- Deep End-Bearing Piles: While technically feasible, deep driven piles would extend to depths in the range of 125 to 145 feet, resulting in a cost prohibitive solution.

PROPOSED FOUNDATION SOLUTION

Given the site subsurface conditions and nature of the proposed structures, Haley & Aldrich recommend the structures be supported on reinforced concrete spread footings after implementation of a ground improvement program.

Because of the relatively high column loads and the presence of undocumented fills and organic soils below the footings, Haley & Aldrich decided that the column and wall footings would be supported on soils modified using rigid inclusions extending through the fill and organic soils and bearing in the underlying medium dense/stiff inorganic soils. The more lightly loaded concrete slabs-on-grade could be supported on either cemented or uncemented elements. The ground improvement design is discussed in more detail below.

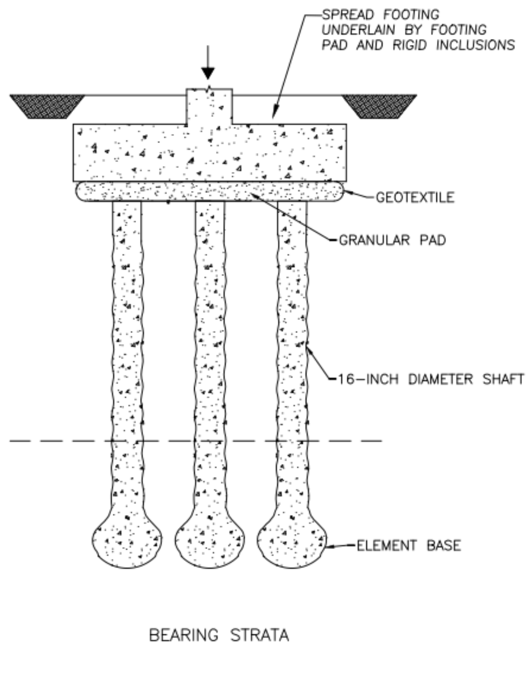

Figure 3: Typical System Configuration

FOUNDATION DESIGN

As noted, the proposed footing foundations were designed to be supported on soils improved with rigid inclusions. Rigid inclusions are grouted or concrete columns that are used to transfer stresses from foundation or embankment loads through very soft/organic soils down to stiffer bearing layers. The elements have a relatively high structural capacity and a high stiffness (particularly compared to the surrounding soils). The high stiffness of the elements compared to the surrounding soils causes the foundation stresses to be attracted to the rigid inclusion elements, forcing the foundation stresses to bypass the very soft/organic soils (via the rigid inclusions) and into the stiffer/denser bearing soils. The transfer of stress through the very soft/organic soils and into the stiffer/denser bearing soils enables control of total and differential settlements of the supported structure to acceptable values.

The rigid inclusion design for this project consists of 75-kip design capacity elements that completely penetrate the fill and organic soils and typically extend at least 5 feet into the underlying naturally-deposited inorganic soils. The rigid inclusions are overlain by an 8-inch thick granular pad that serves three primary purposes: (1) the pad creates a shear break between the rigid inclusion and the spread footing, (2) the pad provides vertical "ductility" to the system, and (3) the pad 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 3 schematically depicts the rigid inclusions, granular pad and overlying spread footing.

The rigid inclusion system design was developed to limit total settlements in the reinforced zone to 1 inch in the parking garage and ¾ inch in the residential buildings. Differential settlements in the reinforced zone were to be limited to ½ inch between column bays or over a distance of 25 feet for continuous footings. Additional components of settlement in the range of ¾ to 1½ inch were anticipated due to consolidation of the underlying marine clay. Note that post-construction settlement monitoring was not performed; however, there have been no reports of unfavorable total and/or differential settlements.

FLOOR SLAB DESIGN

Key areas of the ground floor slabs were designed to be supported on a grid of ungrouted aggregate piers, primarily in the residential structures. The grid spacing depended on the applied slab loads, but typically was in the range of 8 to 10 feet on-center. The aggregate piers were designed to extend through the existing fill and organic soils to tag the underlying inorganic soil deposits.

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

One of the most important aspects to the overall performance of the rigid inclusion system for this project was verifying the base of the elements were seated in competent bearing soils. To verify the elements were bearing on suitable soils, the mandrel was advanced through the fill and organic soils down to the anticipated top of the natural, inorganic soils (based on the borings). Once the anticipated design depth was achieved, an in-situ testing method referred to as crowd stabilization testing (CST) was performed to verify the fill and organic soils were penetrated and competent bearing soils were reached. CST testing consists of using crowd pressure from the mast rig to apply downward vertical force to the mandrel and then monitoring the amount of deflection in the soil. If the CST yielded satisfactory results (i.e., small displacement), it was inferred that suitable bearing material had been encountered. The mandrel was then advanced an additional 5 feet (to meet the design minimum embedment of 5 feet into suitable bearing soils) and the rigid inclusion was constructed as described above. If the CST results were not satisfactory, the mandrel was advanced an additional 5 feet and the process was repeated until suitable bearing material was confirmed (as determined by the CST).

Note that the CST testing did not serve to evaluate the long-term settlement characteristics of the bearing soils, just the suitability of the soils for use as an end bearing strata. Settlement of the underling soils was estimated using elastic compression or consolidation theory (as appropriate).

One of the benefits of the particular rigid inclusion system used on this project 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.

As concrete is pumped into the mandrel, the concrete displaces/compresses the air in the mandrel, increasing the internal air pressure of the system. The opposite occurs when concrete exits the bottom of the mandrel (i.e., when concrete is extruded to construct the rigid inclusion element). As the volume of concrete in the mandrel reduces, the air pressure in the mandrel/system decreases. By utilizing the pressure-volume relationship calibrated for the specific mandrel, one can track the measured air pressures and confirm the volume of concrete that enters/exits the mandrel at any stage during element construction. Further, one can apply these principles to accurately define the air pressure required to construct a quality rigid inclusion element or the air pressure change that yields a given volume of placed concrete.

A sample QC summary form is shown in Figure 4. The summary details the strokes required during each stage of construction, as well as the pressures at various stages of element construction. By checking the air pressure and pump strokes during installation, the QC representative can easily determine if the rigid inclusion has been properly constructed.

Pier		Design Capacity (kips)	Design Depth (feet)		Design Shaft Length (feet)	Theoretical Concrete Volume (cf)	Pump Calibration (cf/stroke)	Rigid Inclusion Construction					System Pressure (psi)		Pier Volume (cf)
No.	Type		Planned	Actual				Initial Strokes	Drive Strokes	Bulb Strokes	Withdrawal Strokes	Total Strokes	Initial Emb.	Bulb	
1	RI	75	19	20	13.3	31.8	0.7	9	23	3	8	43	49	19	30.1
2	RI	75	19	20	13.3	31.8	0.7	9	23	3	8	43	46	15	30.1
3	RI	75	19	20	13.3	31.8	0.7	9	23	3	8	43	50	24	30.1
4	RI	75	19	20	13.3	31.8	0.7	9	23	3	8	43	36	15	30.1
5	RI	75	19	20	13.3	31.8	0.7	9	23	3	8	43	41	17	30.1

Figure 4: QC Summary Form

FIELD TESTING PROGRAM

Haley & Aldrich required that a field testing program be performed to confirm the constructability of the rigid inclusion elements, the settlement characteristics of the elements under loading, and the behavior of the system (rigid inclusion, granular pad, and footing) under loading. Two full-scale load tests were performed: one on a stand-alone rigid inclusion element; the second on a rigid inclusion element overlain by a 12-inch thick granular pad and a 40-inch by 40-inch concrete footing. Test locations were selected to represent ground conditions that were judged to generally be "least favorable" for element bearing.

Figure 5 is a diagram of the test conditions at the stand-alone rigid inclusion. As shown in the diagram, the test element was installed through the fill and organic soils and about 2 to 3 feet into the underlying Marine Deposit (note that the production piers extended 5 feet into the variable naturally-deposited inorganic soils). The element was installed with an approximately 29- to 30-inch diameter expanded base and a 16-inch diameter shaft. The rigid inclusion was outfitted with telltales at the bottom of the element, and a steel pipe sleeve was placed at the top of the element to provide confinement and friction isolation under the test load.

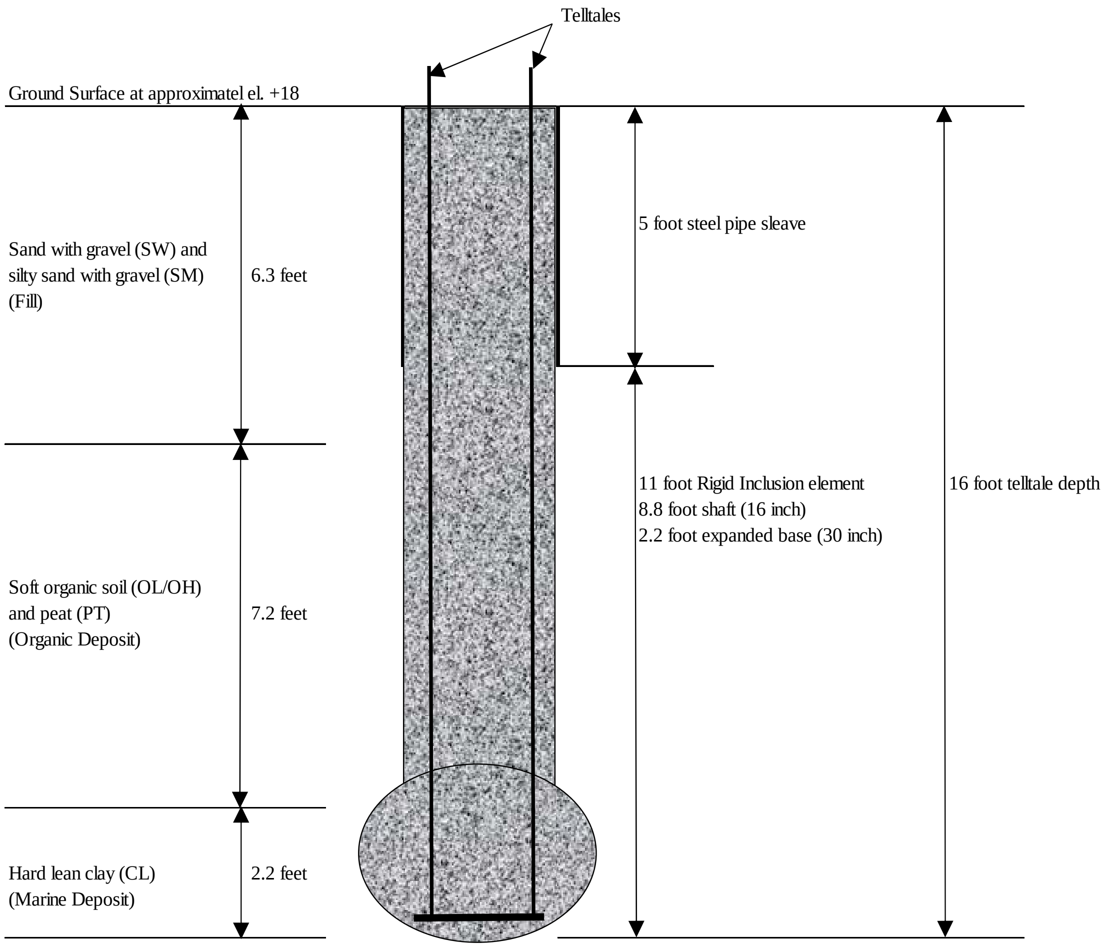

Figure 5: Stand-Alone Test Element

The stand-alone test element was loaded to 200 percent of the design capacity (design capacity of 75 kips, test load of 150 kips). The results of the load test are shown in Figure 6. The stiffness modulus value noted in the third bullet is taken as the stress divided by the deflection at the 100 percent design stress. To summarize:

- The rigid inclusion element deflected about 0.15 inch at the 100 percent stress.
- The rigid inclusion element deflected about 0.35 inch at the 200 percent stress.
- The stiffness modulus at the 100 percent design stress was determined to be about 2,600 pci.

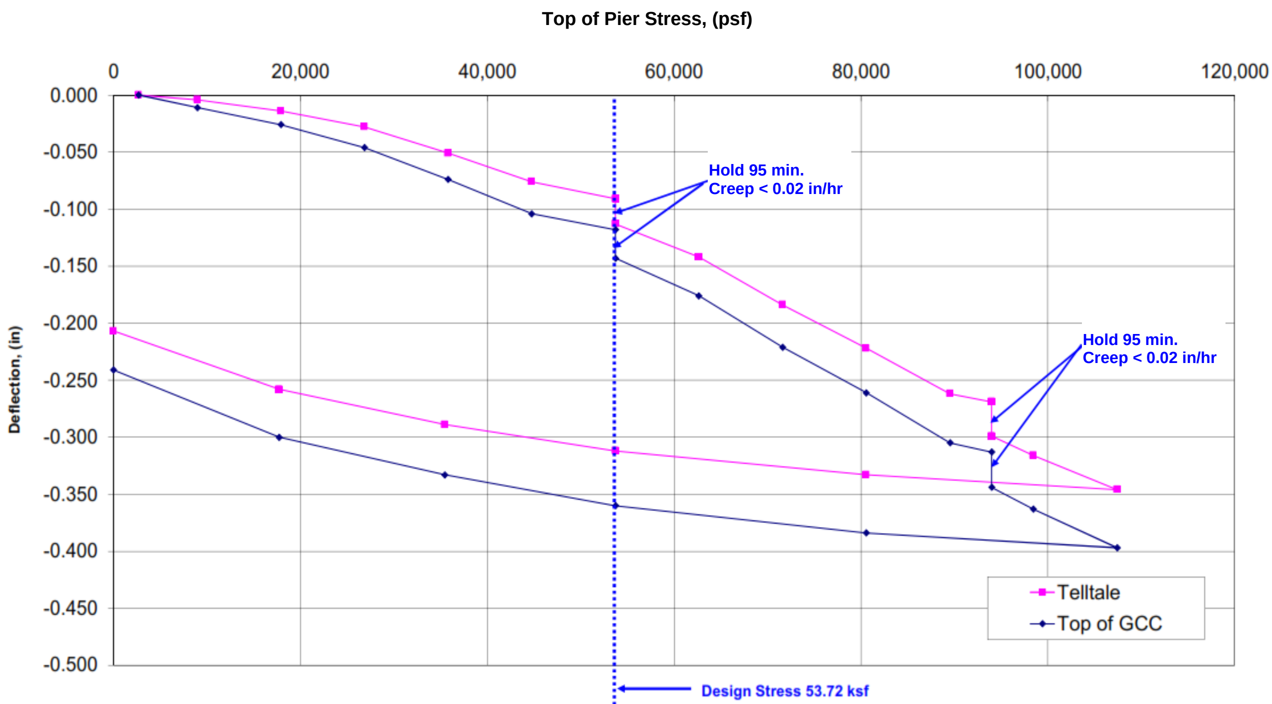

Figure 6: Stand-Alone Load Test Results

Figure 7 is a diagram of the test conditions at the rigid inclusion overlain by a granular pad and footing. Similar to the stand-alone test, the test element was installed through the fill and organics and about 2 feet into the underlying Marine Deposit (as previously noted, the actual production piers were installed 5 feet into the Fluvial Sand and Marine Deposit). The element was installed with an approximately 29- to 30-inch diameter expanded base and a 16-inch diameter shaft. The rigid inclusion was outfitted with telltales at the bottom and top of the element.

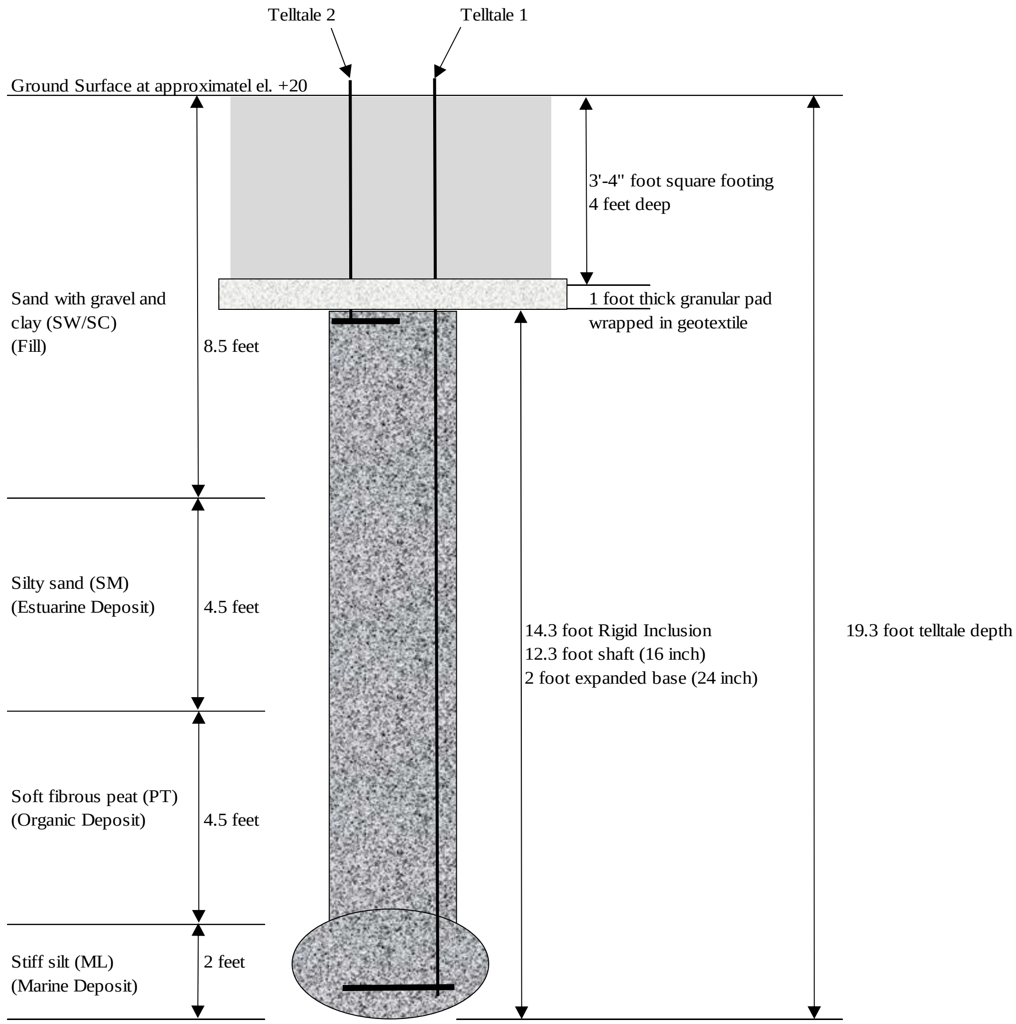

Figure 7: Test with Granular Pad and Footing

The rigid inclusion element overlain by the granular pad and footing was loaded to 267 percent of the design capacity (design capacity of 75 kips, test load of 200 kips). The results of the load test are shown in Figure 8. To summarize:

- The rigid inclusion element deflected about 0.2 inch at the 100 percent stress.
- The rigid inclusion element deflected about 0.35 inch at the 200 percent stress.
- The rigid inclusion element deflected about 0.85 inch at the 267 percent stress.
- The stiffness modulus at the 100 percent design stress was determined to be about 2,000 pci.
- The element penetrated the granular pad about 0.2 inch at the 100 percent design stress.

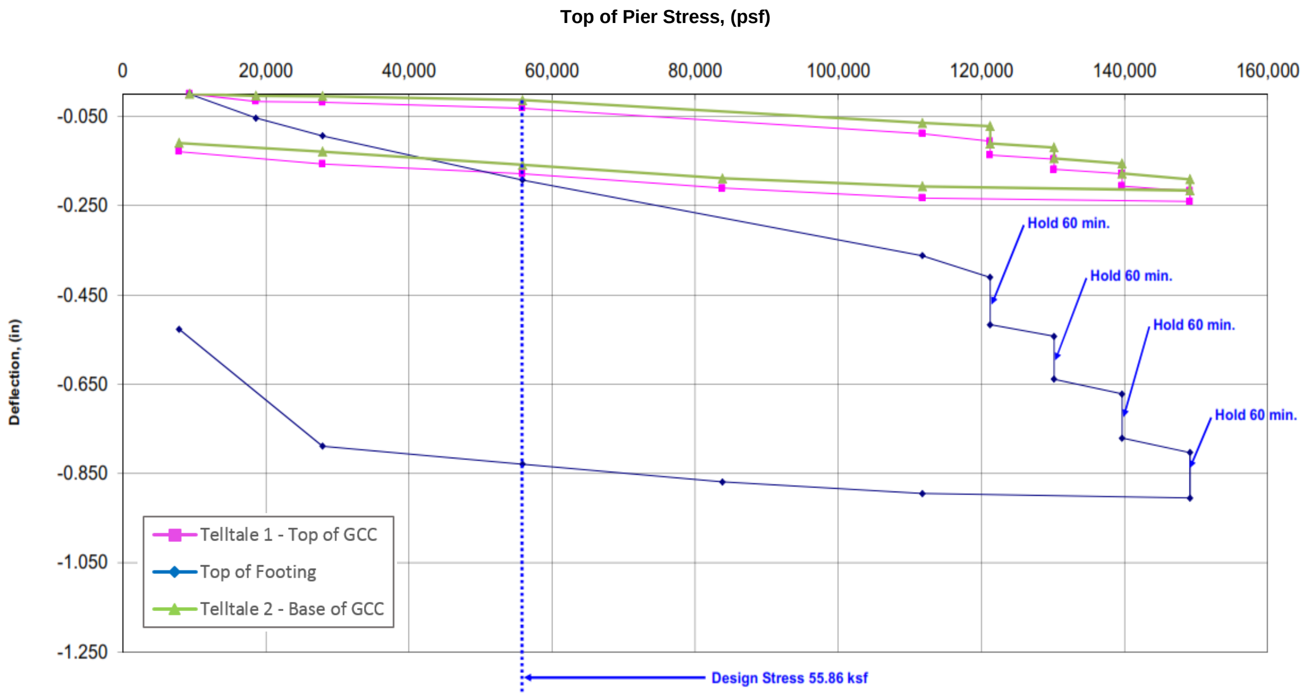

Figure 8: Granular Pad and Footing Load Test Results

Note that the top of footing deflected more than the telltale at the top of the GCC. The difference in the deflection is due to compression of the granular pad. The measured deflection of the granular pad ranged from 0.2 inches at the 100 percent design load to 0.7 inches at 267 percent of the design load.

Also note that the stiffness modulus for the stand-alone test element (2,600 pci) was higher than the stiffness modulus for the footing load test (2,000 pci). The variation in the stiffness is likely due to minor variations in element geometry, material strengths, and the subsurface conditions at the two test locations.

SUMMARY AND CONCLUSIONS

The three structures have been successfully supported on spread footing foundations bearing above variable fill and soft organic soils that were modified using about 2,300 rigid inclusion elements extending to depths of about 10 to 23 feet below the working grade. The rigid inclusions completely penetrated the unsuitable soils and were typically embedded 5 feet into the underlying stiff bearing soils (as confirmed by CST testing). The field test program verified that the designed installation process yielded rigid inclusion elements capable of limiting footing deflections to the project design tolerances under loads in excess of the design capacity of 75 kips.

Spread footings bearing in soils modified by rigid inclusion elements are a viable, cost-effective alternative to deep foundations and removal and replacement at sites with thick fills and organic soils. Load testing programs on this and other projects have verified that such systems can achieve sufficient design capacity while controlling system settlements to less than 1 inch. The closed system also allows for a high degree of QC confidence during construction, allowing mandrel air pressure measurements verifying that quality rigid inclusion elements are being installed.

ACKNOWLEDGEMENTS

The project team included Criterion Development Partners (Project Owner), Cube 3 Studio, LLC (Architect), JML Engineering, Inc. (Structural Engineer), Haley & Aldrich, Inc. (Geotechnical Engineer) and Tetra Tech (Civil Engineer). Helical Drilling, Inc., Geopier Foundation Company, Inc. and Design/Build Geotechnical, LLC designed, tested and installed the rigid inclusions and aggregate piers used to support the buildings.

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