HOLLOW BAR MICROPILES FOR SETTLEMENT CONTROL IN SOFT SOILS

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ABSTRACT

Hollow bar micropiles exhibit outstanding bond transfer values and have the ability to reinforce soft/loose soils thus improving the settlement behavior of foundations utilizing them. The behavior of hollow bar (fully bonded) micropiles in soil will be examined and a case history discussed where over 1000 hollow bar micropiles were used to reinforce soils beneath heavily loaded equipment pads at an aircraft manufacturing facility in soft coastal plain soils. A model of bonded anchors / micropiles in soil is developed for characterizing and describing micropile behavior. An extensive load testing program was implemented to optimize micropile lengths and finite element modeling was utilized to quantify the amount of improvement achieved by the micropiles.

HOLLOW BAR MICROPILE CASE HISTORY: SPIRIT AEROSPACE

The Spirit Aerospace project in Kinston, NC was a fast track, design build project with a number of heavily loaded equipment pads requiring foundation support inside an existing building shell. The equipment pads were to be used to support sensitive composite manufacturing equipment and therefore had a low tolerance for settlement.

GeoStructures, Inc. [design-build contractor based in Purcellville, VA] was under contract with the Haskell Corporation [Jacksonville, FL] to develop a ground improvement system for support of the building's spread foundations and various equipment pads for the Spirit facility.

Background

Based in Wichita, Kansas, Spirit AeroSystems is the world's largest independent supplier of commercial airplane assemblies and components. In addition to its Kansas facility, Spirit has operations in Tulsa and McAlester, Okla., Prestwick, Scotland, and Samlesbury, England. In May 2008, Spirit was awarded a contract with Airbus Americas (headquartered in Herndon, Virginia), to design and produce a major composite fuselage structure for the A350 XWB (Xtra Wide-Body) program. Spirit will design and manufacture the Section 15 center fuselage frame section, a composite structure that will be approximately 19.8 m long, 6 m wide and weigh nearly 4,082 kg.

To accommodate this and other new work packages, Spirit expanded its operations with a new 54,350 m^2 facility in Lenoir County, North Carolina, near the city of Kinston. The

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project General Contractor, the Haskell Company of Jacksonville Florida, began construction of the new facility in September 2008. Operations are expected to commence in mid 2010 with portions of work on the A350 XWB also planned to be performed at Spirit's facility in Wichita Kansas and at the new Spirit Malaysia facility, which is expected to be operational in 2009.

The general design criteria for the proposed new building were as follows:

− Planned finished floor elevation would be approximately 0.6 to 0.9 m above existing grades.

− The floor slab load in many areas of the building could have an applied load of up to 48 kPa.

− Building foundation columns loads could be upwards of 4000 kN with maximum total settlement tolerance of 13 mm.

− Mat foundations with plan dimensions ranging from approximately 7.62 m x 22.86 m to 13.7 m x38.1 m for support of equipment with static loads of up to 72 kPa with a maximum total settlement tolerance of 6 mm.

Subsurface Profile

The Kinston site is located in the Inner Coastal Plain Physiographic Province of the eastern United States. A geotechnical investigation of the Kinston site was completed by Building and Earth Sciences, LLP (Sanford NC & Birmingham AL) in August 2008. The generalized subsurface profile for the site can be described as follows:

− Layer A: Very soft to soft clays (CL-CH) and sandy clays (CL-CH) or very loose to loose clayey sands (SC) extending from near the ground surface to a typical depths of approximately 4.5 to 6 m. Standard Penetration Test (SPT) values were typically less than 6 blows per foot (bpf) with some zones measured as 0 bpf (weight of hammer). Tip resistance measured by the cone penetration test (CPT) was generally less than 20 tons per square foot (tsf).

− Layer B: Medium dense to very dense silty sand (SM) or sand (SW) encountered below Layer A and extending to a depth of approximately 7.62 to 9 m. SPT values were typically recorded in the range of 20 to 40 bpf. CPT results were measured to generally be in excess of 100 tsf.

− Layer C: Medium to very stiff sandy clay (CL-CH) or dense to very dense clayey sand (SC) or sand (SW) encountered below Layer B and typically extending to depths greater than 15 m. SPT values generally exceeded 15 bpf.

Groundwater was recorded in the test borings at depths of 0.6 to 2 m below the existing ground surface at the time of the borings.

Ground Improvement Solutions

Due to the load conditions and settlement criteria for the building foundations and equipment foundations, GeoStructures developed a ground improvement program consisting of grouted Rammed Aggregate Piers and hollow-bar micropiles. The following is a brief description of the each system and a discussion of the design and construction process for each system.

<u>Rammed Aggregate Pier® System</u>

Due to the planned construction and the very soft or very loose soil conditions in the upper 4.5 m, the geotechnical engineer recommended a program of surcharging to pre-consolidate the near-surface soils for support of the equivalent floor load of approximately 48 kPa. To support the building and equipment foundations, the geotechnical engineer recommended ground improvement utilizing a system of Rammed Aggregate Piers® (RAP).

The Impact (or displacement-Geopier) system utilizing Rammed Aggregate Pier technology was used for support of the building's spread foundations designed for a bearing pressure of up to 192 kPa. The Impact RAP elements were amended with low-strength cement grout to further stiffen the elements and limit the theoretical total settlement to less than 13 mm. Grouted Impact RAPs were also used for support of some of the equipment foundations to limit the theoretical total settlement under sustained load to less than 6 mm.

The Impact RAP element is a very stiff compacted aggregate pier created to the full design depth by pushing a special impact apparatus with a relatively large static force augmented by dynamic vertical loading. The hollow-shaft mandrel, filled with open-graded stone, is incrementally raised, permitting the aggregate to be released into the cavity, and then lowered by pushing, ramming or vibrating to densify the aggregate and push it laterally into the adjacent soil. (The selection of optional dynamic forces to augment the static force depends on the soil conditions.) The cycle of raising and lowering the mandrel and impact head is repeated to the ground surface. The raise and push cycle was typically 1.2m and 0.9m, thereby creating the typical 0.3m compacted lift thickness and the minimum design diameter.

<u>Hollow Bar Micropile System</u>

Some of the equipment pads had slightly larger static service loads and more stringent design criteria for deflection tolerance across the mat during the operating load condition. As a result, GeoStructures proposed a system of Con-Tech Systems' CTS/Titan IBO® hollow-bar micropiles for support of these more critical structures. Past experience with the Titan hollow bar had indicated that they would be able to meet the load and deflection requirements needed for the more heavily loaded equipment pads.
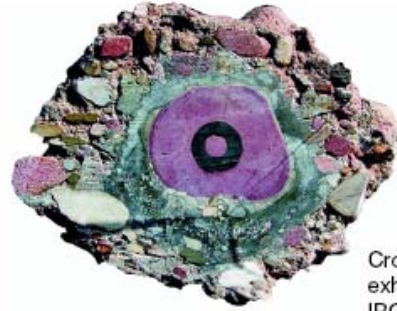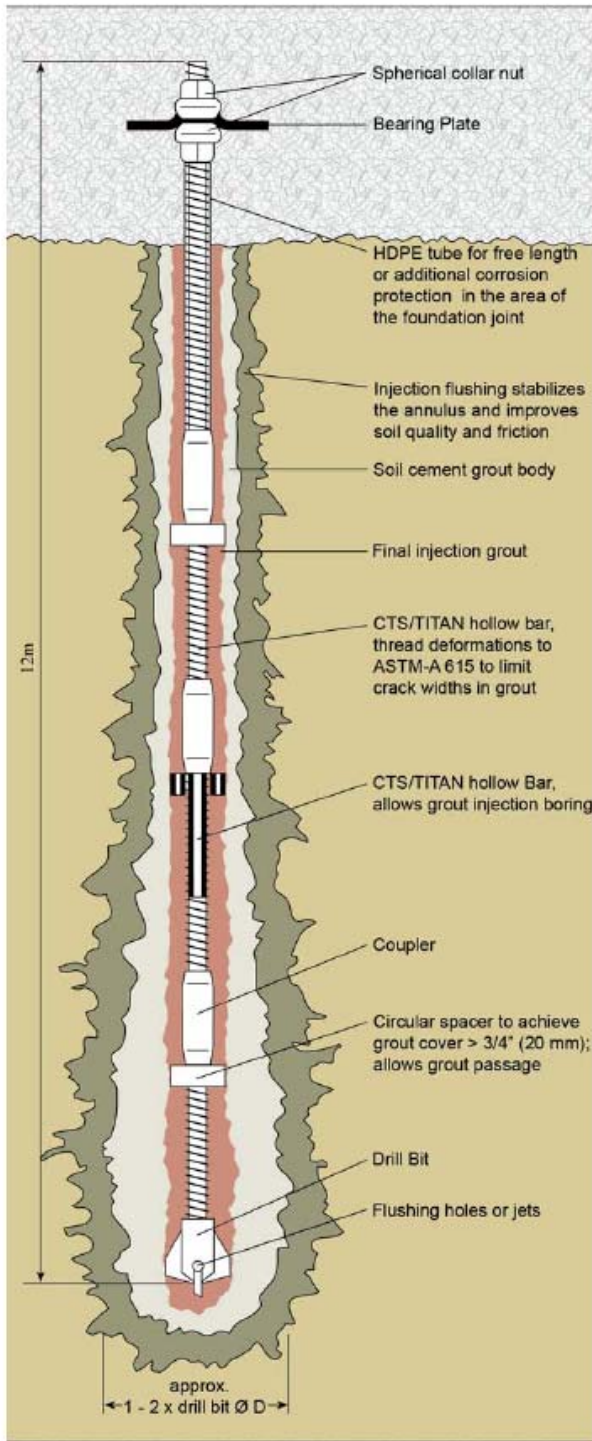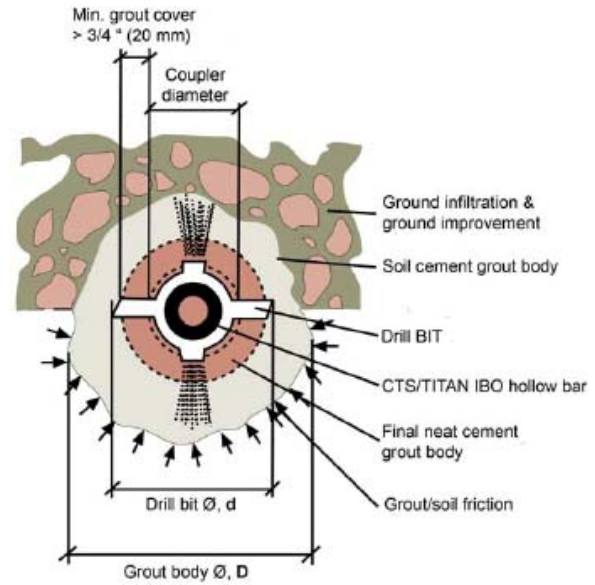
Cross section of exhumed CTS/TITAN IBO® micropile

Figure 1 - Hollow Bar Micropile Schematic (Courtesy of Contech Systems)

Figure 2 - Hollow Bar Sections used for Hollow Bar Micropiles (Courtesy of Contech Systems)

Hollow Bar Micropiles have emerged since the early to mid 1990's as an economical system for installation primarily in soils. This type of micropile is easily installed in low headroom or restricted access applications and exhibits high unit load capacities coupled with superior stiffness performance compared to conventional drilled and grouted ground anchors without the need for temporary or permanent casing.

Hollow Bar Micropiles are fully bonded, drilled and grouted micropiles which consist of segments of load carrying hollow threaded bars, couplers and a sacrificial drilling bit that are bonded to soil or rock by a neat water-cement grout. They are installed by drilling with the hollow bar assembly and flushing the hole with the micropile grout. Due to the installation procedures used, hollow bar micropiles are especially advantageous in subsurface conditions where casing might otherwise need to be employed with conventional micropile configurations. The manner in which hollow bar micropiles are installed results in higher grout to ground bond stresses and greater axial stiffness than conventional solid anchors or uncased micropiles that are drilled and subsequently gravity grouted. Hollow Bar Micropiles are also known as Injection Bore Micropiles or Self Drilling Micropiles.

A variety of types and diameters of sacrificial cutting head / drill bits are available for installation in varying subsurface conditions. The grout to ground bond stress is directly proportional to the drill bit diameter, so proper bit selection is critical both for installation and for optimizing hollow bar micropile capacity. Figure 1 shows a schematic diagram of a typical hollow bar micropile. Figures 2 shows typical hollow threadbar sections used for hollow bar micropile installation.

The CTS/Titan IBO hollow-bar micropile is a composite monolithic structure of micro alloy steel and high-strength cement grout. The hollow steel bar has a continuous external thread running the entire length of the bar and is advanced under rotation and possibly with some hammering action in very stiff or hard soils. As the bar is advanced, the grout is injected through the hollow bar and out through the sacrificial cutting head. Since the outside diameter of the cutting head is typically 1 to 4 times larger than the outside diameter of the bar, the grout (under pressure) will flush the drill cuttings to the surface through the cavity along the outside of the bar and the wall of the excavation created by the cutting head.

Micropile Load Test Program

Due to the large number of micropiles projected for the project, GeoStructures recommended a comprehensive pre-production load test program utilizing a number of different lengths of micropiles utilizing two different cutting head types and sizes so as to be able to optimize the pile length and cutting head configuration. This testing was performed outside the footprint of the existing building shell to eliminate any space constraints that might interfere with handling of the test apparatus.

Four pairs of sacrificial test piles were installed. The pile lengths utilized were 7 meter, 8.5 meter, 10 meter and 11.5 meters, two piles of each length. Each pair of piles utilized one 150mm clay bit and one 115mm cross bit for comparison in terms of installation efficiency and load carrying capacity. Each test pile was tested to ultimate geotechnical failure. The shortest pile pair was able to meet the deflection criteria at a load capacity that was deemed acceptable with the 150mm clay bit performing marginally better than the 115mm cross bit. Therefore the 7 meter micropile with the 150mm clay bit was the pile configuration selected to be used for the majority of the equipment pad locations. Figure 3 shows the load test results for the 7 meter test piles.

The 7 meter piles attained applied axial loads of approximately 480 kN and 460 kN for the 150mm clay bit and 115mm cross bits respectively at the target settlement value of approximately 6mm. The allowable design load for the piles was selected based on the lesser of one half of the ultimate pile test load or the service load at which the target settlement value was reached.
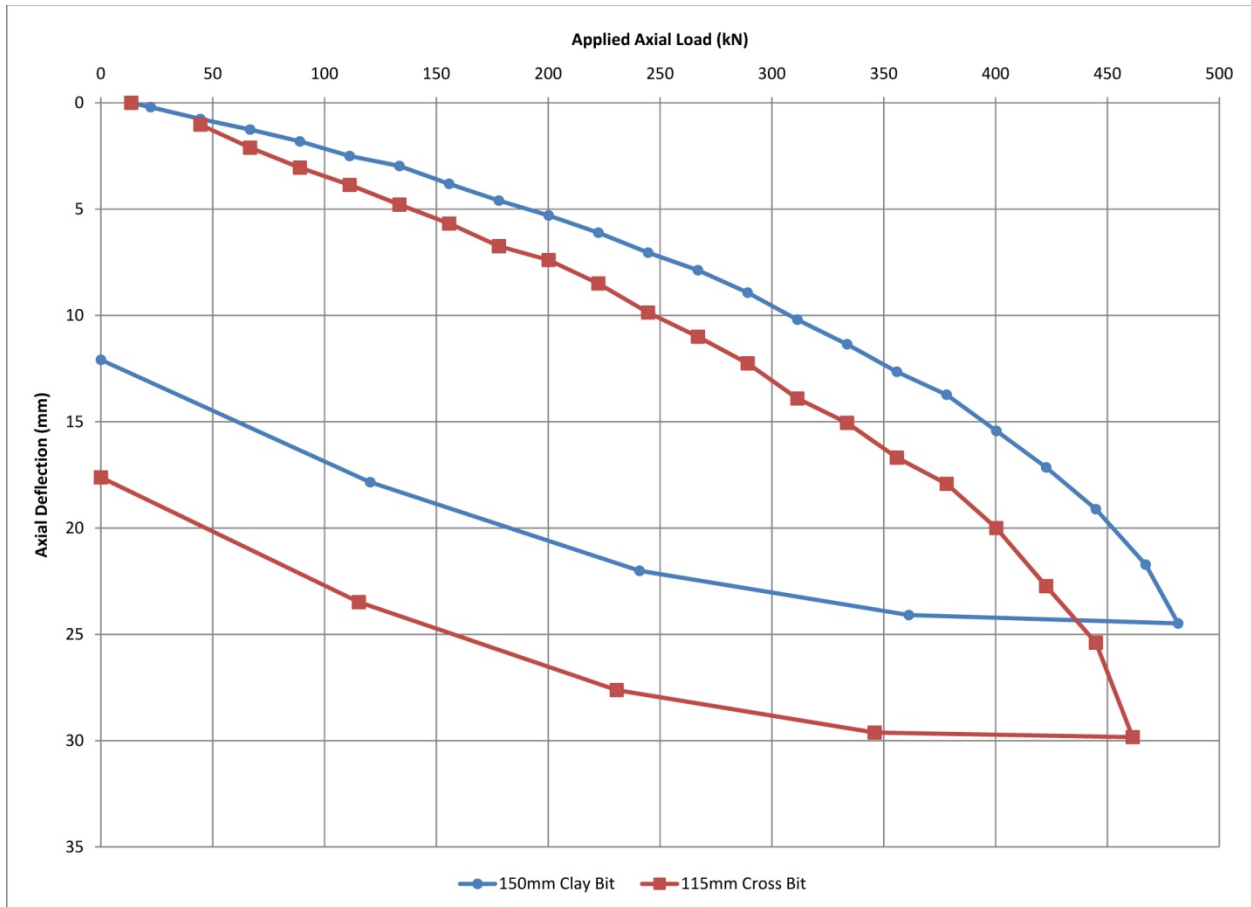
Figure 3 - Load Test Results for 7 meter Test Piles

Performance Modeling

In order to properly analyze the soil-structure interaction between a structure foundation and fully bonded micropiles in soil, it is necessary to have an accurate performance model for the micropiles that can be utilized by the foundation designer for assessment of the foundation's response to applied loads. Currently, it appears that there is no commonly used model that is specifically geared toward describing the performance of ground anchors or micropiles. The historical norm in modeling foundation piles from a structural design perspective appears to be modeling the piles as either rigid supports or as spring supports. The actual performance of fully bonded micropiles in soil does not precisely match either of these models.

A mathematical model has been developed by Bennett based on past and current observations of ground anchor and micropile performance during load testing that provides a force-displacement relationship, apparent stiffness and apparent flexibility of the micropile based on an assumed ultimate load and axial deflection at that ultimate load. The ultimate values can be determined by load testing and the relationships can then be developed to describe the overall behavior of the micropile under load.

The shape of a force-displacement graph used in presenting the results of ground anchor and pile load tests in soil closely resembles that of a parabola with a horizontal axis of symmetry. As a result, the equation for a parabola can be adapted to approximately describe that force-displacement relationship. The adaptation of a mathematical formula for this relationship provides a mechanism to directly compute approximate stiffness and flexibility relationships, approximate loads at various slope or flexibility values and other desired information that is useful in analyzing and possibly predicting ground anchor and pile performance. In the authors' experience, this approach has not been put forward before.

The derivation of the mathematical expressions and detailed analysis will be published separately in a forthcoming paper. However the fundamental expressions are presented below. The expression representing the force displacement relationship for a ground anchor or pile in soil based on a parabolic shape is as follows:

$$x = \frac{P_{AL} - P_{ULT}}{\Delta_{ULT}^2} y^2 - 2\left(\frac{P_{AL} - P_{ULT}}{\Delta_{ULT}}\right) y + P_{AL} \qquad \text{(Equation 1)}$$

Where:
P_{AL} = Alignment Axial Load (kN)
P_{ULT} = Ultimate Failure Axial Load (kN)
Δ_{ULT} = Axial Movement at Ultimate Failure Load (mm)
x = Axial Load (kN)
y = Axial Movement (mm)

The stiffness of a structural member or spring is typically described in terms of force per unit displacement (kN/mm). The first derivative (dx/dy) of the above function yields the rate of change of axial force with respect to axial movement and represents the axial stiffness at any point along the parabolic force displacement function. The inverse of the axial stiffness yields axial flexibility expressed in terms of axial movement relative to axial force (mm/kN).

$$\frac{dx}{dy} = 2\left(\frac{P_{AL} - P_{ULT}}{\Delta_{ULT}^2}\right) y - 2\left(\frac{P_{AL} - P_{ULT}}{\Delta_{ULT}}\right) \qquad \text{(Equation 2)}$$

Figures 4, 5 and 6 are examples of the parabolic force-displacement model, stiffness and flexibility respectively. These examples are based on an alignment load of 0 kN, an ultimate axial load of 445 kN with a corresponding deflection of 25.4 mm at the ultimate load. The stiffness can be seen to be directly proportional to the force-displacement plot. The flexibility plot is the inverse of the stiffness. The plot of flexibility illustrates the rapid increase of movement as the micropile approaches ultimate bond failure. The rate of increase of axial movement relative to axial load stays relatively uniform until approximately 85% of the ultimate axial load.
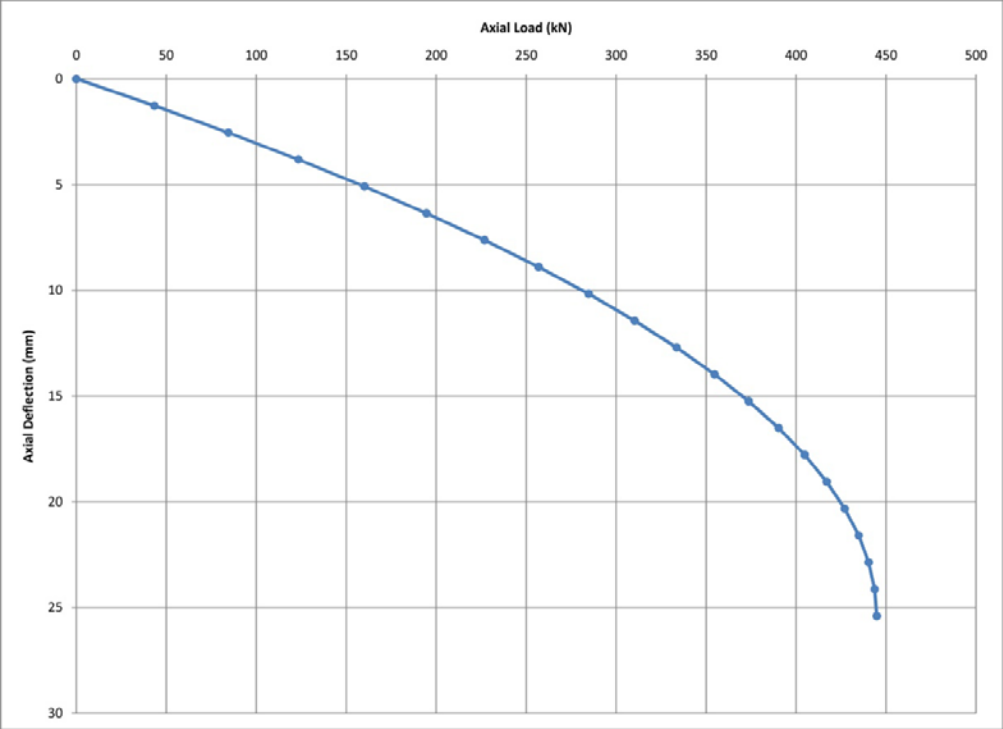
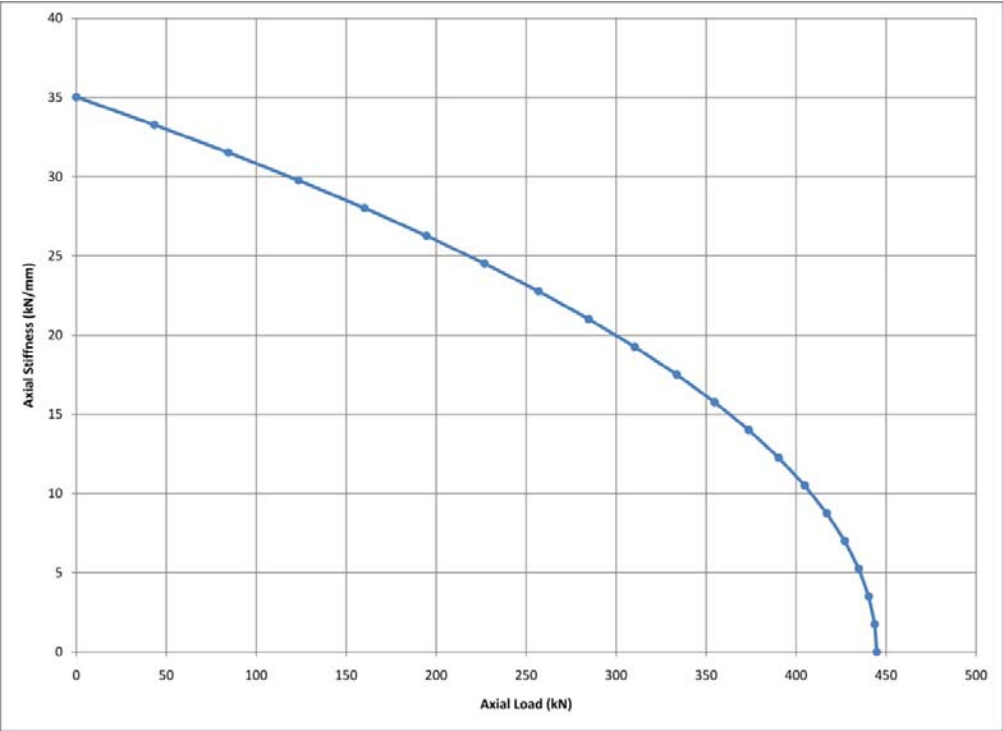**Figure 4 - Parabolic Force-Displacement Model**
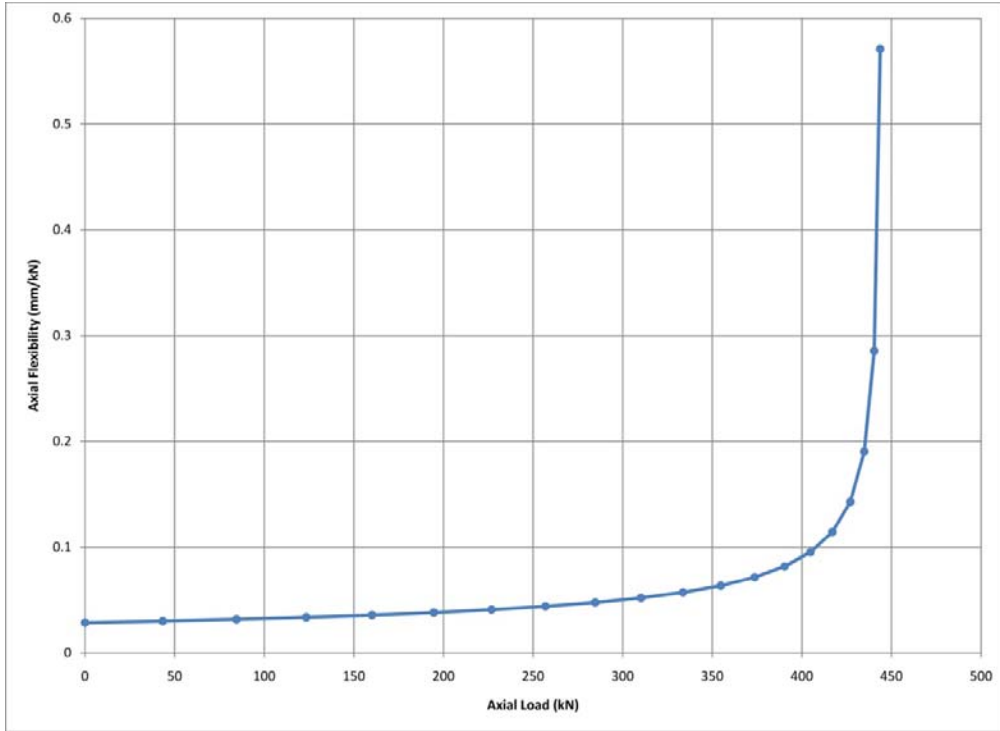

Figure 5 – Stiffness Function

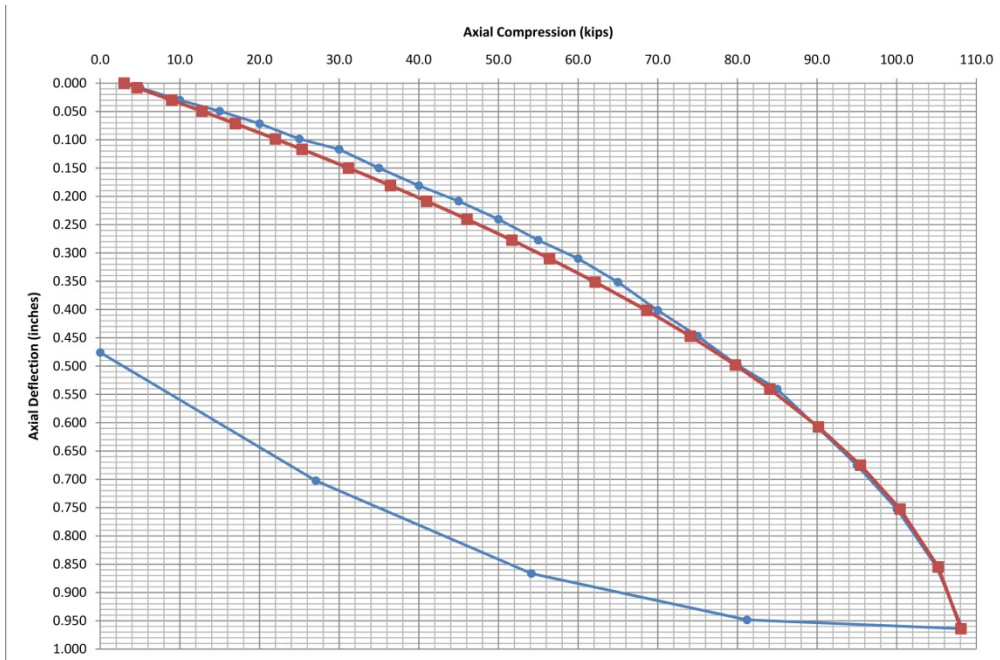**Figure 6 - Flexibility Function**

Figure 7 - Comparison of Actual Data and Parabolic Model

Figure 7 shows how closely the parabolic model correlates to actual load test plot data. In Figure 7, a parabolic model (red line with square data points) is superimposed over the actual load test data (blue lines with round data points) for the 7m hollow bar micropile with a 115mm clay bit. The ultimate load and deflection values were adjusted slightly in the model to obtain a best fit.

This model has a number of potential uses in analyzing hypothetical micropile or ground anchor performance based on assumed performance parameters. The fact that it has been packaged into a mathematical formula allows for mathematical analysis and direct computation of stiffness and flexibility. This model was not actually used on the Spirit project but was developed as a result of the project and necessitated by theoretical shortcomings of other modeling approaches.

Production Micropile Installation

All of the production micropile work was performed inside the building shell that had been constructed in a previous construction phase. A firm working surface was established prior to the installation of the concrete slabs on grade used as the floor surface for the building. Micropiles were installed more or less from existing grade and then excavation for the equipment pads was performed subsequently around the piles. Care was exercised on the part of the excavation contractor not to damage any of the piles. None of the piles were damaged by excavation operations.

Micropile installation was performed utilizing a DK-720 crawler mounted hydraulic drill rig manufactured by Davey Kent. The drilling was performed utilizing rotary only methods and a Contech systems grout swivel adapter compatible with the Contech 40/20 hollow bar micropiles. A colloidal grout mixer was used to mix the neat water-cement grout for the micropiles. No admixtures were needed for the application. The equipment was able to easily fit inside the existing building shell that had been previously erected, allowing for efficient installation operations. Peak productivity achieved during installation was in the neighborhood of 518m/day.

A limited proof test program was conducted in compression on production piles which produced results comparable to the pre-production testing for the lengths utilized for the actual production piles. Helical anchors were used as tiedowns for the proof testing due to the lower test loads and the fact that the testing was being performed inside of the building. It is important to note that compression testing was selected as opposed to tension testing primarily because the deflection under compressive loading was one of the mian design criteria for the project. Tension testing may produce higher deflections than compression testing.

Figure 8 shows some of the micropiles as installed at the Spirit project. The micropiles had been exposed at the top immediately prior to constructing the equipment pads around the tops of the micropiles. Figure 9 shows the load test apparatus that was utilized for proof testing of selected micropiles.

Figure 8 - Hollow Bar Micropiles Prior to Pouring Equipment Pads

Numerical Analysis

A Finite Element Model was created to compare the theoretical settlement of an equipment pad segment founded directly on soil versus on micropiles so that an estimate could be made of the approximate settlement improvement achieved by the use of micropiles and for evaluating stress distributions in the soil surrounding the micropiles. The model was created and analyzed with SigmaW software developed by GeoSlope Incorporated of Calgary, Alberta, Canada. An axis-symmetric model utilizing plane strain elements was used.

Two models were created in SigmaW. The first model was for a single micropile embedded in a representative soil stratigraphy consistent with what it described in the site subsurface conditions portion of the case history. The micropile components are modeled as being fully bonded with the surrounding materials. No mechanisms were introduced to attempt to model and progressive debonding of the grout to the surrounding material, so the model would be applicable under working conditions and not to model failure modes or capacities of the micropiles.

Figure 9 - Proof Load Testing Apparatus

The second model was created to simulate a spread footing bearing directly on the site soils. The area of the spread footing was selected based on the tributary area of one micropile and a uniform pressure was applied over that area such that the total load was equal to the load on a single micropile.

Modulus of elasticity values were applied to the model and adjusted slightly so as to yield approximately the same micropile deflection under load as was found in the pre-production testing program. The same soil modulus of elasticity values were applied to both models.

The improvement in immediate settlement was found to be on the order of 62% (i.e. the micropile foundation exhibited settlement values of approximately 38% of the expected immediate settlement of the foundation without micropiles). Since the micropiles were not able to be in contact with a rock stratum, the foundation was allowed to settle as a whole. However, the reinforcement provided by the micropiles stiffened the soft soils to a level that the settlement was tolerable and transferred the foundation loads to a more competent soil stratum. Long term settlements (i.e. consolidation settlements) were not evaluated because they were not expected to have an effect on differential movements of the foundation.

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Summary

The Spirit Aerospace project had all of the basic requirements in terms of logistics and performance that allowed hollow bar micropiles to be the right solution for equipment pad foundation support. A combination of low headroom installation requirements, high axial stiffness and tight construction schedules in a very soft soil profile aligned perfectly with the capabilities and advantages of hollow bar micropiles.

The comprehensive test program undertaken in advance of final design and installation allowed GeoStructures to provide the project owner with an optimized design resulting in the best price possible and assurance of the performance capability of the micropiles.

The high productivity rates achieved during installation allowed GeoStructures to keep up with project schedules and meet the needs of the General Contractor and Owner. The hollow bar micropile is inherently productive in the type of subsurface conditions that were present at the site due to simplicity of components and installation procedures.

The analytical and modeling tools developed during and as a result of this project provide a powerful framework for assessing and quantifying both the performance of fully bonded micropiles and assessing the potential for settlement improvement as a result of the use of hollow bar micropiles in soft soils.

In the end, the hollow bar micropile solution was an economical solution that met and exceeded the owner's performance and schedule needs.

CONCLUSIONS

- The axial stiffness properties of hollow bar micropiles can provide substantial reductions in surface settlement even in very soft soils.
- High productivity rates and the ability to easily install hollow bar micropiles in low headroom or tight quarters applications results in a very economical approach to settlement reduction where access is restricted.
- The behavior of hollow bar micropiles can be modeled in a more precise manner than simply assuming rigid or spring supports. A model exists that can accurately describe their load-deflection behavior and allow for direct calculation of various parameters.
- Finite element analysis can be a useful tool to estimate the amount of settlement reduction that can be achieved using hollow bar micropiles for settlement control.

ACKNOWLEDGEMENTS