Numerical Modeling in Micropile Design for a Pusher Furnace

Timothy C. Siegel[1], M. ASCE, P.E., G.E., D.GE and R. Michael Bivens[2] P.E.

[1]Principal Engineer, Dan Brown and Associates, PC, 1808 Northshore Hills Blvd., Knoxville, TN 37922, ph. 865-809-4883, tsiegel@danbrownandassociates.com
[2]Chief Engineer, Rembco Geotechnical Contractors, Inc., 10410 Cogdill Road, Knoxville, TN 37933-1009, ph. 865-671-2925, mike.bivens@rembco.com

ABSTRACT: Two new pusher furnaces were installed as part of an expansion to an aluminum facility in Alcoa, Tennessee. These pusher furnaces pre-heat ingots of aluminum prior to rolling into can sheets for beverage containers. The two $20M furnaces replaced 70 individual preheat furnaces of 1950's vintage with a streamlined automated process in a relatively small but heavily loaded footprint. As may be expected, the pusher furnace was very heavy and would be subjected to a wide variety of loading conditions with tight deflection requirements. The subsurface conditions consisted of clay overlying pinnacled limestone. Rock-socketed micropiles were selected as the foundation considering the performance requirements and the karst conditions including the potential for sinkholes, soft soils, and differential depth to bedrock. These challenges justified an innovative approach where the pusher furnace and foundation were modeled using FLAC3D. The FLAC3D model was incrementally updated during production installation to ensure that the computed displacements would be within the project criteria.

INTRODUCTION

An innovative design approach was required when two new preheat furnaces were recently added to an aluminum sheet manufacturing facility in Alcoa, TN. The two furnaces were each approximately 37 m (120 ft) long and placed facing each other to deposit onto a centralized rolling table feeding the rolling mill. Each furnace was placed on a massive foundation of reinforced concrete up to 5.5 m (18 ft) deep below the floor slab. The basic operating principle of the furnaces is to have equipment operators load aluminum ingots weighing approximately 13.6 metric tonnes (30 kips) on the outboard ends of each furnace. Automated equipment tips the ingots up onto their side and the furnace machinery will then push all of the loaded ingots together through the preheat furnace with each ingot exiting at the centralized rolling line in alternating sequence from both the north and south furnaces. The foundations were required to maintain tight tolerances for deflection through many different loading conditions. Deviation from the tolerances could void the manufacturer's warranty.

In addition to the standard dead, maximum live, and seismic loading conditions there were also two variations on partial live load and several different variations of loading when the ingots are pushed through the furnaces. Including all orientations for seismic loading, there were a total of 14 different load cases to consider. The presentation of loading information was also unique to this project since the furnace manufacturer had provided the structural design team with approximately 1,260 individual point loads from each furnace for each of the 14 different loading conditions.

Approximately 6.3MN (14,000,000 lb) of pusher force is required to move the ingots through each furnace when fully loaded. This pushing force is cyclic and repetitive as new ingots are added. High loads combined with small tolerances for deflection required a deep foundation system that could be designed specifically for the variable rock depth present at this location. Typical of eastern Tennessee, the site is underlain by karst geology of limestone and dolomite bedrock with a highly variable and unpredictable depth. It was necessary to fully understand the soil-structure interaction of the massive concrete foundation under the 14 load combinations and to design a deep foundation system that could satisfy deflection requirements during all loading conditions and allow design flexibility as the depth to bedrock was unpredictable.

The solution that was successfully implemented involved a system of micropiles designed using FLAC3D numeric finite difference modeling software to predict deflections of the pile system and mass concrete foundation under the numerous loading conditions. It was likely that the structural response of the complex mass concrete foundation would play a significant role in the deflection characteristics of the system in addition to the pile foundation and FLAC3D was chosen due to its ability to model both the concrete foundation and pile system while receiving loads applied from the furnace.

In addition to the FLAC3D model used by Rembco during the design of the micropiles, the Structural Engineer responsible for the concrete foundations used RISA 3D to compute stresses and strains in the reinforced concrete along with predicted deflections. While this paper focuses on the design of the pile system using FLAC, it is interesting to note that the Structural Engineer's RISA model was used to validate the FLAC results as the project entered field construction. Axial compression load testing was performed on a sacrificial test pile within each furnace foundation to validate design parameters and confirm the axial stiffness parameters utilized in the FLAC3D model. The lateral behavior of the micropiles in the FLAC3D model was calibrated using the computer program LPILE by Ensoft, Inc.

A total of 85 micropiles were utilized to support the south furnace while the north furnace encountered deeper bedrock and required 95 micropiles. Approximately 12 different micropile variations were utilized during construction including the use of 140 mm (5.5 in), 180 mm (7 in), and 245 mm (9-5/8 in) casing and several variations of centralized reinforcing steel.

SITE CONDITIONS

The site is located within the Appalachian Ridge and Valley geologic setting in eastern Tennessee. Locally, the site is underlain by the Knox Group of limestone and dolomite with intermittent shale layering. The strike of the bedrock is approximately Northeast to Southwest and the dip of the bedrock is approximately 40 degrees to the

Southeast. The combination of highly soluble bedrock and high annual rainfall combine with the steeply dipping rock to form an aggressive Karst structure with large rock voids, steeply dipping rock pinnacles, and extremely variable and unpredictable depth to bedrock. Ground surface elevations in the vicinity of the site are approximately 250m (820ft msl). Bedrock depth at the site ranges typically from zero to 12m (40ft) below the subgrade elevation. The project location is shown in the Site Vicinity Map in Figure 1.

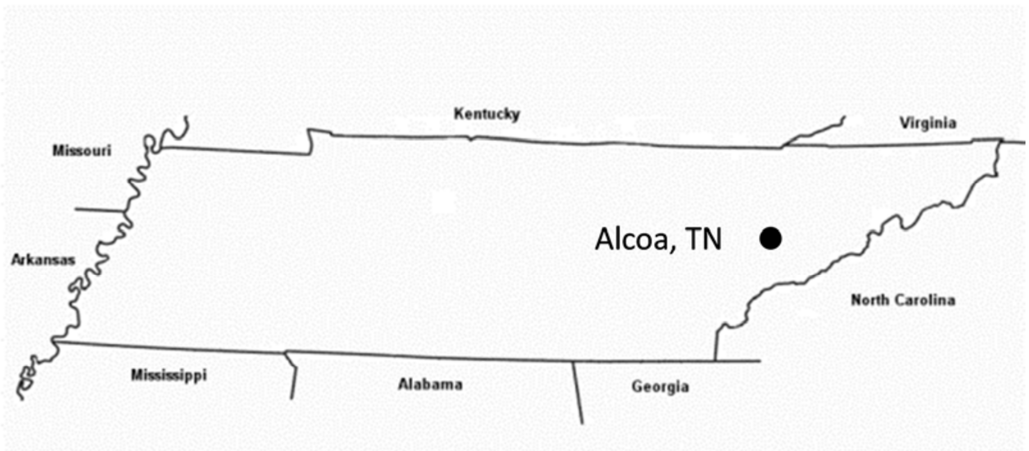

FIG 1. Site Vicinity Map

A typical section through the foundation showing the layout of the furnaces and the central rolling table is shown in Figure 2. Note that the concrete foundations were recessed below floor level.

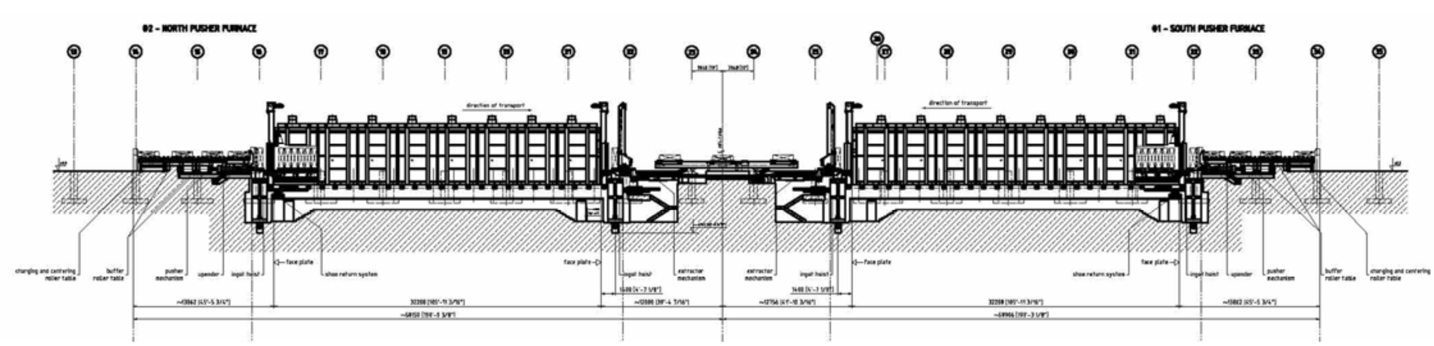

FIG 2. Typical Section Through Furnaces

PUSHER FURNACE FLAC3D MODEL

Two individual FLAC3D models were constructed to represent the two furnace foundations. The goal of the process was to prepare a model that could predict the complex behavior of the irregularly shaped concrete foundations supported on piles of variable length under all 14 different load cases.

A total of approximately 1,260 point loads from each furnace would have to combine with the dead load of the mass concrete foundation to provide the estimated deflection for each load case. For each load case it would be necessary to estimate the working load in each micropile and design the pile system accordingly. The complexity of the mass concrete foundation, undulating bedrock surface and numerous loading conditions made it impractical to estimate pile loads without the use of a sophisticated numerical model such as FLAC3D. Early in the project, several numerical modelling programs were evaluated and FLAC3D was selected because it was best suited to handle input and processing of the many individual point loads and load cases. During the initial stages of the project before piles were drilled, all modeling was completed using estimated depths to bedrock based on geotechnical borings taken before the start of construction.

One FLAC3D run was performed using only the dead load of mass concrete to provide baseline deflections of the foundation system including the elastic response of the micropile foundation system. During the run, the micropiles are theoretically stressed as the concrete load is applied and the end result of this run is to predict the top-of concrete elevation to be used as a baseline for differential settlement estimation for each load case. This run was necessary as subsequent load cases would include deflection due to the dead load of the mass concrete foundation however that deflection would not be transferred to the furnace as the furnaces would be installed including shimming or leveling as required on the top of the poured foundation. The only deflection that would affect the furnaces would be a result of the furnace dead load and the remaining live or seismic loads.

A separate FLAC3D run was performed for each of the 14 load cases and estimated deflections at the top of the concrete foundation were produced from the output results. The baseline deflection of the concrete-only baseline run was subtracted from these results to determine the differential deflection due to each load case non-inclusive of the baseline concrete-only baseline deflection.

Figure 3 illustrates the FLAC3D model of the concrete foundation resting under its dead load only on piles with an estimated length equal to the average found in the exploratory borings. The color contours show stress predicted within the concrete foundation due to the dead load of concrete alone and the interaction of the concrete foundation bearing on micropiles with an estimated elastic length for bedrock at elevation of -7m (-25ft).

Although the superstructure was unchanged during construction, the variable depth of bedrock would make each foundation system unique. For each foundation, the a preliminary estimate was made on the depth to bedrock based on exploratory borings performed for this project. The first iterations for micropile design were based on these bedrock depth assumptions to determine a preliminary micropile layout and to estimate loads in the micropiles. As micropiles were installed, field crews provided daily information to the project's design team and the FLAC3D models were updated accordingly.

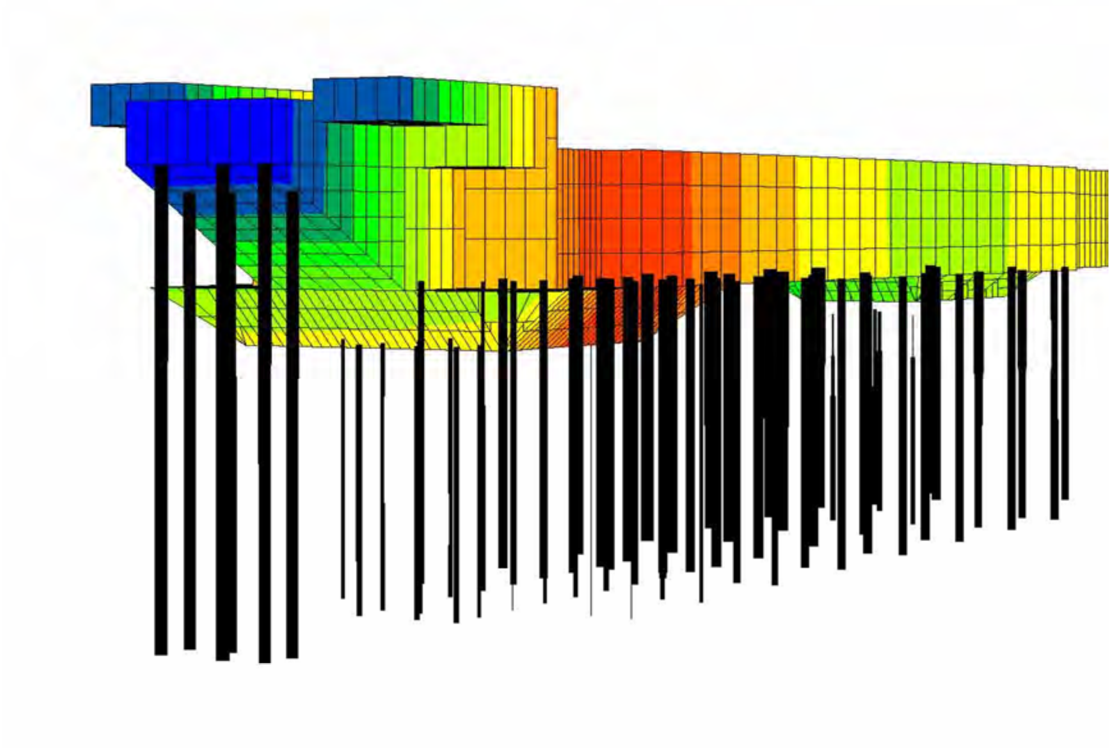

FIG 3. Typical Section Through Furnaces

As micropiles were installed in each foundation, the actual depth to bedrock differed from the preliminary assumed depths. When this occurred, the modeling software was used to predict updated micropile loads and deflections. Micropiles were added or increased in stiffness by inserting additional central reinforcing steel to maintain acceptable performance of each micropile and for the entire system. During the course of construction, approximately 42 additional FLAC3D modeling runs were completed as more field information was obtained and the variable depths to bedrock were discovered.

ALLOWABLE DEFLECTIONS vs. PREDICTED DEFLECTIONS

The reason for using a sophisticated numerical model on this project was driven by extremely tight deflection requirements placed on the concrete foundation by the furnace manufacturer. The settlement criteria specified by the furnace manufacturer were as follows:

- 15 mm maximum (0.59 in)
- 10 mm differential (0.39 in)
- 1/1000 slope (1.2 in over a distance of 100 feet)

These requirements had to be satisfied for all of the 14 load cases otherwise the warranty of the equipment could be voided. Although many of the load cases were similar, one particular load case in particular was exceptional. During operation, there is a large pushing force applied on the foundation at the front end of each furnace. The magnitude of the force is cyclic and variable with a maximum expected value of up to 6.3MN (14,000,000 lb). As you can see in Figure 3 below, the section through the furnace just downstream from the pusher equipment is relatively narrow and does not provide much stiffness or rigidity to the remainder of the mass concrete foundation. The approximate location of the pusher forces, primary flexure, and large micropile reaction forces are shown on Figure 3.

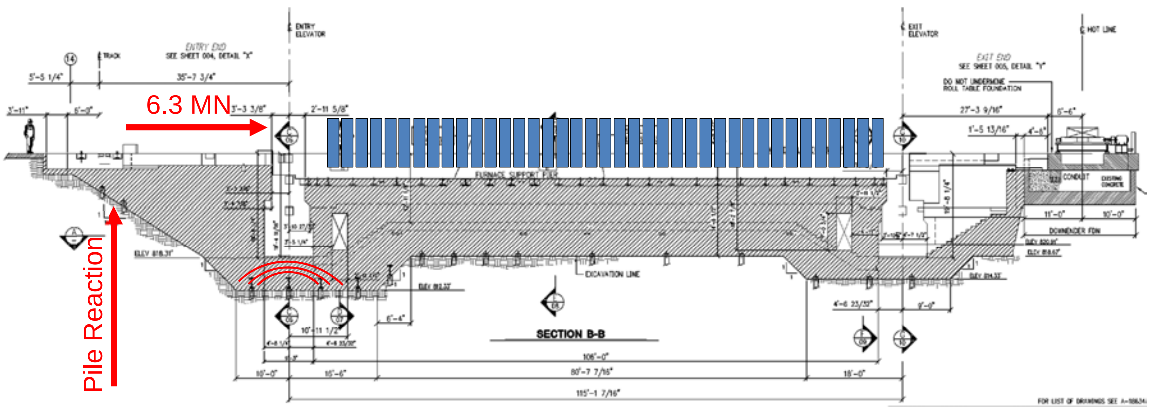

FIG 3. Typical Section Through Furnace Foundation with Pusher Force

This one load case under pusher loading was the source of the highest total and differential deflections predicted in the structure. It was critical to maintain acceptable deflections and provide adequate pile capacity for the maximum load and adequate pile stiffness so that the elastic deflection due to cyclic pusher load was minimized. Figure 4 below illustrates predicted deflection of all load cases and it is clear that the pusher load would play a significant role in the design.

Notice in Figure 4 that the pusher force load case was predicted to produce a maximum deflection approximately 3 times more than any other load case on the entry end of the furnace while the deflections on the central area of the furnace were widely variable depending on the ingot loading of the furnace. Figure 5 below illustrates the deflected shape of the foundation system and micropiles under the pusher force. Notice in the figure below that the rotation of the entry block was forced using a vertical force couple rather than a horizontal pusher force. Since this model was intended to model the behavior of the pile system and predict vertical deflections as it was easier to model equivalent external forces producing this type of rotation rather than the complex relationship of friction along the length of the furnace.

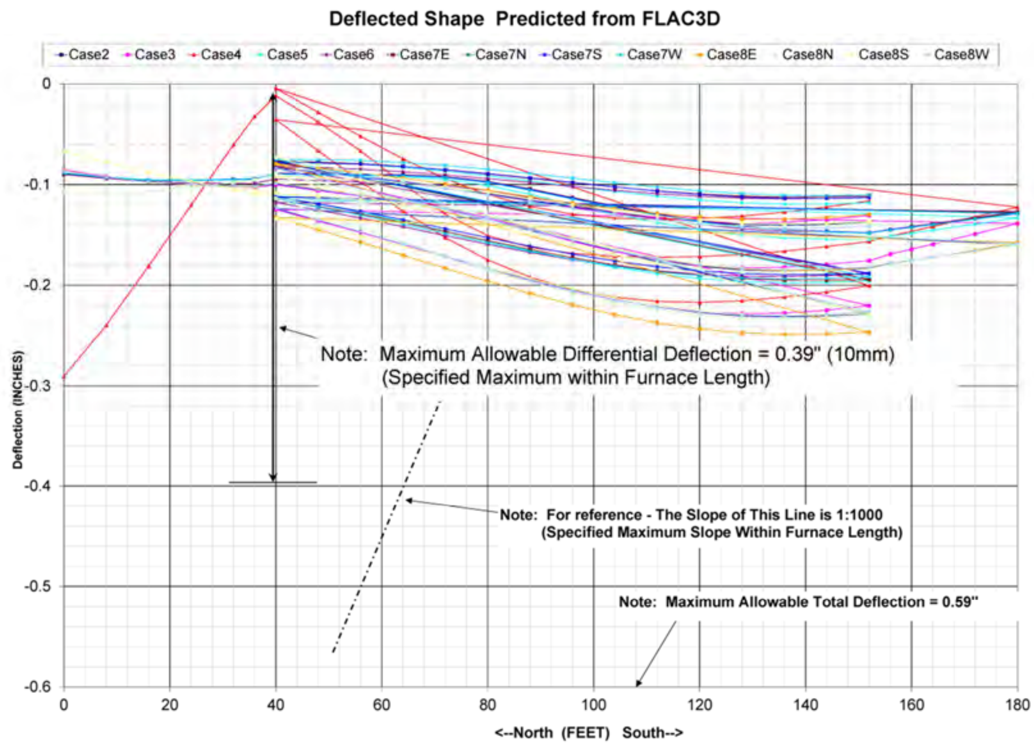

FIG 4. Predicted Top of Concrete Alignment under All 14 Load Cases

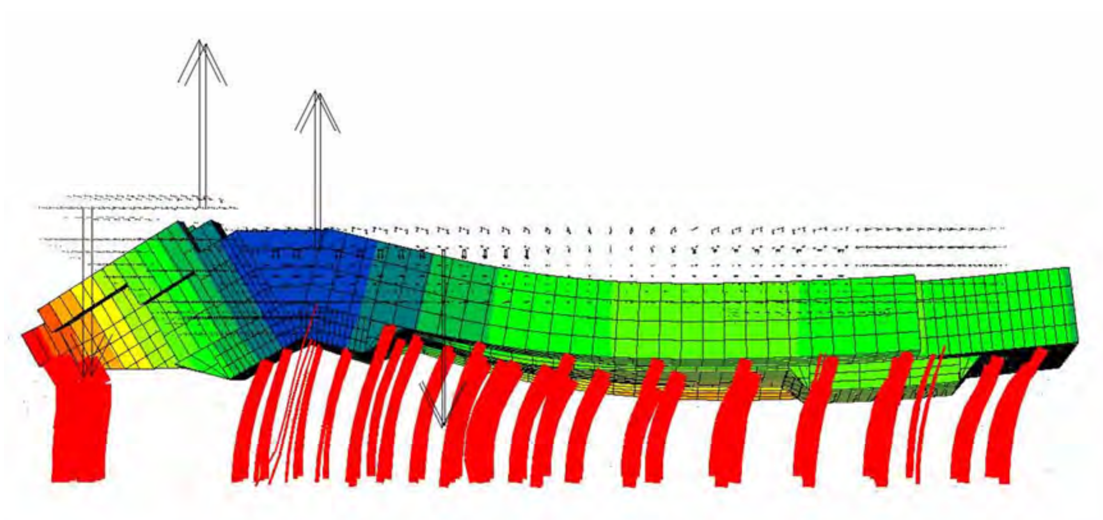

FIG 5. FLAC 3D Prediction of Exaggerated Deflected Shape

MICROPILE DESIGN

A combination of 140 mm (5.5 in), 180 mm (7 in), and 245 mm (9-5/8 in) casings were used on the project to serve as the permanent reinforcing for compression micropiles. Internal GR75 deformed reinforcing steel bars were used where high tension loads were predicted and in areas where the depth to bedrock would require additional stiffness of individual piles. The geotechnical borings suggested a depth to bedrock between 3 m (10 ft) and 10 m (30 ft) below the base of the concrete foundation. During micropile drilling the actual depth to bedrock varied between zero and 16 m (52 ft). The FLAC3D model was used throughout construction to continually evaluate the relationship between the elastic behavior of the micropiles and the flexural stiffness of the irregularly shaped mass concrete foundations. In many cases it was necessary to add steel to individual micropile cross-sections to provide a more uniform effective stiffness between adjacent piles of varying length.

Individual micropile compressive loads varied from 300 kN (67 kips) to 2,650 kN (596 kips) and the predicted actual load in a single micropile would change significantly from the original design in the cases where shallow bedrock resulted in a very short micropile. These short piles were expected to behave very stiff and, as a result, attract greater axial load. In these situations, it often was necessary to adjust rock socket lengths and pile cross-section to accommodate the greater axial load. Tension loads on the micropiles were only significant in the area where the foundation tended to bend upward under maximum pushing force during operation. Full length centralized reinforcing bars were utilized with a suitable top connection to the mass concrete foundation.

A typical micropile design for this project is shown in Figure 6. In the micropile cross-section shown, notice that there are actually three telescoped sections of permanent casing used in the design. This type of construction was necessary where the depth to bedrock was deeper than expected and additional stiffness was required beyond what could be achieved with a full length reinforcing bar or bar bundle. In all cases, the main casing responsible for handling the vertical design load was extended to the bottom of the rock sockets using an overburden drilling system where the casing is advanced as the hole is drilled.

CONCLUSIONS

Adaptable construction techniques available with micropile construction came together with numerical modelling using FLAC3D to allow successful completion of this technically challenging project. In order to design for manufacturer's deflection criteria, the foundation analyses using FLAC3D explicitly considered the varying bedrock depths and numerous complex loading scenarios during production pile installation. On the basis of the results of the analyses, the micropile design was essentially continuously throughout construction adjusted (by either adding or subtracting micropiles or changing the cross-section detail) to best meet the deflection criteria. .

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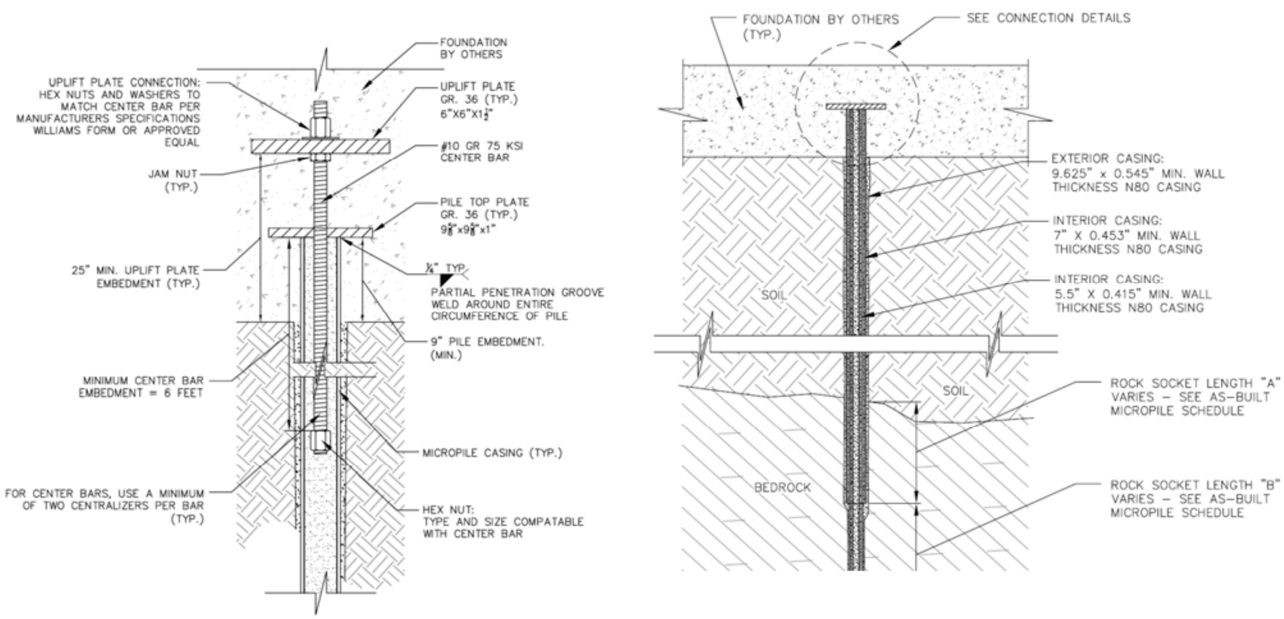

FIG 6. Typical Micropile Designs