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THE UNIVERSITY OF TEXAS AT ARLINGTON

OVER THE MOUNTAIN AND THROUGH THE SWAMP
Foundation Alternatives for Extreme Access Conditions

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Introduction

With aging electrical infrastructure and steadily increasing power demands in North America, there continues to be strong investment in the electric transmission and distribution sectors. Transporting electricity to urban areas increasingly requires construction through environmentally sensitive areas, rugged terrain, and challenging geotechnical conditions, resulting in significant foundation challenges.

Micropiles have been instrumental in overcoming foundation design and construction obstacles on several high-profile projects over the past two decades. The necessary materials and installation equipment can accommodate access challenges and construction footprint requirements. Additionally, specialized design and installation methods allow each foundation to be adjusted for site-specific conditions during construction, removing much of the geotechnical risk. Innovative steel and concrete pile cap designs drive innovation and economy into these foundation structures, further augmenting the solution.

This paper will present the impact of micropile foundations and related design techniques on the success of electric transmission development, and illustrate this success through two recently completed projects.

Micropile Overview

Micropiles have been used throughout the world since their development in Italy in 1952 (FHWA, 1997). In North America, the use is somewhat more recent, and is widely considered a specialty geo-construction technique, with most of the technical knowledge residing with the contractor. The industry standard for design and construction utilizing micropiles remains the FHWA State of Practice review in 1997 and updated in 2005. There have been major efforts made in the quest for a “unified” design approach, including publications by AASHTO and the IBC in recent years. For micropiles however, the FHWA manual remains the most comprehensive resource available to designers to date. The Deep Foundations Institute (DFI) is currently developing a comprehensive foundation design guide through its Electric Power Systems Foundations Committee, which will focus on micropile state of the practice as well.

Micropiles are a small diameter (typically less than 12 inches), high-capacity drilled and grouted replacement pile. In the electric transmission industry, most foundation designs utilize composite micropiles reinforced with a solid threaded bar and steel casing. They are constructed by drilling a borehole through overburden material and into a bearing stratum, placing reinforcement, and grouting. They are capable of resisting axial tension and compression with applied lateral load. While similar in makeup to a grouted anchor, the design of the pile for buckling and combined loading differentiate this pile element from traditional anchor type components.

Micropiles have a cased upper section, composed of steel tubes, and an uncased lower bond section, which develops friction with the surrounding bearing stratum. The cased section interacts with the surrounding soil or rock to provide lateral capacity to the foundation. The piles are also reinforced with a high-capacity threaded steel bar, which extends from the top of the pile through the lower bond section, transferring axial force through friction with the grout and ground. Micropiles are capable of developing very high axial loads, 400-500 kips, in rock and highly consolidated strata. They are generally designed in a group or array to resist lateral loading and overturning moment through composite action with a steel or concrete pile cap. The pile group works in tension and compression to resist overturning as shown in Figure 1.

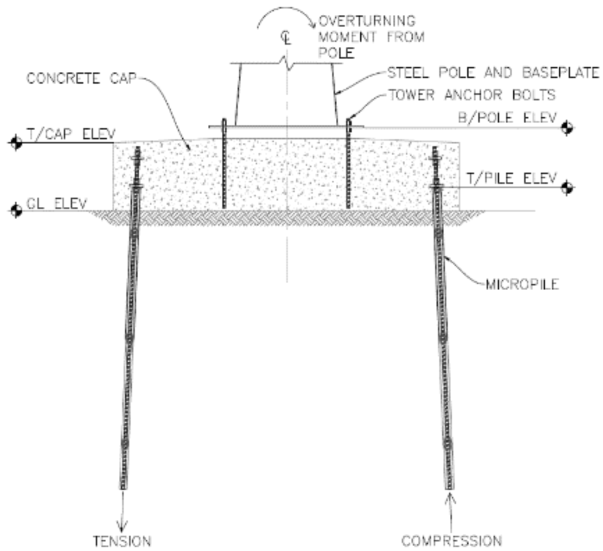

Figure 1: Micropile Tension and Compression

Micropiles are advantageous to projects with one or more significant geological, structural, logistical, environmental, access or performance challenge. They are an especially favorable option where:

- The subsurface conditions are "difficult", e.g., hard rock, soils with boulders/debris, existing foundations, high groundwater
- There is restricted access and/or limited overhead clearance
- There are subsurface voids (e.g., karstic limestone)
- Vibrations and noise must be limited
- Structural settlement must be minimized
- Relatively high unit loads (e.g., up to 450 kips axial for a single pile) are required

The various micropile types (A, B, C, and D) are defined by the drilling and grouting methods employed during installation (FHWA, 1997). The selection of the micropile type will usually be left to the discretion of the contractor and dictated by the applied loading and subsurface conditions. Foundations designed for the projects detailed in this paper consisted of a varying number of grouped micropiles arranged in circular arrays. The piles were battered away from the center of the arrays and derive their axial capacity through interaction with the native soils/bedrock. The interaction of the piles with the pile cap, the type of pile to cap connection, and 3D geometry of the pile group, all contribute to the composite stiffness of the foundation.

A Foundation Schedule was prepared for each foundation to specify the required capacity over a range of anticipated geotechnical materials and foundation reveals/projections. Micropile installation requirements were defined by the Foundation Schedule for each foundation site. Micropile cased lengths and bond lengths were identified on the Foundation Schedule and selected based on a patented method of material characterization during installation of the first pile at each foundation.

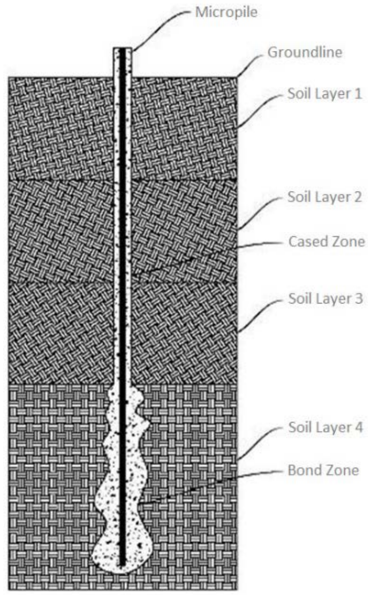

Figure 2: Micropile Installation Schematic

As an industry standard, micropile-supported foundations are load tested to validate a variety of design assumptions. These include installation methods, design axial load capacity, and assumed geotechnical bond strengths. Micropiles are typically tested axially, in either tension or compression, at defined loading increments up to a predefined ultimate test loading, with total pile deflection measured at specific intervals. The two primary load tests performed as part of a construction project are Ultimate/Verification Tests, to determine or validate the ultimate geotechnical grout-to-ground bond strength used in the design; and Proof Tests, to verify axial strength and deflection capacity at specified design loads.

Case Study: Construction Through Protected Wetland

The Susquehanna to Roseland Electric Reliability Project is a 500 kV transmission line spanning from Berwick, Pennsylvania to Roseland, New Jersey. A portion of the alignment crosses Troy Meadows, a 3,100-acre freshwater marsh. The area has been designated as a Priority Wetland by the U.S. Environmental Protection Agency as well as a National Natural Landmark by the National Park Service. Within the protected area, the project scope included replacement of seven lattice structures with new double-circuit 500 kV monopoles in the existing right of way. Micropiles were employed as a foundation alternative at all seven structures.

Micropile Selection

A variety of conventional foundations, including drilled shaft and driven pile, were initially considered, but transportation of the necessary equipment and materials would have required extensive timber matting. This was determined to pose too many cost and schedule risks, and helicopter-supported concrete cap micropile foundations were ultimately selected.

The foundations could be installed with lightweight, componentized equipment and materials, making them conducive to light and medium lift helicopter transportation. The compact nature of the equipment also allowed for a minimized area of temporary and permanent disturbance, which was crucial within the wetland. Finally, micropiles had the unique ability to efficiently bridge through weak soils and reach underlying bedrock. The project team opted to employ a design-build delivery method, which they believed created the highest level of risk management and assurance of on-time project completion.

Geotechnical Conditions

Initial geotechnical investigations were tailored for drilled shaft designs founded in weak overburden materials, and several borings terminated prior to reaching bedrock. Micropiles are highly effective when founded in rock, so this left some geotechnical uncertainty as micropile design commenced and required designers to speculate using the available information. The initial steps of micropile installation can serve as a geotechnical boring, allowing the contractor to characterize the site and adjust the foundation to site specific conditions. Table 1 summarizes the anticipated geotechnical conditions on the alignment, consisting of weak cohesive soils over bedrock at variable depths of approximately 50 feet to 110 feet below ground surface.

Table 1: Expected Geotechnical Conditions

Depth	Soil Type	Average N	Fringe Angle	C (psf)	Unit Weight (psf)
0-5.5	Peat/Organic	0	0	250	100
5.5-40	Stiff Clay	14	0	940	125
40-51	Hard Clay	30	30	100	130
51-65	Very Dense Gravel/Sand	100	36	-	135
Variable	Sandstone	100	-	-	145

Rock quality was also a variable in the design, so a location was selected to install a sacrificial Ultimate Test pile to verify the assumed ultimate grout-to-ground bond stress in the anticipated rock type common to this area. This test validated the use of a 200 Psi ultimate grout-to-ground bond strength for the piles founded in bedrock.

Value Engineering

Prior to foundation construction, two rounds of value engineering were completed, effectively decreasing the number of micropiles and the total disturbance area of the foundation. The first round investigated altering the original conceptual foundation design supplied by the contractor, which featured larger diameter micropiles utilizing a bolted steel pile cap. While steel pile caps can provide a variety of benefits to project cost and schedule, the magnitude of tower loads and difficult geotechnical conditions within Troy Meadows were not conducive to an economical steel cap design. Changing the cap material from steel to concrete improved the fixity between the piles and cap, and eliminated the field fit-up associated with the bolted steel cap. The revision to the cap design led to a reduction in micropile casing diameter and a more efficient layout of individual micropiles.

The second round of value engineering analyzed the use of site-specific directional structure loading. By utilizing directional loading components, longitudinal and transverse to the tower orientation, and individual load combinations, the foundation design team was able to reduce the size of the concrete pile cap. The resulting design modified the circular cap to a rectangular shape, successfully decreasing the total permanent wetland disturbance area by 33%.

Figure 3: Value Engineered Concrete Pile Cap

Design

Micropiles and pile caps were designed to satisfy strength requirements by utilizing the maximum directional structure reactions applied longitudinally and transversally to the foundations. The reactions were provided by the pole manufacturer and listed as a group of individual load combinations. All load combinations were individually considered to ensure an economical design could be achieved by eliminating the traditional enveloping of maximum foundation reactions. Representative tower loads are shown in Table 2.

Table 2: Controlling Reactions for 190 Ft. Tower with Overload Factor

Case	Axial (kip)	Trans. Shear (kip)	Long. Shear (kip)	Trans. Moment (kip-ft)	Long. Moment (kip-ft)
Transverse	218.1	155.9	0	19251	12.1
Longitudinal	413.7	33.7	56.8	4371	11307

The micropile analysis subjected pile groups to vertical, lateral, and overturning loads in a three-dimensional model for symmetric and asymmetrical pile groups. The pile head condition was reviewed as fixed, pinned, or elastically restrained by the pile cap *(GROUP, 2013).* The designer generated the nonlinear response of the soil in the form of t-z and q-w curves for axial loading, t-θ curves for torsional loading, and p-y curves for lateral loading in flat ground conditions. A unique solution requires iterations to accommodate the nonlinear response of each of the piles *(Reese, 2001)*. The equations of equilibrium are satisfied, and compatibility is achieved between pile movement and soil response, and between the movement of the pile cap and the pile heads. Following numerous design iterations, a final micropile solution for each soil unit was chosen. The designer solved for individual-pile loads (axial, shear, and moment) and the maximum internal stress in each pile. Through analyzing this data along the length of each pile, the depth-to-fixity of the pile casing (the depth below which the casing is no longer needed to resist lateral loading) was determined. The designer also considered vertical, lateral, and rotational foundation deflections. The number of micropiles, casing size, and minimum casing embedment were selected for each foundation option to efficiently satisfy loading and deflection criteria, and were summarized in a Foundation Schedule for each structure.

The geotechnical report included soil corrosivity tests at several micropile foundation locations, which indicated that aggressive soils would be encountered. The designer conservatively chose to follow a corrosion resistance method which used a sacrificial steel thickness of 4 millimeters applied to the radius of the casing for a 75-year design life in accordance with recommendations in FHWA NHI-05-039.

The structural concrete pile cap was designed in accordance with American Concrete Institute (ACI) standards using Load and Resistance Factor Design (LRFD) methodology *(American Concrete Institute, 2008)*. Embedded steel elements in the concrete pile cap were designed in accordance with the current edition of the Steel Construction Manual published by the American Institute of Steel Construction, Inc. (AISC) using LRFD *(American Institute of Steel Construction, 2008)*. The Micropiles were designed using the methods of FHWA Micropile Design and Construction Guidelines (FHWA 2000), in combination with LRFD methodology per AISC and ACI.

Foundation Construction

Once it was determined that helicopter support and micropile foundations would be employed, individual activities needed to be scheduled within a condensed project time frame. The construction schedule for this section of the project was governed by when the contractor could gain access and when the contractor had to complete work. An active bald eagle nest located in close proximity to the ROW further limited construction within the wetland habitat to a 106-day window, with just 60 days allotted for foundation work.

Figure 4: Drill Site Setup

As shown in Figure 4, lightweight and componentized drill rigs were utilized, providing for efficient helicopter transport. In addition to the previously mentioned access constraints, special construction considerations included drilling spoils containment with the presence of standing surface water, concrete placement within a protected habitat, and support of heavily loaded structures in deep, soft soils. The tubular steel pole design loads were approximately 20,000 kip-feet overturning moment with 600 kips axial and 160 kips shear, and geotechnical reports suggested rock at depths ranging from 80 to 120 feet.

The uncertainty of depth to rock and rock quality prior to installation necessitated designs be developed for both Type A and Type B micropiles. Type A micropiles are gravity-grouted piles installed in rock or other consolidated material. Type B refers to low-pressure-grouted micropiles installed in unconsolidated materials. Pressures for a Type B micropile typically range between 20-200 psi, and neat cement grout is injected into the drilled hole as temporary steel drill casing or auger is withdrawn. A patented field characterization method was employed to determine the grouting method and adapt the pile design to actual geotechnical conditions at the time of installation. Geological characterization was completed during the drilling of the first pile at each foundation location, effectively determining the pile type, quantity, and depth for each structure. The accelerated project schedule did not allow for delays associated with redesign, and the ability to employ predetermined solutions removed much of the risk associated with limited geotechnical data.

A unique closed cell cofferdam setup was employed at each site to reduce construction impacts to the wetland. The setup consisted of curved steel sheets, weighing approximately 2,000 pounds. The sheets were driven into the ground to provide a stable platform for equipment in soft soils and groundwater, contain drill cuttings and fluids from entering the wetland, and act as a form for concrete placement during micropile cap construction. Cofferdams were constructed utilizing helicopter portable cranes and small excavators set onto local areas of crane matting. The use of this equipment significantly reduced helicopter hours, contributing toward schedule compliance and control of overall project costs. A rotating drill carriage and micropile drill were set on the cofferdam and used to install micropiles in an array of vertical and battered piles.

During the drilling operation, the portable cranes were used to handle casing and drill rods, which were staged on temporary crane mats as shown in Figure 5. The cranes fed the drill as piles were installed to depths ranging from 90 to 150 feet. The cranes also served to place micropile testing equipment during the verification test program at each foundation, and delivered reinforcing bar to the iron workers during concrete cap construction.

Following micropile installation, the drill and drill carriage were removed from the site to allow for pile testing, tying of rebar, and form construction. One production micropile was proof tested to the specified design load at each foundation. A pre-constructed anchor bolt cage was flown to the site and supported by the cofferdam. Concrete was flown with crane-type concrete buckets. A high early concrete design was chosen to accelerate sufficient strength for form removal, which allowed poles to be set as early as six days following concrete placement.

Summary

The use of micropile foundations contributed to the owner meeting an aggressive construction schedule within an environmentally protected area. Foundation work was completed ahead of schedule, and all seven monopoles were erected in just three days.

Innovative design and construction methods allowed for work to be completed with minimal impacts to the wetland. Accessing foundation sites by helicopter eliminated the significant risk associated with installing and managing a minimum of 108,000 square feet of matted access roads and 120,000 square feet of matted work areas. This also reduced the total impacts to the wetland by more than five acres. The use of the closed cell cofferdams allowed foundation crews to contain drill cuttings and fluids, and created a minimal area of impact from drilling activities.

Case Study: Construction Through Rugged Hawaiian Terrain

Micropile foundations can be equally beneficial to projects experiencing access difficulties due to rugged terrain and in-service lines. Hawaiian Electric’s Koolau-Wailupe 46 kV Structure Replacement project involved upgrading several wooden structures to self-supporting steel poles on the island of Oahu. Once complete, the Koolau-Wailupe segment will link to the Koolau-Poahakupu line, crossing through mountainous terrain from Honolulu to Waimanalo. The project featured steep, rugged slopes and unpredictable weather patterns, with the added challenge of working under existing overhead lines.

Figure 5: Helicopter Transporting Material to Foundation Sites

Micropile Selection

Road construction to a number of replacement structures was unfeasible, and it was determined these sites would require helicopter-only construction methods. Faced with these access challenges the owner began to explore deep foundation alternatives that would accommodate all project requirements. As detailed previously, the equipment and materials necessary for micropile installation can be efficiently transported by medium and light lift helicopter. Micropiles can also accommodate low overhead clearances, allowing for new foundations to be constructed within the general footprint of existing foundations, and enabling existing lines to remain energized throughout construction, which was a main concern on this project. Ultimately, the owner determined micropiles offered an efficient solution, and specified micropile foundations for 13 tubular steel poles.

Geotechnical Conditions

The owner provided limited geotechnical data, including three borings in the proximity of six of the replacement structures, requiring initial designs to be based on representative and non-site-specific data. Anticipated conditions derived from this representative information are included in Table 3.

Table 3: Typical Subsurface Profile Reported in Geotechnical Data

Sub Layer		Material Description	Dry Density (pcf)
Top (ft)	Bottom (ft)		
0	15	Saprolite (MH)	55-80
15	30	HW Basalt	105
30+	-	Saprolite (MH)	90

The majority of the replacement structures were located on steep, narrow ridges comprised of an inconsistent matrix of saprolite and highly weathered bedrock. Saprolite, characterized as elastic SILT (MH) in the provided geotechnical data, is a chemically weathered rock that forms in the lower zones of soil profiles and can create major foundation challenges. The material behaves as a soil in engineering terms, but may still exhibit some rock properties. Precise identification of saprolite zones was integral to micropile design and the successful performance of the foundations. Detailed onsite monitoring allowed the foundation contractor to accurately identify areas of concern, avoiding any related complications.

The highly-weathered basalt bedrock exhibited strengths similar to hard and very hard soil, and was easily penetrated with the auger drill equipment used in original explorations.

Design

Micropile foundation designs were developed to resist maximum ground line moment reactions ranging from approximately 300 ft-kips to 3,800 ft-kips. The designs included a varying number of micropiles arranged in a circular array and connected utilizing a steel pile cap. Steel pile caps were selected due to their ability to be prefabricated and set in one helicopter trip. The micropiles were battered away from the center of the array and derived their capacity from the native soils/bedrock.

The same patented field characterization method employed in the Troy Meadows project was utilized to optimize designs at the time of construction. Detailed Foundation Schedules provided foundation capacities in a range of expected materials, considering the impact of adjacent slopes, the variable nature of the subsurface conditions, and the limited geotechnical data available at the time of design. Three, six, and eight-pile designs were developed to support the varying pole types selected. Site topography also played a major role in micropile orientation and layout. Custom lateral resistance models were developed to account for variable pile stiffness based upon site slope and individual pile reveal, leading to a 3D model that more accurately represented load redistribution based on overall foundation stiffness.

Pile caps were designed as single steel plates with large openings to accommodate the micropile alignment tolerances required by the contractor. Given the omnidirectional loading applied by the steel poles, the caps were designed using finite element analysis to better predict bidirectional stress and stress concentrations around the openings in the steel plate. The plate surface stresses, as illustrated in Figure 6, are reported as Von Misses Stress at the top and bottom of the elements. Steel caps ranged from 2.25 to 3.75 inches in thickness and 58 to 76 inches in diameter. Geological characterization completed during the drilling of the first pile at each location determined the number and length of piles, as well as cap specifications for that foundation.

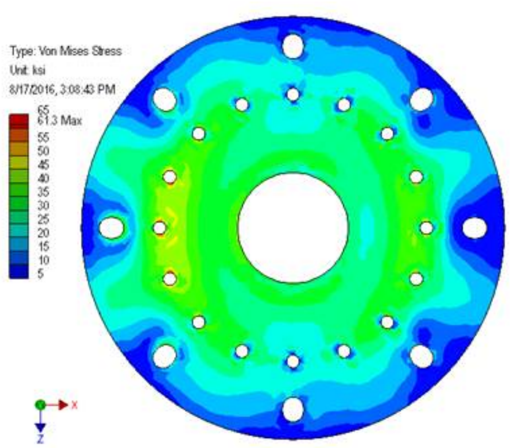

Figure 6: Autodesk Inventor Output Showing Localized Stresses at the Surface of a Cap

Construction

Specialized micropile drills were broken into helicopter-portable components and transported to foundation sites. Leveling drill platforms were placed, providing stable surfaces for equipment and materials, neutralizing the steep slopes, and minimizing excavation requirements in the rugged terrain. The platforms also provided a template for the rotating micropile drill, allowing for all piles in each array to be installed without relocating the drill or requiring helicopter support. A typical site setup is shown in Figure 7.

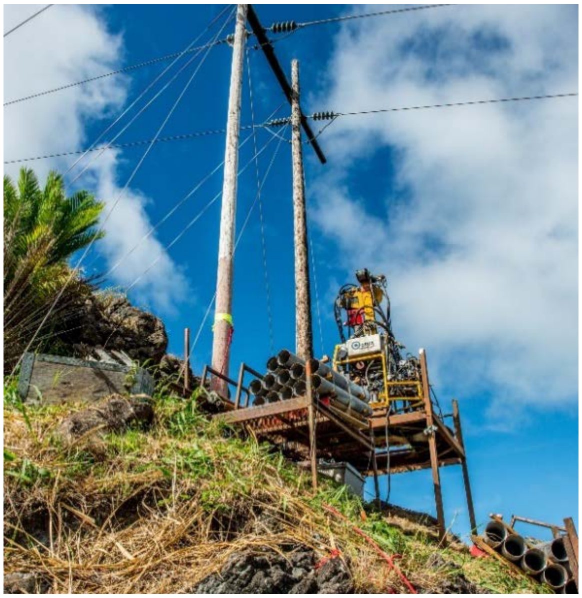

Figure 7: Steep Slope Configuration

Brief outages were permitted during helicopter operations to place and remove equipment, but all drilling activities took place under in-service overhead lines. The lines sat approximately 25 feet above ground line and had a Minimum Approach Distance (MAD) of 10 feet, requiring the total combined height of the micropile drill and platform to be less than 15 feet above ground line. Casing and all thread bar with the ability to be installed in variable section lengths efficiently accommodated the required MAD as well.

Extreme and unpredictable weather compounded project challenges, including strong winds, rain storms and heavy fog. To minimize schedule impacts, crews needed to be prepared to move on and off foundation sites quickly during windows of opportunity. The use of steel pile caps allowed crews to take full advantage of these short windows, as they are fabricated in an offsite facility and set in one helicopter trip. Compared to concrete pile caps, the use of steel caps reduces helicopter use by an average 74% and onsite labor time by an average 64%.

Figure 8: Installed Steel Pile Cap

Summary

The Koolau-Wailupe project illustrates micropiles as a deep foundation solution for electric transmission structures in rugged terrain and on steep slopes, featuring low overhead clearance. Where conventional construction methods were not possible, and the ability to construct the foundations exclusively by helicopter support provided the owner with a constructible alternative. Leveling platforms and segmented materials offered additional benefits to construction, and the use of innovative steel pile caps enabled the project team to work flexibly around a variety of weather-related challenges.

Concluding Statements

Micropiles provide a unique solution to developing high capacity foundations for areas with limited access, challenging geotechnical conditions, and environmental sensitivity. Utilizing lightweight and helicopter transportable equipment and materials allows for installation that generates a minimal area of impact. The ability to characterize actual site-specific geotechnical conditions during the installation of the micropiles, allows for pre-design activities to occur with little or no geotechnical input and real-time field optimization to occur.

Installation of prefabricated steel pile caps has generated a significant advantage to schedule and safety on these challenging construction sites. The implementation of lightweight steel caps has been precipitated through the use of advanced finite element analysis techniques. Utilizing these techniques to validate plate deflection, buckling, and yielding, and to determine welding requirements based upon principal plate stresses, allows for a significant reduction in total pile cap weight. This is critical to limiting the lifting demand placed on construction helicopters.

Utilizing similar advanced techniques for concrete analysis has created vastly more economical concrete pile cap designs. By pushing installed micropiles further apart and utilizing concrete caps to support structures over the longer spans between piles, substantial overturning moments can be resisted. By making use of concrete cap thickness dictated by site and structure geometry, economical reinforcing layouts can be employed, allowing for rapid construction and more field tolerance.

The pursuit of renewable resources and increased energy demands combined with expanding developed areas and increasing environmental restrictions, will continue to push electrical transmission into more remote areas. As construction challenges are encountered in these areas, foundation designers will be pushed to find foundation solutions that are constructible with smaller pieces of equipment and smaller areas of impact. Micropiles have proven to be an efficient solution to these challenging construction sites.

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