Seismic Design of Micropile Foundation Systems

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Over the last decade, drilled and postgrouted micropile foundations have come to be increasingly relied on for resisting seismic loads in building foundations on the West Coast. Micropiles have been successfully deployed in a range of soil conditions, in vertical as well as battered configurations, to support a variety of structural systems on difficult soils. Three factors have made micropiles indispensable in the seismic strengthening of existing structures: their high-load capacity in tension and in compression, and the practicability of installing them in confined spaces with minimal overhead clearance and of directly testing them once installed.

More recently, growing industry experience, along with improvements in design guidelines, have led to wider acceptance of micropiles among engineers and building officials. The increasing availability of the specialized materials, coupled with growing familiarity with drilling technologies among design-build contractors has made micropiles a more cost-effective and competitive option. For the first time, micropiles are finding applications in the construction of new buildings, where they are combined with shallow footings in hybrid foundations to efficiently resist seismic loads. These new applications rely on more intensive engineering analyses to evaluate the performance of micropile foundation systems and develop detailed requirements for design and construction. This paper describes the design approaches and the analytical methods for the seismic design of hybrid micropile foundations and provides examples of recent construction projects that demonstrate the application.

INTRODUCTION

The inherent difficulties of designing complex deep foundation systems, particularly those supporting high-performance structures, necessitate advanced modeling techniques to adequately capture soil-structure interaction during seismic loading. Balancing cost with seismic performance places more emphasis on the accuracy of analytical models to minimize the number of micropiles required in a given application. Doing this effectively requires a more detailed way of characterizing micropiles, which considers their behavior under cyclic loading and the mode of failure at ultimate capacity.

Translating the necessary design considerations into construction and verifying the adequacy of the installation relies on establishing a performance envelope or backbone curve. The performance specifications for the drilling contractor typically define the performance envelope as a set of limits on forces and deformations at various load increments.

A key aspect of this approach is the emphasis on controlling deflections, which relies on a project-specific field testing program for assurance. The practicability of testing installed micropiles not only provides quality assurance but also provides a wealth of data from field testing that informs the analytical process and results in a more efficient design of the deep foundation system.

Examples of recent construction projects around the San Francisco Bay Area are presented to highlight a variety of design solutions using standard micropile installations. These demonstrate how recent innovations in design, analysis, and construction techniques have facilitated the rapid adoption of micropiles in seismic country.

BACKGROUND

The seismic design of buildings has been undergoing significant shifts driven by an enhanced understanding of structural behavior, improved analysis tools, and advances in seismic hazard characterization.

Observed damage to buildings in recent earthquakes, ongoing laboratory research, and an increasing emphasis on performance-based design have provided insights into the building of more seismic-resistant structures and have led to an evolution in building codes. The most significant aspect of these shifts is a greater focus on deformations as a measure of seismic damage, rather than just the consideration of forces.

It is difficult to overstate the role of advanced engineering analysis tools and techniques in the evolution of seismic design. The recognition that earthquake forces are the only ones under which the structure is actually expected to yield requires an assessment of inelastic response and dynamic effects. Conventional elastic analyses often are not adequate for seismic design. Making sufficiently accurate estimates of seismic response requires sophisticated analysis tools, with detailed material and non-linear dynamic modeling capabilities. Most of these are recent developments in engineering practice and still relatively specialized.

Moreover, advances in seismology are now providing a more complete picture of earthquake hazards on a probabilistic basis. While site-specific ground-motion hazard spectra are fairly standard for larger projects, there is an increasing amount of emphasis on using simulated ground-motion histories to analyze structures. These offer the most reliable way to evaluate seismic performance methods.

These shifts have allowed engineers to evaluate and design structures using a more rational approach and greater precision. Simultaneously, drilling contractors have been gaining experience with micropile installations using a variety of materials and methods. The increased familiarity with micropile systems, along with wider availability of large-diameter, high-strength reinforcing bars has led to a more competitive market, pushing micropiles into the mainstream of deep-foundation solutions.

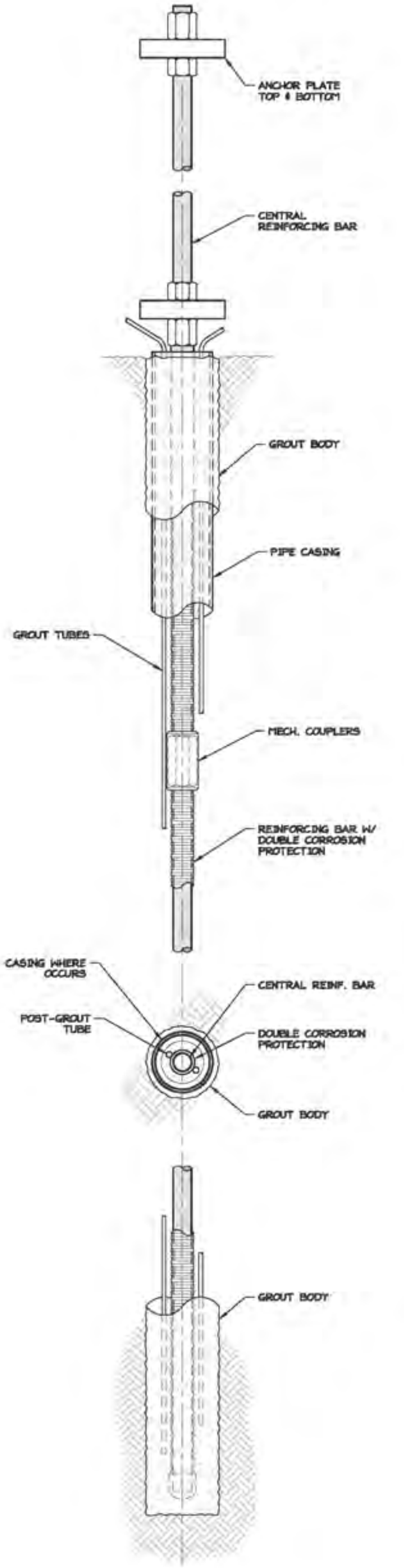

Figure 1: *Detail of a typical seismic micropile*

SEISMIC APPLICATIONS

The typical application consists of a single reinforcing bar, ranging in diameter from 1½ to 3 in., placed in a 9 to 12 in. diameter drilled hole, with lengths between 60 to 100 feet, as shown in Figure 1. Depending on the requirements for strength and stiffness, the central reinforcing bars may consist of mild-steel or high-strength threaded bars. The central bar is made continuous with mechanical couplers and typically incorporates double corrosion protection. The installation also often includes a permanent steel casing at the upper portion of the pile. To maximize effectiveness, the micropiles are typically postgrouted under high pressure shortly after their installation to enhance the bond between the grout body and the surrounding soil. The configuration of the pile depth, the drill diameter, the reinforcing, and the grouting method is adapted on a project-to-project basis to suit specific load requirements and site conditions.

Micropiles are used extensively in renovation projects that involve seismic strengthening to provide foundation support to resist overturning forces delivered by shear walls or braced frames. In some cases, battered micropiles are installed to transfer lateral loads efficiently on sloping sites or for laterally stabilizing elevated ground floor slabs as shown in Figure 2.

Micropiles can provide very high resistance values relative to the cost and size of installation, with a range of ultimate strengths between 200 and 600 kips. They can also be installed in a wide range of soil and site conditions, with little noise or ground vibration. However, their performance is sensitive to drilling and grouting methods, which can vary significantly depending on the drilling equipment and soil conditions.

In the past, micropiles foundations were most cost effective in confined situations inside existing buildings with limited overhead clearance, where few alternatives are available. Recently, micropiles have become more competitive against traditional deep-foundation solutions for new structures.

Owing to their compact size, they can be integrated with footings and mat slabs to create hybrid foundations that develop resistance through a combination of bearing on the soil surface as well as through pile skin friction at depth.

Figure 3 depicts the example of a fourteen-story structure supported by a mat-slab foundation, which is augmented with micropiles for seismic loading. Figure 4 shows the underside of the foundation system. These kinds of applications have created new opportunities, innovations, and engineering challenges, which require a more detailed analytical approach.

DESIGN AND ANALYTICAL APPROACH

For large and complex structures in seismic zones, nonlinear dynamic shaking simulation models are often used to validate the design. These analyses are geared towards making accurate predictions of structural displacements during earthquakes of varying magnitudes. The flexibility of the foundations supporting the seismic load-resisting system can have a significant contribution on the overall movement of the structure above and can have adverse impacts on the design if not

Figure 2: *Battered micropile installation in an existing structure*

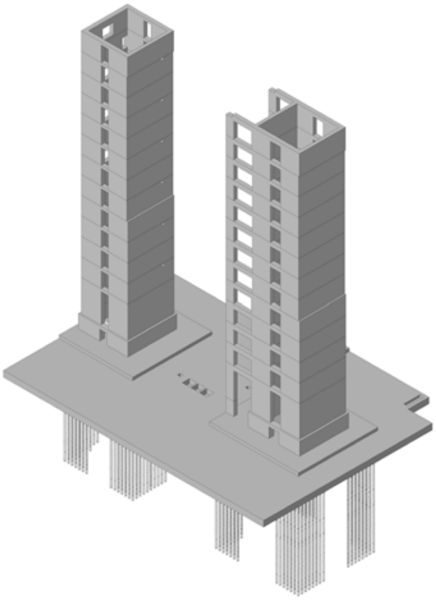

Figure 3: *Concrete shear walls supported on a hybrid foundation*

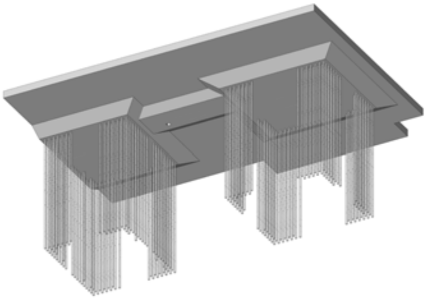

Figure 4: *Underside of hybrid mat-slab micropile foundation*

properly accounted for. This is particularly important in hybrid foundations, where micropiles are used in combination with footings that bear directly on the soil. In these systems, the behavior of the soil and piles has to be accurately analyzed to ensure that the stiffness of the piles is compatible with that of the soil in bearing.

While the strength capacity of an individual micropile can be determined reliably using standard geotechnical methods based on ultimate skin-friction values, predicting the deformation of a micropile at a given load is a much more difficult task. Soil frictional resistance can be highly non-uniform and depends on the way in which the post-grouting affects the surrounding soil matrix. As a result, a more sophisticated approach, relying on calibrated test results, is required to make accurate predictions of actual micropile response.

The fundamental step in design of micropile systems is the selection of the "backbone" curve defining the performance envelope of the piles as described in Figure 5. The initial values for the required pile strength and stiffness are determined based on global seismic demands on the structure and expected soil friction capacities. Establishing these initial parameters on the basis of field test data from previous installation relies on experience and engineering judgment and is best done through close collaboration between the structural engineer, geotechnical engineer, and the drilling contractor on the basis of soil conditions and test data from similar installations.

The dashed line represents the minimum performance envelope. The dark solid line represents the mean of tested values.

A further consideration is the response of the micropile when subjected to repeated cycles of loading and unloading as described in Figure 6. A certain amount of energy is absorbed as loads are cycled depending on the deformation magnitudes and frictional stresses developed along the pile surface. This hysteretic behavior of the piles can have a significant impact on the analysis results and needs to be modeled accurately, based on calibrated field tests, to adequately capture the seismic response of the structure.

A plan view of the sample hybrid foundation is shown in Figure 7, indicating the arrangement of micropiles in clusters around the main concrete walls. For this application, the micropiles were designed to develop approximately 350 kips, at a target displacement of ½ in., with an ultimate capacity of 600 kips at 1 in. of displacement. The piles were drilled

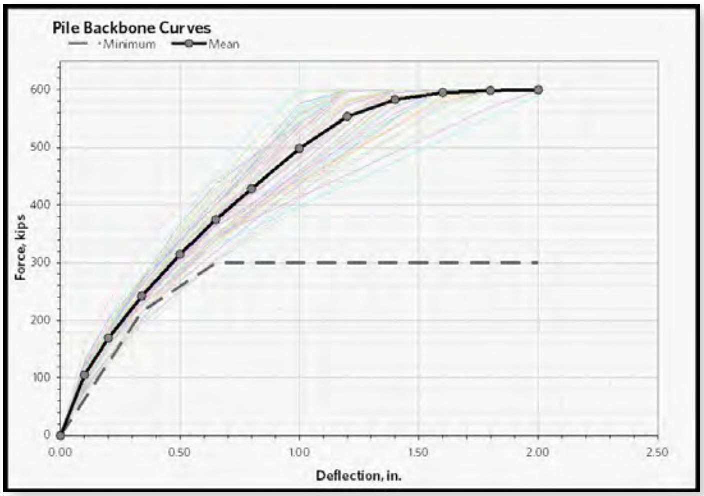

Figure 5: *Micropile backbone curves comparing minimum criteria with tested values for piles*

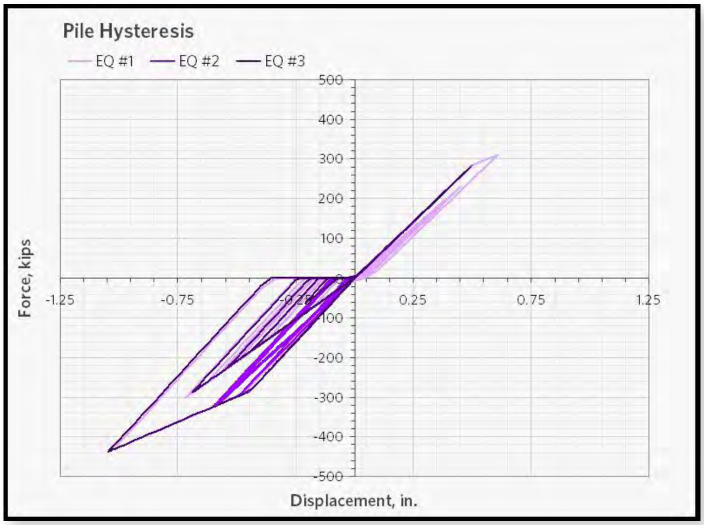

Figure 6: *Cyclic response modeling of micropile*

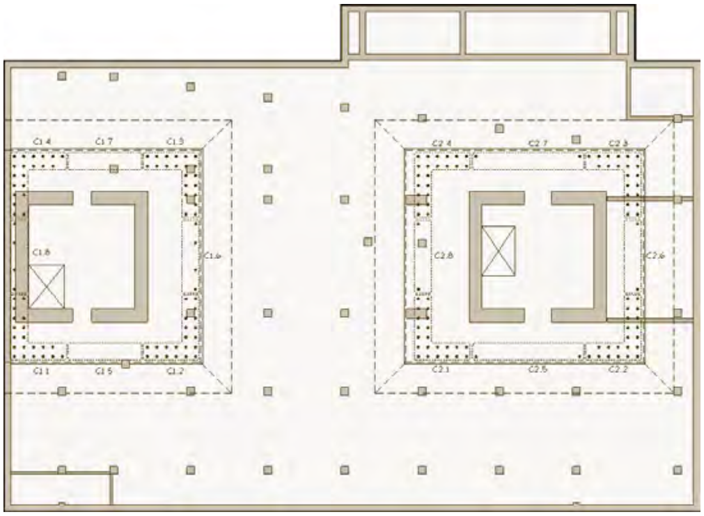

Figure 7: *Plan view of hybrid mat slab foundation showing micropile clusters*

to a depth of 65 ft. with a nominal grout body diameter of 10 inches. The micropiles incorporated a 3 in. diameter high-strength reinforcing bar and an 8 in. diameter steel pipe casing at the top 10 feet. They were post-grouted typically a day after the initial grout placement.

The spring values for each cluster are adjusted to reflect the sum of the expected response of the piles in that cluster. The spring elements representing the clusters of micropiles are grouped and calibrated according to the backbone curves. The springs representing the behavior of the pile are combined with the entire structural model, as shown in Figure 8, to capture the effects of structure–foundation interaction for seismic analysis.

Figure 9 shows the combined backbone curves for each of the pile clusters in comparison to the performance envelope. The amount of stretch under tension is greatly affected by the inelastic action of the bond between the grout body and the soil and cannot be determined accurately without the explicit consideration of slippage and yielding along the interface.

Typically, the initial verification tests for a project provide the opportunity to investigate and confirm the mechanisms of load transfer from the micropile to the surrounding soil. Coupled with the data obtained from the soil borings, the testing data can provide a reasonably accurate estimate of pile elongation under load.

Verifying key design assumptions regarding maximum stresses in the soil and the effective stiffness of the piles under different loading conditions is done using nonlinear substructure models that incorporate distributed soil springs along the full bond length of the pile. These soil springs successively transfer forces from the top of the pile to soil strata at increasing depths until equilibrium is reached. A diagram of this model is shown in Figure 10.

On the left side of the figure is the nondeformed condition of the pile and springs. The top end of the pile model represents the connection of the central reinforcing bar to the concrete foundation. Below that are individual friction springs representing soil properties within each horizontal stratum. The pile models towards the right of the figure show the distribution of slippage and yielding of the soil bond as the force applied at the top of the pile is increased. At the peak load, the model indicates that maximum soil stresses have been mobilized along the entire design length of the pile.

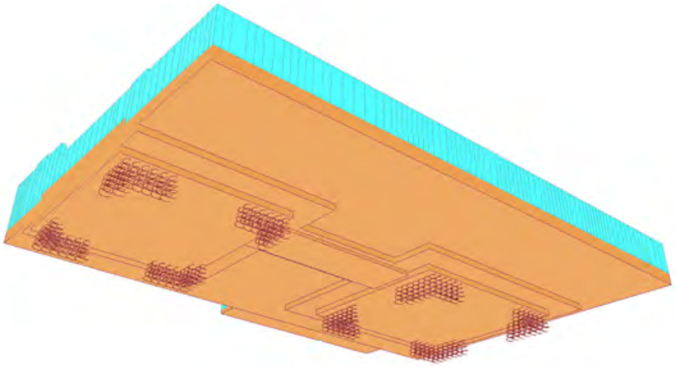

Figure 8: *Structural-analysis model, hybrid foundation*

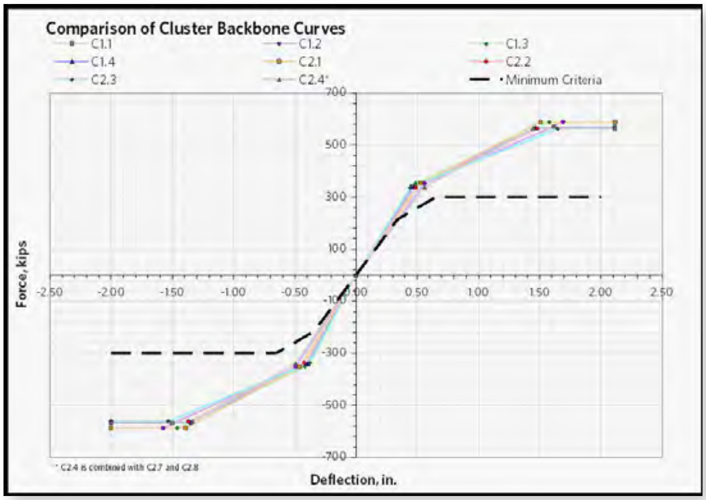

Figure 9: *Comparison of pile clusters*

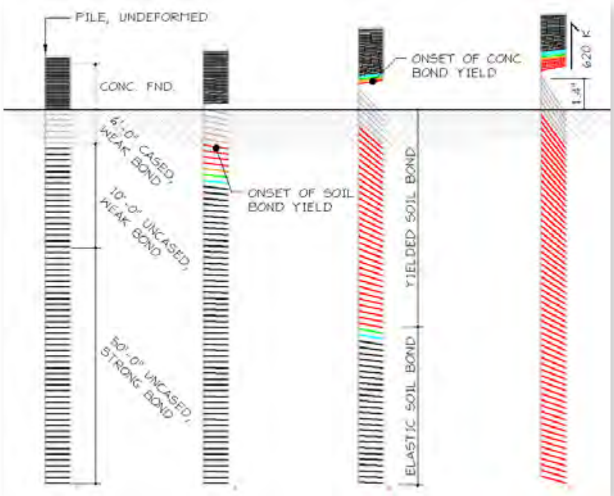

Figure 10: *Nonlinear micropile friction bond model*

The graph in Figure 11 shows the force distribution in the pile along its length under increasing loading, based on the nonlinear soil-bond model. The graph also shows how the complex load shedding from the pile to the soil occurs at ultimate loads.

When calibrated to field tests, these analytical methods can yield detailed information about the expected stiffness of micropiles to inform the design of the building as a whole.

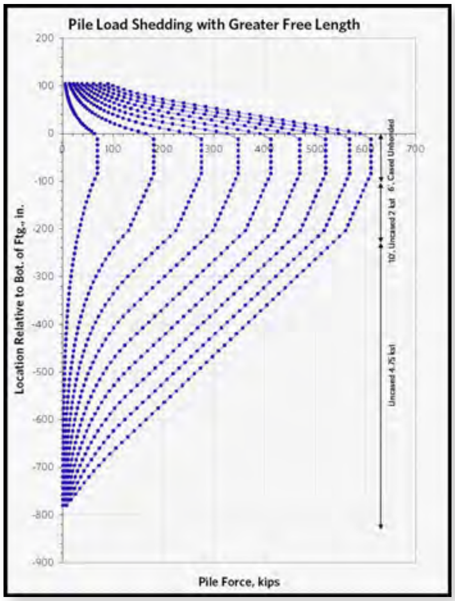

Figure 11: *Force distribution along pile length with increasing load*

CONSTRUCTION CONSIDERATIONS

A successful installation relies on a good understanding of subsurface soils and drilling conditions. The selection of appropriate performance criteria cannot be done adequately without recognizing construction issues that affect drilling and grouting methods. Most often, a design-build approach is favored to allow the drilling contractor to determine the most effective drilling and installation equipment and methods to deploy. In this way, the backbone performance envelope can be specified directly, while other design parameters such as bond length, drill diameter, and casing requirements are left to the design-build contractor to determine.

Figure 12 depicts micropile installation, using a continuously cased, air-flushed drilling method with high pressure postgrouting.

Figure 12: *Installation of postgrouted micropiles*

The approach described relies on an detailed field quality assurance and testing program that is explicitly documented in the construction plans. Tension-only testing using a simple load-cell apparatus, as shown in Figure 13, is usually sufficient for establishing pile performance for seismic design.

An initial round of verification testing of a small number of micropiles is usually required to demonstrate that the installation methods are adequate to meet the performance criteria. When this is verified, the remaining production piles are installed and proof tested to ensure quality control.

In some instances, the tested backbone curves for the verification micropiles may deviate appreciably from the idealized target envelope. This often requires some readjustment of pile details and installation methods to optimize the design. Where appropriate, the target envelope may be redefined to reflect measured performance.

Verification testing should be performed early enough to allow the time necessary to make adjustments and optimize the design based on reported test data. This is particularly important for piles in difficult soil conditions, where the uncertainty in design is greater.

For new construction, additional efficiencies can be gained owing to fewer site restrictions and height limitations. Figure 15 shows the installation of a micropile with a single continuous reinforcing element. This allows for a more rapid installation and higher production rates, making it more cost effective.

Figure 13: *Tension testing apparatus*

CONCLUSIONS AND RECOMMENDATIONS

In summary, micropile foundation systems are being increasingly relied upon to provide seismic support for structures. The practicability of testing and verifying each installation not only improves confidence but reduces the need for conservative safety factors that add to cost.

In addition, important data gained from field testing can be integrated into the design process to improve and optimize the foundation system. These factors have come together to advance micropile technology, reduce their cost, and broaden their application

While the performance-based methods described here can result in more cost-effective foundation systems and improve the seismic response of structures, the successful implementation of this approach in construction relies on intensive collaboration between the structural engineer, the geotechnical engineer, and the drilling contractor.

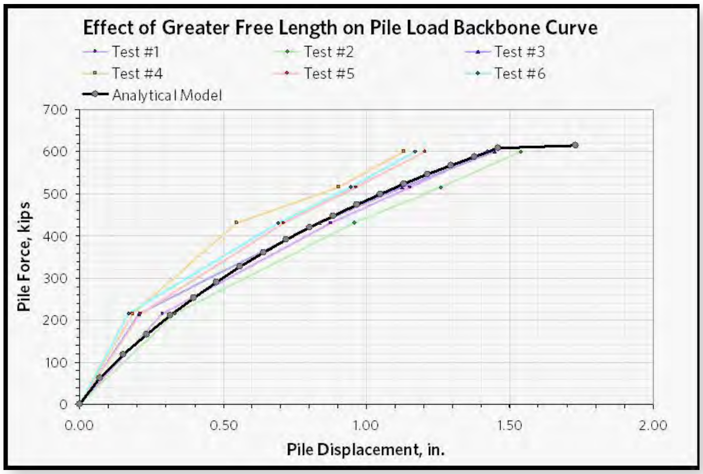

Figure 14: *Verification test results in comparison with calibrated backbone curve*

Figure 15: *Micropile installation*