CASE HISTORIES OF MICROPILE IN KARST: THE INFLUENCE OF INSTALLATION ON DESIGN AND PERFORMANCE

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ABSTRACT

Micropiles are small diameter replacement piles that are capable of developing high axial capacities. Their installation equipment can penetrate hard rock with greater efficiency than tools used for other more conventional foundation types. It is due, in part, to their high capacity and their ability to penetrate hard unsuitable rock, that micropiles have emerged as an effective, and often preferred, foundation for heavier structures located in karst terrain composed of hard limestones and dolostones. However, the implementation of micropiles in karst terrain involves the combination of two complex systems. Typical karst conditions can include very soft soils, chert boulders, sloping rock surface, and cavitose bedrock. Meanwhile, the micropile installation process involves subsurface grouting and a variety of possible drilling techniques. The first case history illustrates how certain micropile drilling techniques can significantly degrade the clay above the rock surface and reduce the lateral resistance around the upper micropile. The second case history describes how unconventional micropile design details coupled with associated accommodations during installation can lead to quality problems. The third case history illustrates a success in anticipating the karst conditions and selecting the appropriate drilling technique to fulfill the intent of the design. Understanding that success depends on anticipating potential modes of failure, the case histories are offered to help others anticipate, and thereby avoid, future micropile failures.

INTRODUCTION

Foundation engineering in karst terrain is often reduced to selection between the lesser of two evils. That is, either the most robust foundation or the foundation with the least amount of disadvantages is selected in anticipation of the often very challenging subsurface conditions that can be present. This is especially true where the foundation loads are relatively high. It is within this atmosphere that micropiles have recently experienced widespread application (Heath, 1995; Cadden *et al*., 2001; Tarquinio and Pearlman, 2001; Uranowski *et al.,* 2004; Traylor *et al*., 2002; Massoudi, 2004).

The implementation of micropiles in karst terrain involves the combination of two complex systems – (1) a karst subsurface and (2) drilling and grouting with advanced tools. Typical karst conditions can include very soft soils, chert boulders, sloping rock surface, and cavitose bedrock. Meanwhile, the micropile installation process involves subsurface grouting and many possible advanced drilling techniques that are often dictated by efficiency. An engineer faces the task of anticipating the karst conditions, as well as the influence of installation, in preparing a design. The case histories presented herein are taken from the authors' experiences in the hard limestones and dolostones of southern Appalachia. In two of the examples, micropile installation dramatically influenced the as-built pile conditions and the emphasis is to help others avoid similar problems. The third example illustrates a success in anticipating the karst conditions and selecting the appropriate drilling technique to fulfill the intent of the design.

KARST CHARACTERIZATION

The karst regions of Appalachian Valley and Ridge province (stretching from Georgia and Alabama through Tennessee, Kentucky, Virginia, West Virginia, and Pennsylvania) are underlain by limestones and dolostones. These rocks are typically hard with unconfined compressive strengths ranging from 35 to 200 MPa (about 5000 to 30,000 psi) and can develop ultimate bond capacities confirmed through full-scale load testing in the range of 1 to 2 MPa (about 150 to 300 psi). The significant rainfall in the eastern United States results in a steady downward flow of the groundwater which drives the weathering process over geologic time. This weathering process can create bedrock conditions ranging from predictably flat and essentially continuous to extremely irregular and cavitated, depending on the rock chemistry, joint systems, and other factors. The conditions above bedrock can include very soft soils, open voids, and chert boulders (Siegel and Belgeri, 1995; Sowers, 1996).

RAILROAD BRIDGE IN JOHNSON CITY, TENNESSEE

In 1996, the expansion to a major traffic artery required construction of a new railroad bridge in Johnson City, Tennessee. The geotechnical exploration at one end of the bridge revealed that the rock surface beneath an upper soft to firm clay overburden was extremely irregular and that the overall upper rock conditions were poor. Although the railroad typically prefers driven steel H-piles, a portion of the bridge was designed to be supported by 177.8-mm (7-inch) diameter micropiles because of concerns regarding the competency of the rock surface. The design of the micropiles for the railroad bridge is illustrated in Figure 1. Lateral analysis during design showed that there was a substantial lateral load from train traffic. Consequently, the piles were battered at a variety of angles to help reduce the resistance required by the clay overburden surrounding the upper pile.

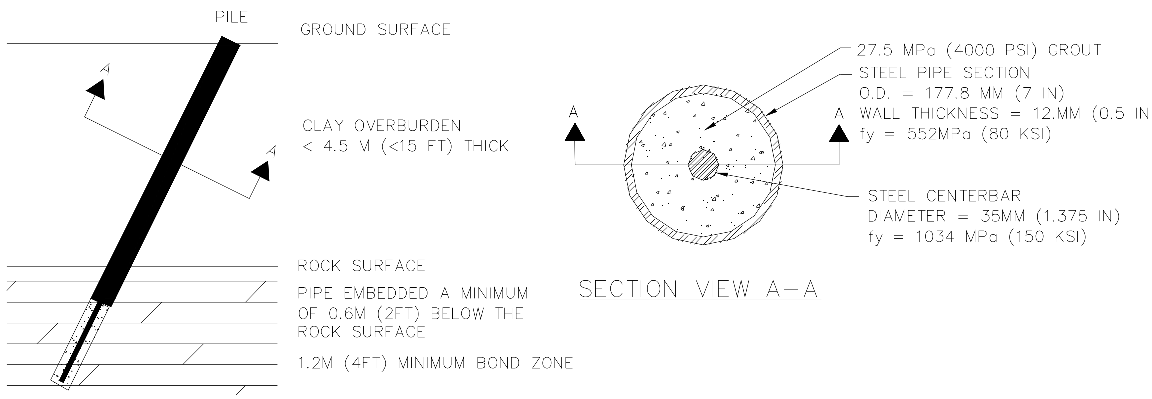

Figure 1. Micropile Design for Railroad Bridge, Johnson City, Tennessee

During installation of the micropiles, the ground surface and subsurface, were dramatically disturbed. It is believed that the water and air introduced during drilling promoted the soil softening and downward soil migration that is characteristic of karst. This latter conclusion is based on the localized subsidence observed around the micropiles. Figure 2 illustrates the consistency of the soils after disturbance. The localized subsidence and extremely soft soils led the design team to be concerned that the actual lateral resistance would be lower than it was represented in the design analysis. To restore lateral support to the micropiles, cap/compaction grouting was performed in the area to: (1) place low mobility grout at the rock surface to create a physical barrier to the downward migration of the overburden clay soil, and (2) place low mobility grout at incremental depths to fill voids, displace very soft soils, and reinforce the overall soil profile.

Figure 2. Disturbed Soil after Micropile Installation

CONDOMINIUM COMPLEX IN KNOXVILLE, TENNESSEE

In the spring of 2005, micropiles were installed for a multi-story condominium complex along the riverfront in Knoxville, Tennessee, USA. The preliminary project plans driven H-piles bearing on karstic limestone. During the early phases of structural design and cost estimation, an alternate foundation system consisting of 140mm (5.5 inch) diameter micropiles and 178mm (7 inch) diameter micropiles were suggested as part of a value engineering proposal. The project team selected the micropile alternate based on expected money and time savings.

The structural loading conditions for the project were unique in that significant shear loading was present on each interior column. An extensive design effort by the micropile design engineering team resulted in an efficient system of battered piles operating in matched pairs connected by grade beams. Of the 100 micropiles installed on the project, all but 12 were battered, with angles up to 25-degrees from vertical. The micropile section and typical layout are shown in Figure 3.

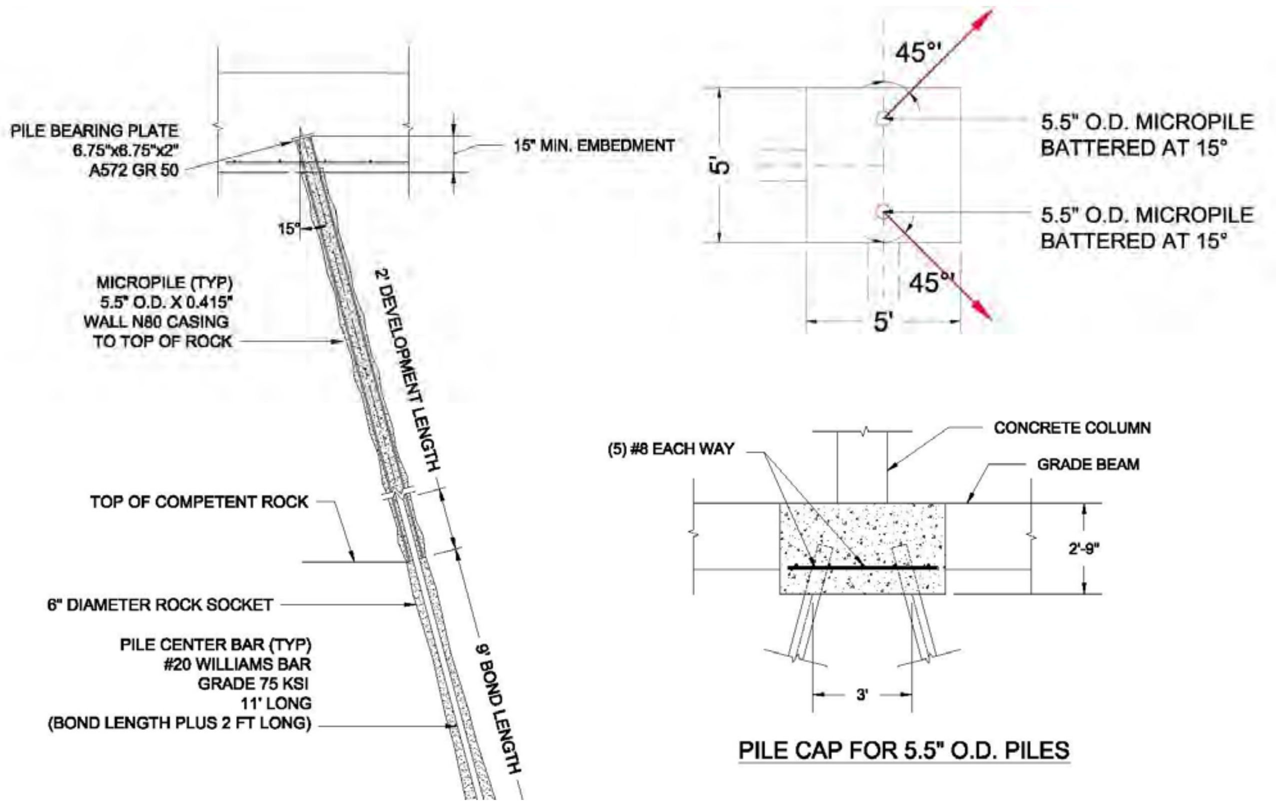

Figure 3. Micropile Detail and Layout for Condominiums, Knoxville, Tennessee (1inch=25.4mm; 1ft=0.305m)

Drilling was accomplished using rotary percussive drilling methods. Specifically, down-hole hammers were used with retractable concentric under-reaming bits known commonly as the "super-jaw system". The bits used with this system are constructed to allow multiple cutting shoes to extend outward from the bit upon advancement to cut a hole in the subsurface material larger than the retracted outer diameter of the bit itself. This allows the drill to advance the cutting bit and the outer casing as a matched pair. This style of installation allowed the casing to be fed completely to the bottom of the drilled hole and then be retracted to the designed top of bond zone elevation. During the initial part of construction, two test piles were installed and tested in compression. On the basis of two favorable load tests, the specialty contractor proceeded with the installation of production micropiles.

During excavation of a pile cap prior to cutting off the micropiles, the pile tops appeared to be moved by the excavation equipment. Upon closer inspection, it was discovered that the piles were easily lifted by the excavator bucket and had obviously failed under the minor tension loading placed on the pile by the excavator. Additional field observations indicated that other piles exhibited the same behavior in uplift. The problems were communicated to the pile system's design engineer and a comprehensive testing program was implemented to determine the extent of the problem. It was concluded that the central reinforcing bar that was designed to connect the bond zone of the pile to the upper cased zone failed to extend to the bottom of the drilled hole. Figures 4a and 4b are photographs taken of one of the faulty micropiles where the central bar did not get placed low enough in the pile. Figure 4a shows a pile that was pulled from the ground with no reinforcing bar extending past the casing bottom. Figure 4b illustrates that the central reinforcing bar had not fallen through the grout to the bottom of the drilled hole as designed; rather it was located at a higher elevation, completely inside the structural casing. This problem was found on several of the piles and was attributed to a thick grout mixture, battered piles, and poor quality control procedures.

Figures 4a and 4b: Photographs of Faulty Micropiles following Extraction

In order to identify the affected piles, a tension load was applied to all of the installed piles. Each of the affected piles was extracted and new piles were installed. Investigation of the extracted piles led to the conclusion that a combination of thick grout, tight-fitting centralizers, and steep batter angles all worked in combination to create the problem. Each of these problems could be traced back to a decision to alter the normal micropile installation procedures used by the specialty contractor to suit the site-specific project requirements. Nevertheless, it became apparent that no significant documentation efforts were made during pile installation to check that critical stages of the construction process were completed successfully on each pile.

COMMERCIAL FACILITY NEAR NASHVILLE, TENNESSEE

During the spring of 2006, micropiles were installed for a distribution center at Portland, Tennessee, north of Nashville, Tennessee, USA. The site was located in an active karst region of the

Interior Low Plateau (similar in subsurface conditions to the Valley and Ridge karst) where a significant risk of sinkhole development was present. Construction was to consist of a warehouse-style structure with a partial mezzanine. The overall footprint of the building was to cover approximately 56,000 square meters (600,000 square feet). The conceptual foundation design shown on the project drawings estimated a quantity of approximately 611 micropiles. The aggressive schedule allowed only nineteen calendar days for the micropile installation.

The successful contractor proposed to use a combination of efficient design engineering, aggressive work schedule, and extensive drilling resources to meet the required schedule. A system consisting of 547 micropiles was used to meet the design loading requirements for the project. Five different micropile designs, with diameters ranging from 140mm (5.5 inches) to 245mm (9.625 inches) were used in the project at various locations to meet the loading requirements without excess conservatism. Pile groupings ranging from a single vertical pile to twelve battered piles were required to complete the project. Three batter angles ranging from 15-degrees to 25-degrees plus vertical piles were used at various locations on the project.

The exceptionally aggressive project schedule required the use of some less common installation practices. A system of open-hole drilling combined with welded casing joints and tremie grouting allowed the system to be constructed with materials that were immediately available, avoiding unacceptable schedule delays associated with the manufacturer of threaded casing. Some conventional threaded casing was used in areas of the site where difficult drilling or collapsing holes were encountered. The use of multiple drill rigs operating around the clock allowed up to 50 micropiles to be completed in a day.

Two full-scale verification load tests were performed early in the project to validate the design assumptions for the micropiles. Figure 5 graphically presents the results for one of the load tests. The load testing effort was designed to allow sufficient test capacity to fail the sacrificial test piles and determine the ultimate bond stress available between the grout and the karstic limestone. Unexpectedly, the load testing fell short of achieving a failure in either test pile. During the load tests, the actual available bond stress between the grout and the bedrock was validated to be at least 192% of the assumed design value. Based on the extremely successful load tests, the decision was made to adopt an increased allowable bond stress 150% of the original design value. This change allowed the contractor to shorten the bond zones on all remaining piles, gaining valuable time. At the same time, this successful load test program provided a high level of confidence to the owner and construction manager in the construction practices used on the project.

A significant construction procedure that proved its worth was the use of a thorough quality control program. During the course of the micropile installation, records were maintained for each installed micropile that allowed verification, often by multiple personnel, of each significant stage of construction. This system of checks used by the installation team proved to be valuable at preventing mistakes. While the time spent performing these validations is noticeable, it is impossible to estimate the amount of disruption avoided by installing a quality product and having the confidence inspired by a well-functioning quality control program. During the course of the pile installation, three piles out of the entire project indicated conflicting information regarding the amount of grout placed in the piles and each of these three piles was tension tested to validate that the grout had in fact been placed as designed. No other faults were noted during the installation or since the completion of micropile installation.

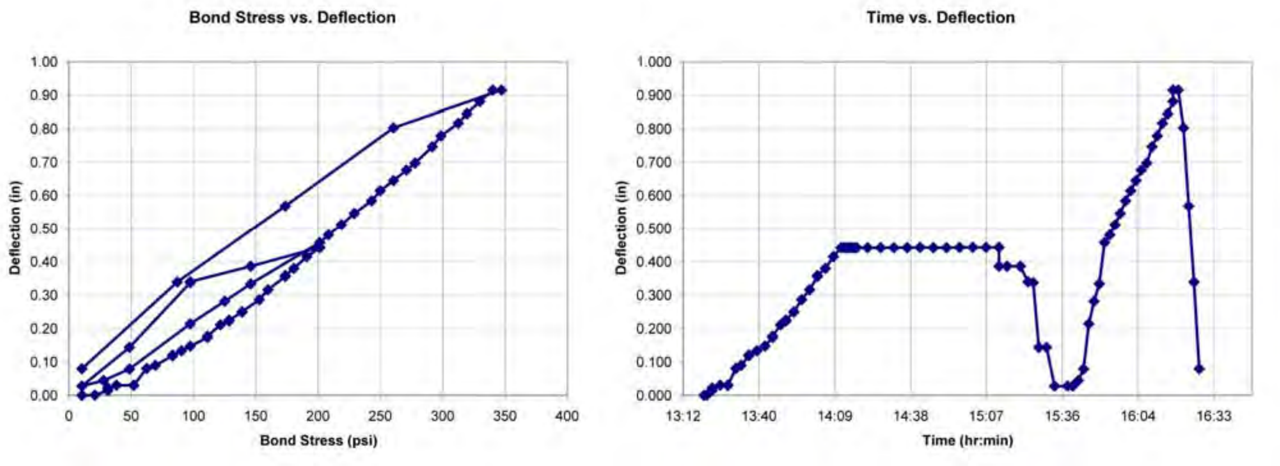

Figure 5. Load Test Results for Commercial Facility, Portland, Tennessee (1inch=25.4mm; 1psi=6.9kPa) (Note that a standard test to 200% was completed prior to reloading to a higher load)

The installation of all micropiles, including additional piles added midway through the work due to structural loading changes was completed in only 18 working days, one day ahead of schedule. This feat was accomplished even though the depth to competent bedrock was approximately 3% greater than initially assumed. Through the use of careful grout placement methods the total grout overrun amount for the project was approximately 0.75% of the total project cost, even though the project was completed in karst geology, where less than desirable grouting strategy can generate large overruns.

CONCLUDING REMARKS

In his book *Success through Failure: the paradox of design,* Petroski (2007) examines the relationship between success and failure. He writes:

> Success and failure in design are intertwined. Though a focus on failure can lead to success, too great reliance on successful precedents can lead to failure. Success is not simply the absence of failure; it also masks potential modes of failure.

Petroski's point could be no more relevant to the implementation of micropiles in karst terrain. That is, there have been previous successes that may serve to obscure potential problems arising from either the complexity of the karst conditions, the wide variation of installation techniques, or a combination of the two. Case histories for sites in Johnson City (TN) and Knoxville (TN) illustrate that the implementation of installation methods established on previous projects do not necessarily ensure success in different subsurface and/or design conditions. The case history for a site near Nashville (TN) illustrates that micropiles can be very effective, considering both time and money, when the installation approach and quality controls are tailored to the project conditions.

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