High Capacity Grouted Micropiles: The State of Practice in the United States

MICROPIEUX INJECTES DE HAUTE CAPACITE: Les Règles de l'Art aux Etats Unis

D.A. BRUCE, Geosystems, L.P., Venetia, PA, U.S.A.
I. JURAN, Polytechnic University, Brooklyn, NY, U.S.A.
A.F. DIMILLIO, Federal Highway Administration, McLean, VA, U.S.A.

ABSTRACT: High capacity, drilled and grouted micropiles have been used in the United States for almost 30 years, although their origins date from Italy in 1952. Activity levels are high as a result of urban, industrial, and seismic challenges and strong Federal interest is reflected in several major reviews and research initiatives, which are described in this paper.

RÉSUMÉ: Les micropieux de haute capacité, perforés , mis en place et injectés sont utilisés aux USA depuis presque 30 ans, bien que leur origine date de 1952, en Italie. Leur utilisation est actuellement en forte progression pour cause de développements urbains et industriels techniquement ambitieux ainsi que la mise en place de nouvelles normes sismiques. L'interet Fedéral américain se reflète dans plusieurs initiatives de recherches et d'études sur ce sujet, qui sont présentées dans cet article.

1 INTRODUCTION

1.1 *Background*

The technology of micropiling was conceived in Italy in the early 1950s and was introduced over two decades later into the United States (Bruce, 1988-89). Since the middle 1980s in particular, there has been a rapid growth in use, mainly as foundation support elements in static and seismic applications and as in situ reinforcement for slope and excavation stabilization.

Many of these applications are directly related to transportation projects, and therefore in 1993, the Federal Highway Administration (FHWA) funded a major state of practice study into the technology. This decision largely reflected the industry's growing awareness of the potential of micropiling as a means of resolving difficult foundation and slope stability problems. However, it also underlined the commitment of the FHWA to cooperate with their French colleagues who in 1992 had commenced a new National Research Project termed "FOREVER" (<u>Fo</u>ndations <u>Re</u>nforcées <u>Ver</u>ticalement).

The major tasks set for the FHWA study (1997), were:

a) state of practice determination, including a review of research and development results, laboratory and field testing data, site observations and monitored case studies; a critical assessment of the available analytical models and design tools; and comparisons of contemporary construction methods, specifications, and quality assurance procedures;
b) a research needs assessment; and
c) coordination with foreign programs and specialists.

In the mid 1990s, the FHWA also commissioned two parallel studies – the first being the drafting of an "Implementation Manual," based on the State of Practice and intended as a practitioner's guide, the second being fundamental research into the seismic performance of micropile groups and networks. Each study therefore addressed specific needs in the U.S. market reflecting the rapidly growing interest in, and application of, high capacity micropiles in the U.S.

1.2 *Definitions and Characteristics*

Micropiles are, generically, small-diameter, bored, replacement piles, being grouted-in-place and incorporating steel reinforcement. They have been used throughout the world since 1952 for various purposes, and this has spawned a profusion of national and local names, including pali radice, micropali (Italian), pieux racines, pieux aiguilles, minipieux, micropieus (French), minipile, micropile, pin pile, root pile, needle pile (English), Verpresspfähle and Wurzelpfähle (German) and Estaca Raiz (Portuguese). All, however, refer to the "special type of small diameter bored pile" as discussed by Koreck (1978).

Such a pile can sustain axial and/or lateral loads, and may be considered as either one component in a composite soil/pile mass or as a small-diameter substitute for a conventional pile, depending on the design concept. Inherent in their genesis and application is the precept that micropiles are installed with methods that cause minimal disturbance to structure, soil and environment. This therefore excluded other related techniques from the FHWA study such as those that employ percussive or explosive energy (driven elements), ultra-high flushing and/or grouting pressures (jet piles) or large diameter drilling techniques that can easily cause lateral soil decompression (auger cast piles).

With such conventional cast-in-place replacement piles, most, and occasionally all, the load is resisted by concrete as opposed to steel. Small cross-sectional area is therefore synonymous with low structural capacity. Micropiles, however, are distinguished by not having followed this pattern: innovative and vigorous drilling and grouting methods like those developed in related geotechnical practices such as ground anchoring, permit high grout/ground bond values to be generated along the micropile periphery. To exploit this potential benefit, high capacity steel elements, occupying up to 50 percent of the hole volume, can be used as the principal (or sole) load bearing element, with the surrounding grout serving only to transfer, by friction, the applied load between the soil and the steel. End-bearing is not relied upon, and in any event, is relatively insignificant given the pile geometries involved. Micropiles thus can work well in both compression and tension. Early micropile diameters were around 100mm, but with the development of more powerful drilling equipment, diameters of up to 300mm are now common. Thus, micropiles are capable of sustaining surprisingly high loads (compression loads of over 5000 kN have been recorded), or conversely, can resist lower loads with minimal movement.

1.3 *Applicability and Applications*

Micropiles are mainly used in the U.S. for structural support, but are becoming increasingly popular for in situ reinforcement (Figure 1). This paper reviews only the former application wherein groups of Case 1 micropiles (Section 2 below) are employed to accept load directly, as small diameter substitutes for other pile types. Micropiles are used to solve problems where logistical and/or geotechnical factors conspire to rule out other types of support.

Physical constraints include
- Situations with low overhead clearance;
- Tight working conditions inside existing structures;
- Sites with limited plan area access, e.g., in hallways or against a face of walls; and
- Situations where it is necessary to attach small piling elements directly through the existing foundation elements.

Geotechnical constraints include
- Karstic limestone geology (with voids or soil-filled solution cavities);
- Bouldery ground or glacial till;
- Variable and/or random fill;
- Underlying existing foundations or man-made obstructions;
- Rock formations with variable weathering (e.g., hard zones overlying softer layers); and
- Soils under a high water table.

Micropiles offer the following advantages
- Small and powerful equipment is used to negotiate tight physical spaces;
- Drilling is quiet, vibration free, and causes little or no loss of ground around each pile installation;
- Drill spoil can be diverted from the hole location to provide a clean environment within operating facilities;
- The drilling equipment can be used to install tie-down anchors that provide the primary uplift resistance for vertical pile load testing;
- Larger casing pipes can be used in the upper portions of the piles to obtain significant lateral load resistance; and
- Many variations of drilling, grouting, and structural configurations make for a fully customized and optimal solution.

Various practitioners have proposed classifications based on diameter, some constructional process, or by the type of reinforcement. The FHWA team derived a new classification which is now being used nationwide and is based on two criteria:
- The philosophy of system behavior, and
- The method of grouting.

The former criterion dictates the basis of the overall design concepts, and the latter is the principal determinant of grout/ground bond capacity.

2.1 *Classification Based on Philosophy of Behavior*

Micropiles are usually designed to transfer structural loads to more competent or stable strata. They therefore act as substitutes or alternatives for other conventional pile systems. For axially loaded piles, the pile/ground interaction is in the form of side shear and so is restricted to that zone of ground immediately surrounding the pile. For micropiles used as in situ reinforcements for slope stabilization, pile/ground interaction occurs only relatively close to the slide plane, although above this level, the pile group may also provide a certain degree of continuity to the pile/ground composite structure. In both cases, however, the pile (principally the reinforcement) resists directly the applied loads. This is equally true for cases when individual piles or groups of piles are used. In this context, a group is defined as a tight collection of piles, each of which is subjected to direct loading. Depending on prevailing codes relating to pile group design, individual pile design capacity may have to be reduced in conformity with conventional “reduction ratio” concepts. These concepts were typically developed for driven piles, and so this restriction is almost never enforced for micropiles, given their mode of construction which tends to improve, not damage, the soil mass between piles.

When axially-loaded piles of this type are designed to transfer their load only within a remote founding stratum, pile head movements will occur during loading, in proportion to the length and composition of the pile shaft between structure and the founding stratum, and the load. Piles of this type can be preloaded (Bruce et al. 1990) to ensure that the overlying structure can be supported without further movements occurring. Equally, if suitably competent ground conditions exist all the way down from below the structure, then the pile can be fully bonded to the

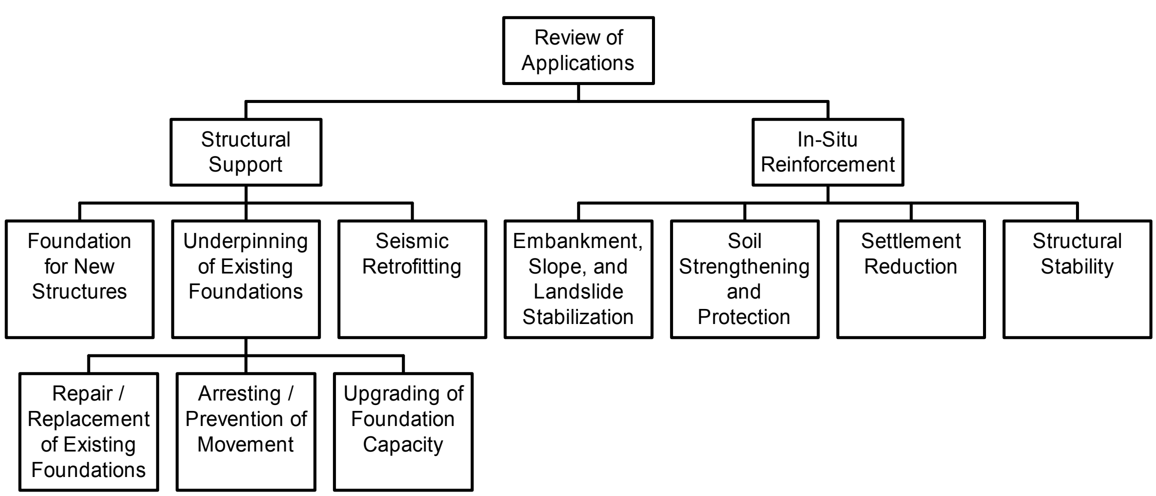

Figure 1. Classification of micropile applications.

2. CLASSIFICATION OF MICROPILES USED IN THE U.S.

soil over its entire length and so movements under equivalent loads will be smaller than in the previous case. These directly loaded piles, whether for axial or lateral loading conditions, are referred to as CASE 1 elements. They comprise virtually all North American applications to date, and at least 90 percent of all known international applications.

On the other hand, one may distinguish the small group of CASE 2 structures. Dr. Fernando Lizzi of Naples introduced the concept of micropiling when he patented the Aroot pile≅ (palo radice) in 1952. The name alone evokes the concept of support and stabilization by an interlocking, three-dimensional network of reticulated piles similar to the root network of a tree. This concept involves the creation of laterally confined soil/pile composite structure that can provide underpinning, stabilization or earth retention. In this case, the piles are not heavily reinforced since they are not individually and directly loaded: rather, they circumscribe a zone of reinforced, composite, confined material that offers resistance with minimal movement. The piles are fully bonded over their entire length and so for this case to work, the soil over its entire profile must have some reasonable degree of competence. Lizzi=s research (1982) has shown that a positive "network effect" is achieved in terms of load/movement performance, such is the effectiveness and efficiency of the reticulated pile/soil interaction in the composite mass.

It is clear, therefore, that the basis of design for a CASE 2 network is radically different from a CASE 1 pile (or group of piles). This is addressed in Volume 2 of the FHWA study. Notwithstanding this difference, however, there will be occasions where there are applications transitional between these designs (although this attractive possibility is currently, conservatively, ignored for pile groups), while a CASE 2 slope stability structure may have to consider direct pile loading conditions (in bending or shear) across well defined slip planes. By recognizing these two basic design philosophies, even those transitional cases can be designed with appropriate engineering clarity and precision.

2.2 *Classification Based on Method of Grouting*

The successive steps in constructing micropiles are drill; place reinforcement; and place and typically pressurize grout (usually involving extraction of temporary steel drill casing).

There is no question that the *drilling* method and technique will affect the magnitude of the grout/ground bond which can be mobilized, while the act of placing the *reinforcement* cannot be expected to influence this bond development. Generally, however, international practice both in micropiles and ground anchors confirms that the method of *grouting* is generally the most sensitive construction control over grout/ground bond development. The following classification of micropile type, **based primarily on the type and pressure of the grouting** (Figure 2) is therefore adopted.

Type A: Grout is placed in the pile under gravity head only. Since the grout column is not pressurized, sand-cement Amortars≅, as well as neat cement grouts, may be used.

Type B: Neat cement grout is injected into the drilled hole as the temporary steel drill casing or auger is withdrawn. Pressures are typically in the range of 0.3 to 1 MPa, and are limited by the ability of the soil to maintain a grout tight Aseal≅ around the casing during its withdrawal, and the need to avoid hydrofracture pressures and/or excessive grout consumptions, particularly in upper, permeable, fills.

Type C: Neat cement grout is placed in the hole as for Type A. Between 15 and 25 minutes later, and so before hardening of this primary grout, similar grout is injected, once, via a preplaced sleeved grout pipe at a pressure of at least 1 MPa. This type of pile, referred to in France as IGU (Injection Globale et Unitaire), seems to be common practice only in that country to date.

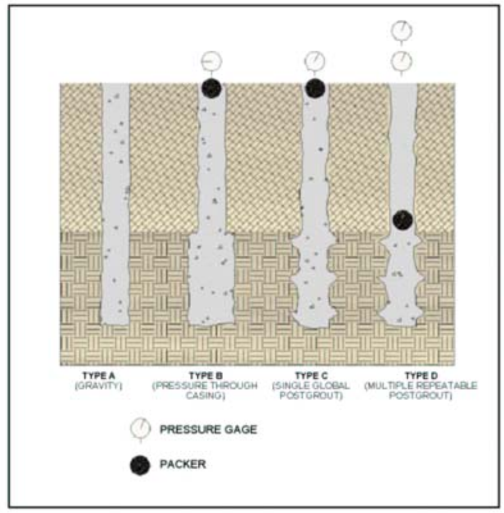

Figure 2. Classification of micropile based on type of grouting.

Type D: Neat cement grout is placed in the hole as for Type A. Some hours later, when this primary grout has hardened, similar grout is injected via a preplaced sleeved grout pipe. In this case, however, a packer is used inside the sleeved pipe so that specific horizons can be treated, several times if necessary, at pressures of 2 to 8 MPa. This is referred to in France as IRS (Injection Répétitive et Sélective), and is common practice worldwide, including the U.S.

2.3 *Combined Classification*

Micropiles are therefore allocated classification numbers denoting the philosophy of behavior (CASE 1 or CASE 2), which relates fundamentally to the design approach, and a letter denoting the method of grouting (Type A, B, C, or D), which reflects the major constructional control over capacity.

In the U.S. the most common pile types are 1A (for rock and very stiff cohesives), 1B (non-cohesives), and 1D (cohesives).

3. ASPECTS OF DESIGN, CONSTRUCTION, AND TESTING

3.1 *Design*

An extremely thorough review was provided by Juran et al. (1999), and detailed guidance is given in the FHWA Implementation Manual (1997). To date, however, design procedures have not been unified or codified nationally, and typically designers have had to observe the rules of the numerous local or city building codes, often focussed on other more "conventional" types of pile. This has not helped the expansion of the technique in certain geographic locations. In general, however, the following statements reflect common practice.

- Steel casing for load bearing must ASTM A252 Grade 3, to a minimum yield stress of 550 MPa.
- Core steel reinforcing is normally Grade 60, 75, or 80 (ASTM A615, 616, and 617, respectively) or less commonly Grade 150 (ASTM 722).
- Grouts are typically neat, low water cement ratio mixes with a minimum 28-day unconfined compressive strength of 30 MPa.
- The micropile working load is calculated from using 40 to 45% of the steel yield value plus 30 to 40% of the grout unconfined compressive strength, ignoring strain incompatibility issues.
- For geotechnical design, end bearing is typically ignored, and empirical data used to determine the appropriate grout-soil

bond. For the typical range of micropile diameters and installation methods, this ultimate figure can range from, say 50 kN/m (soft clay) to 500 kN/m (dense gravels).

- For the infrequent occasions when micropiles are designed as simple struts between the structure and a particularly resistant bedrock surface of sufficient "punching" resistance, the internal pile design clearly governs.

3.2 *Construction*

Most micropiles are installed in urban or industrial settings where the upper strata at least may be very challenging to drill. Contractors have therefore evolved many overburden and rock drilling methods (Bruce, 1989) to guarantee penetration without causing damage to the structure or the environment. Most feature water flush and some form of rotary duplex drilling. Contractors have been quick to take advantage of the valuable developments in high powered, mobile hydraulic drill rigs, mainly as produced by European sources. Reinforcement is provided in lengths commensurate with the overhead access, which may be as little as 2.5 m. Casings are threaded and reinforcing bars are coupled. No welded connections are permitted. Grouting techniques are similar to those of ground anchoring practice, and at their best, feature colloidal mixers and strong quality control over mix designs and injection parameters.

3.3 *Load Testing*

It is common on projects of significant scale and scope to conduct a test pile program prior to production work commencing. The number of piles reflects the variability of the ground and the extent of prior experience in such conditions. Typically between two and six such piles are installed and usually they are tested to failure to provide ultimate values. Thereafter, it is common to subject a certain small percentage of production piles to some quicker and more economical test to verify adequacy of routine installation methods. Testing is typically conducted to the relevant ASTM standards for compressive, tensile, and lateral loading, often modified to incorporate specific features from other sources, e.g., PTI Recommendations for Rock and Soil Anchors (1996). Micropile testing can be relatively inexpensive and the increasing volume of published data has undoubtedly encouraged the expansion of the technology nationwide.

4. RESEARCH AND DEVELOPMENT

As has been common for virtually every new geotechnical process introduced into the U.S. in the last 25 years, the onus (and cost) of research and development has largely fallen on the specialty contractors themselves. During the beginning of the rapid growth of usage in the mid to late 1980s much invaluable and fundamental research was conducted, either as "extra effort" on existing sites (Bruce, 1992), or as specially funded programs in cooperation with universities (e.g., Bruce et al., 1993). However, responding to the aftermath of the Loma Prieta Earthquake in California, the California Department of Transportation, the FHWA, and industry, partnered to conduct a very large and important full-scale field test in South San Francisco in 1992 (DFI, 1993). This provided a great deal of useful information.

As further offshoots of the 1993 FHWA-FOREVER initiative, fundamental seismic research was conducted by Juran and coworkers (2000) at the Polytechnic University of Brooklyn, while other researches into micropile networks have been conducted by Cornell University (Mason, 1999), and the U.S. Marine Corps (Weinstein, 2000). From 1997 onwards, the International Workshop on Micropiles (IWM) has convened to hold three major workshops (Seattle, Ube, and Türkü) involving leading practitioners and theoreticians from North America, Europe, and Japan. Most recently there are strong indications that leading trade associations like the International Association of Foundation Drilling (ADSC) (formerly referred to as the Association of Drilled Shaft Contractors) are becoming keen to cosponsor research, while a committee of the Deep Foundations Institute is devoted to micropiles, and to issuing guideline specifications.

This level of activity is perhaps the clearest evidence of a vibrant and growing micropile market in the U.S.

5. REFERENCES

American Society for Testing and Materials. (1998a). "A252-98: Standard specification for welded steel pipe piles."

American Society for Testing and Materials. (1998b). "A722/A722M-98: Standard specification for uncoated high-strength steel bar for prestressing concrete."

American Society for Testing and Materials. (2000a). "A615/A615M-00: Standard specification for deformed and plain billet – steel bars for concrete reinforcement."

American Society for Testing and Materials. (2000b). "A996/A996M-00: Standard specification for rail-steel and axle-steel deformed bars for concrete reinforcement." (replaced A616/A616M and A617/A617M).

Bruce, D.A. (1988 – 1989). "Aspects of minipiling practice in the United States." *Ground Engineering*, Vol. 21, No. 8 pp. 20-33 and Vol. 22, No. 1, pp. 35-39.

Bruce, D.A. (1989). "Methods of Overburden Drilling in Geotechnical Construction-- A Generic Classification." Ground Engineering 22 (7), pp. 25-32. Also published in "Drill Bits - The Official Publication of the International Drilling Federation", Fall 1989, pp. 7, 8, 110, 11, 13, 14.

Bruce, D.A. (1992). "Recent Progress in American Pinpile Technology." Proc. ASCE Conference, "Grouting, Soil Improvement and Geosynthetics, New Orleans, LA, Feb. 25-28, pp. 765-777.

Bruce, D.A., S.L., Pearlman, and J.H. Clark. (1990). AFoundation Rehabilitatin of the Pocomoke River Bridge, MD, Using High Capacity Preloaded PinPiles.≅ Proc. 7th Annual International Bridge Conference, Pittsburgh, PA June 18-20, Paper IBC-90-42, 9 pp.

Bruce, D.A., Bjorhovde, R. and Kenny, J.R. (1993). "Fundamental Tests on the Performance of High Capacity PinPiles^sm." Proc. 18th Annual DFI Conference, Pittsburgh, PA, October 18-20, 33 pp.

Deep Foundations Institute. (1993). "CalTrans Pile Load Test Results Seminar Proceedings." Deep Foundations Institute, Englewood Cliffs, NJ.

Federal Highway Administration. (1997). "Drilled and Grouted Micropiles: State of Practice Review, Volumes I, II, III, and IV." Prepared for the Federal Highway Administration, Co-Principal Investigators D.A. Bruce, I. Juran. Publication Nos. FHWA-RD-96-016. –017, -018, and –019, July.

Federal Highway Administration. (1997). "Micropile Design and Construction Guidelines: Implementation Manual." Publication No. FHWA-SA-97-070. June, 317 pp.

Juran, I., D.A. Bruce, A. DiMillio, and A. Benslimane. (1999). "Micropiles: the state of practice. Part II: design of single micropiles and groups and networks of micropiles." *Ground Improvement*. Vol. 3, No. 3. July.

Juran, I. (2000). Personal communication.

Koreck, H.W. (1978). ASmall-Diameter Bored Injection Piles.≅ *Ground Engineering*, Vol. 11, No. 4 pp. 14-29.

Lizzi, F (1982). *Static Restoration of Monuments*. Sagep Publisher. Genoa, Italy.

Mason, J.A. (1999). Personal communication.

Post Tensioning Institute. (1996). "Recommendations for Prestressed Rock and Soil Anchors," Phoenix, AZ, 52 p.

Weinstein, G. (2000). Personal communication.