Introduction to Micropiles: An International Perspective

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Members

Abstract

A major study of micropile technology has recently been funded by the Federal Highway Authority and completed by the authors. The subject is defined as a drilled and grouted, cast-in-place, reinforced pile of nominal diameter less than 300 mm. Micropiles have exceptional qualities not least of which are their relatively high axial load holding performance and their ability to be installed in very difficult locations and geologies. The bulk of the FHWA study relates to design, construction and performance. However, this paper provides an overview of the technology with respect to characteristics, definitions, historical development and applications, in order to establish common background for other publications on the subject.

Introduction to the FHWA Study

The technology of micropiling was conceived in Italy in the early 1950s and was introduced over two decades later

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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 (Pearlman and Wolosick, 1992), and therefore in 1993, the Federal Highway Administration (FHWA) decided to fund a major 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 desire of the FHWA to cooperate with their French colleagues who in 1993 had commenced a new five-year National Project termed "FOREVER" (Fondations Renforcées Verticalement). The FOREVER project was organized under the aegis of the Institute for Applied Research and Experimentation in Civil Engineering (IREX) and is under the technical direction of Prof. François Schlosser of the National Civil Engineering School (ENPC) and Dr. Roger Frank of the Center for Education and Research in Soil and Rock Mechanics (CERMES). It is also supported by the National Public Works Federation (FNTP), the Center for Studies and Research on Construction and Public Works (CEBTP), the system of Civil Engineering Laboratories (LPC), and a collection of other research and testing bureaus, businesses, contractors, and owners. FOREVER includes desk studies, numerical modeling, laboratory testing (centrifuge), and full-scale field testing. Its chief objective is to promote the use of micropiles in all fields: deep foundations of new buildings and structures, stabilization of slopes and embankments, "consolidation" of existing foundations, retaining walls, reduction of embankment settlement, and shallow foundations.

The major tasks set for the FHWA study, to be published in late 1995, 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.

- a research needs assessment.

- coordination with foreign programs and specialists.

The contract was awarded to Nicholson Construction Company, with Dr. Donald Bruce and Professor Ilan Juran of the Polytechnic University of Brooklyn, being nominated as the two Principal Investigators. The International Advisory Board initially consisted of Dr. Fernando Lizzi (Italy), Professor Schlosser (France), Professor Stuart Littlejohn (United Kingdom), and Dr. Thomas Herbst (Germany), although it was later supplemented by specialists including Mr. Mike Turner (United Kingdom), Professor Fred Kulhawy (Cornell University, United States), Mr. James Mason and Mr. Ray Zelinski (California Department of Transportation [CalTrans], United States), Professor Reidar Bjorhovde (University of Pittsburgh, United States), and Mr. Bob Lukas (Ground Engineering, United States). This group therefore provided a blend of contractor, consultant, academic, and client which mirrored the team assembled in France.

The subject can be referred to generically as small diameter drilled and grouted piles. They have been used throughout the world for various purposes, and this has spawned a profusion of local names, including pali radice, micropali (Italian), pieux racines, pieux aiguilles, minipieux, micropieux (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 withstand 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 nails) or large diameter drilling techniques that can easily cause lateral soil decompression (auger cast piles).

Likewise, micropile construction techniques are amongst those used to install soil nails sub-horizontal in-situ reinforcements used in excavation support and slope stabilization (Figure 1). However, soil nailing was regarded in concept, design, and function to be beyond the scope of the report and had already been the subject of major federal (NCHRP 1987; FHWA 1994) and private studies (Juran and Elias 1990; Bruce 1993).

Characteristics and Definition of Micropiles

Typical overviews of bearing pile types (eg. by Fleming et al., 1985) begin by making the distinction between displacement and replacement types. Piles which are driven are termed displacement piles because their installation methods displace laterally the soils through which they are introduced. Conversely, piles that are formed by creating a borehole into which the pile is then cast or placed, are referred to as replacement piles because existing material, usually soil, is removed as part of the process. **Micropiles are a small-diameter subset of cast-in-place replacement piles**

With conventional cast-in-place replacement piles, in which most, and occasionally all, the load is resisted by concrete as opposed to steel, small cross-sectional area is synonymous with low structural capacity. Micropiles, however, are distinguished by not having followed this pattern: innovative and vigorous drilling and grouting methods such as those developed in related geotechnical practice such as ground anchoring, permit high grout/ground bond values to be generated along the micropile's periphery. To exploit this potential benefit, therefore, 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 (Figure 2). Early micropile

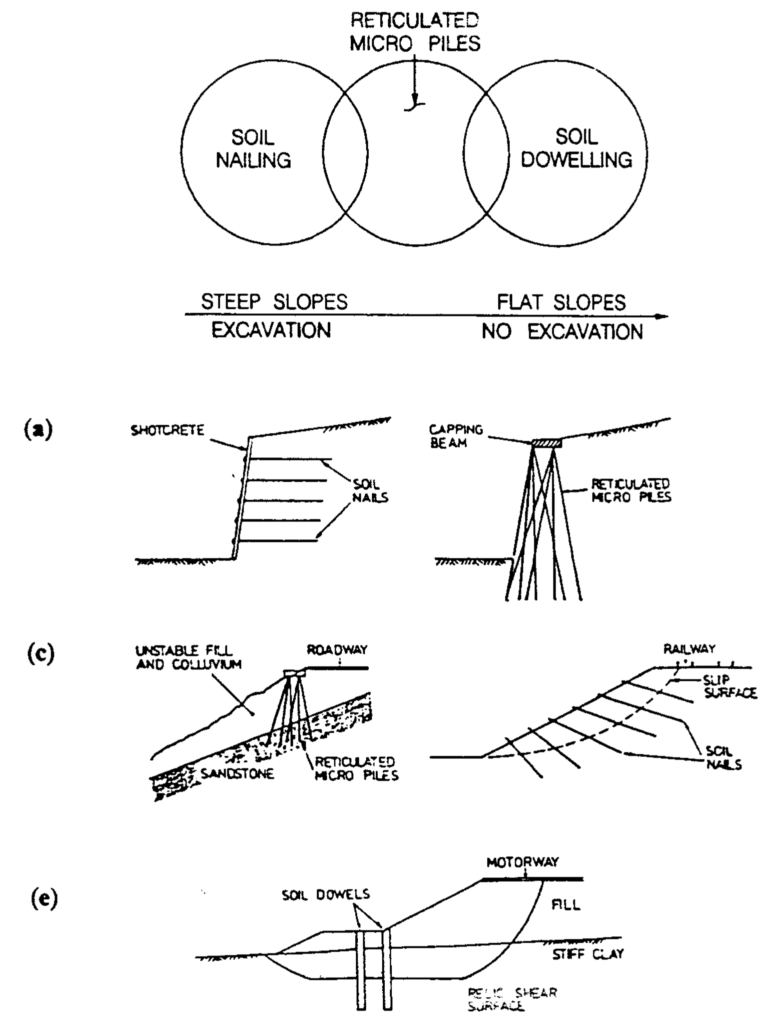


Figure 1. Overlap of in-situ soil reinforcement applications: (a) and (b) in excavations; (c) and (d) for general slope stabilization; and (e) to stabilize residual slips in clay (Bruce and Jewell, 1986, 1987).

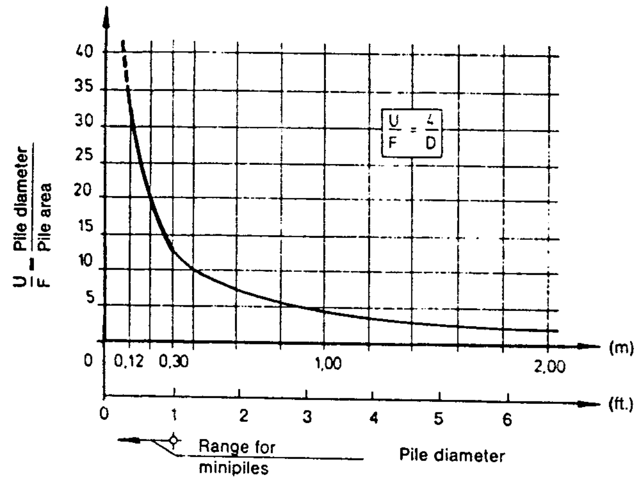


Figure 2. Ratio of pile circumference to pile cross section (DSI, 1992).

diameters were around 100 mm, but with the development of more powerful drilling equipment, diameters of up to 300 mm are now considered practical. Thus, micropiles are capable of sustaining surprisingly high loads (compressive loads of over 5000 kN have been recorded), or conversely, can resist lower loads with minimal movement.

The development of highly specialized drilling equipment and methods also allows micropiles to be drilled through virtually every ground condition, natural and artificial, with minimal vibration, disturbance and noise, and at any angle below horizontal. Micropiles are therefore used widely for underpinning existing structures, and the equipment can be further adapted to operate in locations with low headroom and severely restricted access.

All of these observations of its traditionally recognized characteristics therefore lead to a fuller definition of a micropile: a small diameter (less than 300 mm*), replacement, drilled pile composed of placed or injected grout, and having some form of steel reinforcement to resist a high proportion of the design load. This load is mainly (and initially) accepted by the steel and transferred via the grout to the surrounding rock or soil, by high values of interfacial friction with minimal end bearing component, as is the case for ground anchors (FHWA, 1984) and soil nails. They are constructed by the type of equipment used for ground anchor and grouting projects, although micropiles often must be installed in low headroom and/or difficult access locations. They must be capable of causing minimal damage to structure or foundation material during installation and must be environmentally responsive. The majority of micropiles are between 100 and 250 mm in diameter, 20 to 30 m in length, and 300 to 1000 kN in compressive or tensile service load, although far greater depths and much higher loads are not uncommon in the United States.

*In France, the limit is set as 250 mm.

Classification of Micropiles

It has been common to find micropiles sub-classified according to diameter, some constructional process, or by the nature of the reinforcement. However, given the definition of a micropile provided above, the authors conclude that a new, rigorous classification be adopted based on two criteria:

- The philosophy of behavior, and
- The method of grouting.

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

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 (Figure 3a). 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, recent research by Pearlman et al. (1992) suggests that 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 pile group

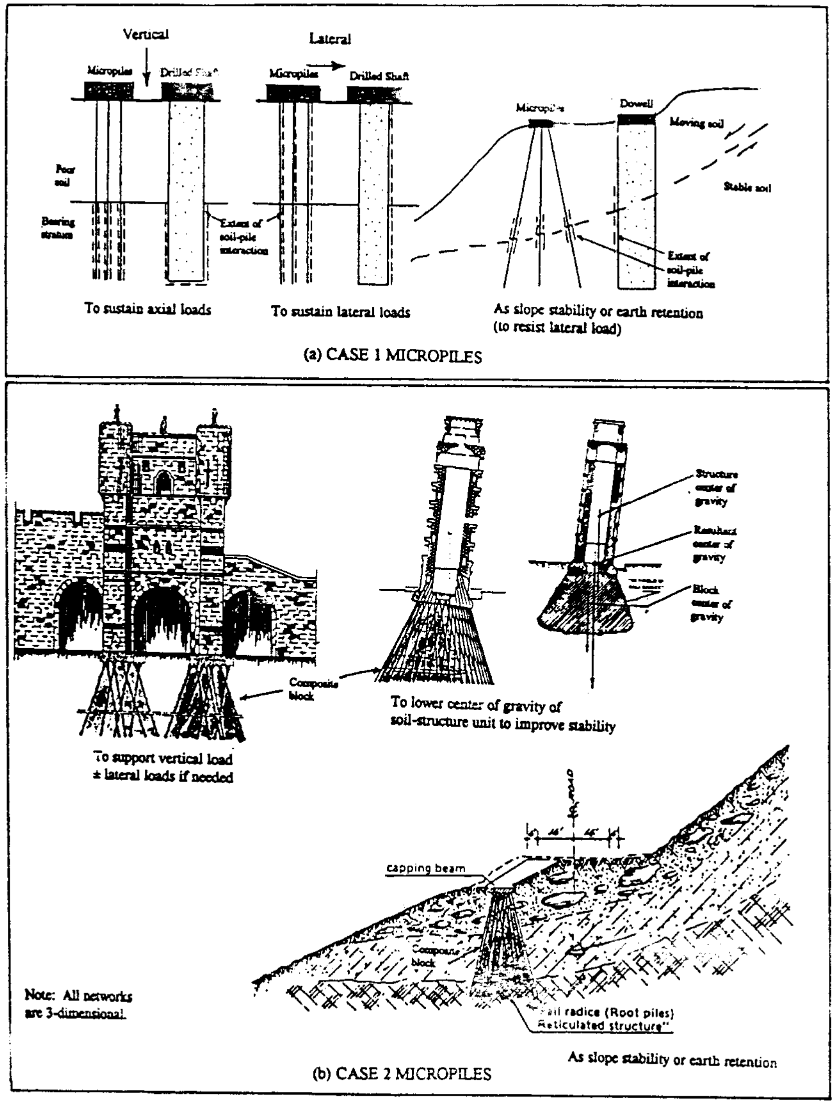


Figure 3. Fundamental classification of micropiles based on their supposed interaction with the soil.

codes, the individual pile design capacity may even 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 inter-pile soil.

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. In this instance, the pile can be preloaded (Bruce et al., 1990) to ensure that the 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 soil over its entire length and so movements under load will be smaller than in the previous case.

The authors refer to such directly loaded piles, whether for axial or lateral loading conditions, 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. Lizzi introduced the concept of micropiling when he patented the "root 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 a laterally confined soil/pile composite structure that can work for underpinning, stabilization and earth retention, as illustrated in Figure 3b. In this idea, the piles are not heavily reinforced since they are not individually and directly loaded: 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 suggested 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 producing 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). Notwithstanding this difference, however, there will be occasions where there are applications transitional between these cases. For example, it may be possible to achieve a positive group effect in CASE 1 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.

This classification also permits us to accept and rationalize the often contradictory opinions made in the past about micropile fundamentals by their respective champions. For example, Lizzi (1982), whose focus is CASE 2 piles, was understandably an opponent of the technique of preloading high capacity micropiles, such as those described by Mascardi (1982) and Bruce (1992): these latter piles are now recognized as being of a different class of performance, in which complete pile/soil contact and interaction is not fundamental to their proper behavior.

Classification based on Method of Grouting - The successive steps in constructing micropiles, are simply:

- Drill,
- Place reinforcement, and
- Place and typically pressurize grout (usually involving extraction oftemporary steel drill casing.)

There is no question that the *drilling* method and technique will affect the scale of the grout/ground bond which can be mobilized. On the other hand, the act of placing *reinforcement* should not influence this bond development. Overall, however, international practice both in micropiles (e.g. French Norm DTU 13.2, 1992) and ground anchors (e.g. British Code BS 8081, 1989) 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** is therefore adopted. It is shown schematically in Figure 4.

- Type A: Grout is placed in the pile under gravity head only. Since the grout column is not pressurized, sand-cement "mortars", as well as neat cement grouts, may be used. The pile drill hole may have an underreamed base (to aid performance in tension), but this is now very rare and not encountered in any other micropile type.
- 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 "seal" around the casing during its withdrawal, and the need to avoid hydrofracture pressures and/or excessive grout consumptions.

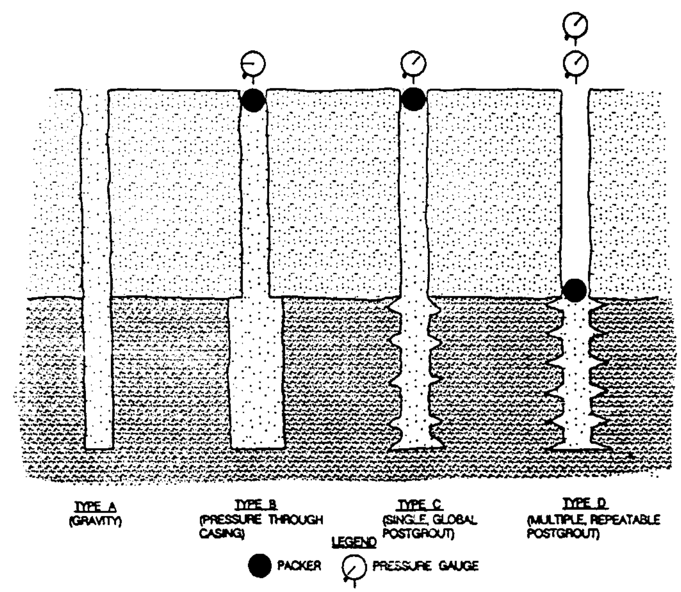


Figure 4. Classification of micropile type based on type of **grouting**.

- 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.

- 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, if necessary, several times, at pressures of 2 to 8 MPa. This is referred to in France as IRS (Injection Répétitive et Sélective), and is a common practice worldwide.

Table 1 provides more details about this classification and also indicates the relationship between other proposed classifications and terminologies.

Combined Classification - Micropiles can therefore be allocated a classification number 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.

For example, a repeatedly post-grouted micropile used for direct structural underpinning is referred to as Type 1D, whereas a gravity grouted micropile used as part of a stabilizing network is Type 2A.

Historical Development of Micropiles

The concept of micropiles dates back to Italy in the early 1950s when innovative and reliable methods of underpinning historic buildings and monuments were being sought (Lizzi, 1982) in that war damaged country. Specifically, a system was

Micropile Type and Grouting Method	Subtype	Drill Casing	Reinforcement	Grout	Comparison with other Types or Classifications	Notes
TYPE A Gravity grout only	A1	Temporary or unlined (open hole) or auger	None, monobar, cage or tube	Sand/cement mortar or neat cement grout, tremied to base of hole (or casing), no excess pressure applied	• Original "Root Piles" • GEWI Pile • French Type I or II	• Majority of Type A micropiles now used only when bond zone is in rock or stiff cohesives.. • Includes underreamed piles but very rare. • Unreinforced micropiles now not used (or allowed by codes).
	A2	Permanent, full length	Drill casing itself		• NCC Types S2 and R2	
	A3	Permanent, upper shaft only	Drill casing in upper shaft, bar(s) or tube in lower shaft (may extend full length		• NCC Types S1 and S2	
TYPE B Pressure grouted through the casing during withdrawal	B1	Temporary or (fully extracted)	Monobar(s), or tube (cages rare due to lower structural capacity)	Neat cement grout is first tremied into drill casing. Excess pressure (up to 1 MPa typically) is applied to additional grout injected during withdrawal of casing	• Later "Root Piles" • French Type I • Italian "Steel Pile" • GEWI Pile	• Very rarely are sand/cement mortars used, since these may cause problems during pressurization.
	B2	Permanent, full length	Drill casing itself		• NCC types S2 and R2	
	B3	Permanent, upper shaft only	Drill casing in upper shaft, bar(s) or tube in lower shaft (may extend full length		• NCC Types S1 and S2	

Table 1. Details of micropile classification based on type of grouting (continues).

Micropile Type and Grouting Method	Subtype	Drill Casing	Reinforcement	Grout	Comparison with Other Types or Classifications	Notes
TYPE C Primary grout placed under gravity head, then one phase of secondary "global" pressure grouting	C1	Temporary or unlined (open hole or auger)	Monobar(s), or tube (cages rare due to lower structural capacity)	Neat cement grout is first tremied into hole (or casing). Between 15 and 25 minutes later, similar grout injected through tube (or reinforcing pipe) from head, once pressure is greater than 1 MPa.	• French Type III (Injection Globale Et Unitaire)	• Appears to be used in France only. • Secondary grouting via a separate sleeved pipe or through the reinforcement tube equipped with sleeves
	C2	Not possible	–		–	
	C3	Not conducted	–		–	
TYPE D Primary grout placed under gravity head, then one phase of secondary "global" pressure grouting	D1	Temporary or unlined (open hole or auger)	Monobar(s), or tube (cages rare due to lower structural capacity)	Neat cement grout is first tremied into hole (or casing). Some hours later, similar grout injected through sleeved pipe (or sleeved reinforcement) via packers, as many times as necessary to achieve bond.	• French Type IV (Injection Répétitive Et Sélective) • Tubfix • IM Pile	• Typically the classic tube à manchette is used with double packer. Alternatively, the steel tube can be equipped with sleeves or the DSI regrout tube (with return) can be used (Chapter 3) • Secondary grouting via a separate sleeved pipe or through the reinforcement tube equipped with sleeves
	D2	Not possible	–		–	
	D3	Permanent, upper shaft only	–		• NCC Type S1 • GEWI Pile	

Table 1. Details of micropile classification based on type of grouting (continued).

needed that could accept structural loads with minimal movements and be installed in restricted working areas and in various soil types. In addition, it was essential that the construction method imposed minimal adverse effects on the structure being underpinned or on adjacent structures.

In response to this need, the Italian specialty contractor Fondedile, under the technical direction of Dr. Lizzi, developed the "palo radice" (root pile), a small-diameter, drilled, cast-in-place, lightly reinforced grouted pile (Type A). These piles were ideally suited for underpinning applications. Their small diameters of around 100 mm permitted construction with small-sized rotary drill rigs that could operate in confined access conditions and could drill through existing structures and subsoils with minimal disturbance. In addition, the injection of the grout, consisting of coarse sand, cement, and water, promoted high frictional bond with the surrounding soil. Such piles were tested to loads of over 400 kN, and no grout/soil interfacial failures were recorded. At that time, the anticipated load calculated from guidelines on large diameter drilled shafts was only about 100 kN.

That year also saw the first *application* of root piles, for the underpinning of the A. Angiulli School in Naples. The piles were 13 m long, 100 mm in diameter and centrally reinforced by a 12-mm diameter bar. The excellent load-holding performance of the first test pile in the volcanic ashes and sands at this site drew widespread professional attention, as did the publication of similar data from numerous sites thereafter. It is easy to concur with Dr. Lizzi's later assessment (1982) that "the introduction of 'Pali Radice' gave rise to a complete change in the field of underpinning."

The acquisition and publication of such essential test information were facilitated by the relatively low cost of direct full-scale load tests in the field, and were driven by research into new applications. In contrast, most contemporary European construction regulations, for cast-in-place bored piles, permitted diameters only in excess of 300 mm, only vertical installations, and very little scope for alternatives or innovation.

With the growing acceptance of the technique in international circles, the use of root piles spread quickly throughout Europe. For example, Fondedile introduced root piles to the United Kingdom in 1962, mainly to underpin historic structures threatened by decades of neglect. By 1965, similar systems had been used in Germany in association with underground urban transportation schemes, and in the same decade, root piles were used during construction of parts of the Milan subway. During this project, the Milan Subway Authority introduced the term micropali (micropiles), in preference to root piles because the latter term was proprietary. It is noteworthy that at the time of the introduction of micropiles to German practice, the German Code (Din 4014) for Bored Piles limited the capacity of a *400-mm diameter pile* to the range 300 to 370 kN, compared to demonstrated micropile capacities in excess of 1000 kN for 120-to 250-mm diameter elements. Micropiles in Germany have been covered since 1983 by a separate, specific code (DIN4128).

While the great majority of these applications were direct underpinning (CASE 1), the demands of urban engineering had encouraged the appearance of the CASE 2 "reticulated pali radice" (Figure 5), the first full-scale tests of which were carried out in 1957. Such structures were then applied for slope stabilization, reinforcement of quay walls, protection of buried structures, and other soil and structure support and reinforcement needs.

Elsewhere, other contractors had begun to develop their own proprietary micropiles, such as the GEWI pile (first used at the Hoechst facility in Frankfurt by Dywidag in 1971), the Rodio Tubfix Micropile (first reported being tested in Switzerland in 1962), and the pieu aiguille (Soletanche 1974). These Type A, B or D micropile types were quickly exported overseas by branches or licensees of the original European contractors.

Refinements continue to be made by European contractors, driven by the need to provide highly engineered, high quality solutions to progressively more difficult construction challenges, in an extremely competitive economic climate. One example is the growing use of Type D piles, in which <u>bond enhancements</u> by high pressure grouting are favored over <u>bond area enlargement</u> by enlarging the pile perimeter. Indeed in France, very lightly or totally unreinforced Type A piles (equivalent to the original root pile) are no longer used on economic grounds. CASE 2 applications appear to be considered only in Italy and Japan, although increasing awareness of their potential is clear, especially in France.

Fondedile introduced micropiles into North America in 1973 by executing a number of CASE 1 underpinning jobs, principally in New England. The first example of a reticulated CASE 2 structure was in 1975 for a structure to support and stabilize the abutment and pier foundation of a bridge along I-55 in Jackson, Mississippi (Figure 6). In November 1977, a similar structure was completed in the Mendocino National Forest, California to stabilize a landslide area along Forest Highway 7. Both projects were instrumented by the U.S. Army Corps of Engineers, under contract with the Research Division of the FHWA (Palmerton, 1984).

By the mid 1970s, American specialty contractors, who were previously engaged in drilling, grouting and anchoring work, began to develop their own variants, such as the Nicholson Pin Pile (Bruce, 1988), a Type A, B or D highly reinforced pile. All applications were CASE 1. The skepticism of a traditional East Coast piling market, however, did not encourage rapid application of the technique, and indeed by 1984, Fondedile decided to close their American venture for commercial reasons. Ironically, the period from 1987 onwards then saw rapid growth in the number of applications, as the pressure from innovative contractors, the weight of successful case histories, and the newly realized needs of consultants and owners working in old urban environments finally overcame the concerns of the traditionalists (Bruce, 1992). As illustration, Bruce (1994) listed 25 case histories of micropile projects completed by his company, in the United States,

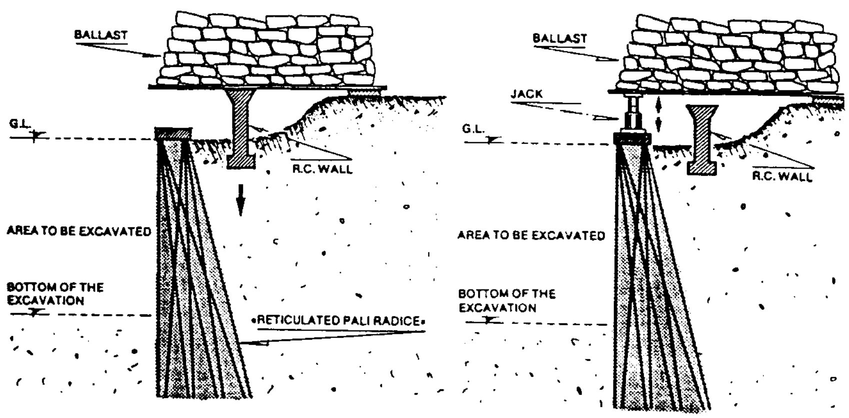


Figure 5. Early load tests on reticulated micropile structures; 1st phase - loading being applied behind wall; 2nd phase - load directly on the wall. Milan Subway, 1957. (Lizzi, 1982).

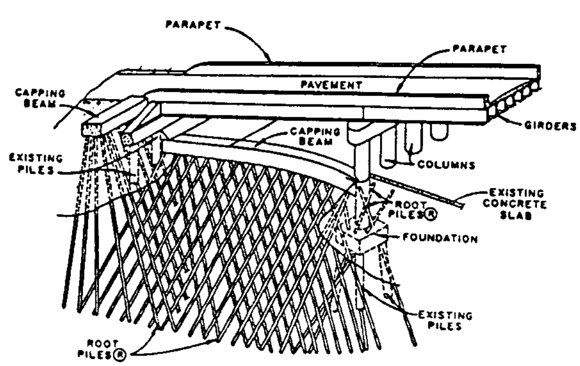


Figure 6. Reticulated micropile structure, for abutment and pier support, Jackson, Mississippi (Lizzi, 1978).

between the years 1978 and 1988, but an additional 20 projects completed in the subsequent 2 years. All of these applications were in the older urban areas of the East Coast or the "Rust Belt", or for industrial facilities in the Southeast. Since then, the number of applications conducted by a wide range of specialty contractors - for underpinning alone - has continued its rapid advance, with much activity now centering on seismic retrofit applications on the West Coast.

There has also been a significant, if less dramatic, growth in the use of micropile structures for slope stabilization, especially in the rural areas of the Appalachian Mountains, where more conventional solutions using large-scale equipment may not be feasible. These systems have been designed conceptually as CASE 1, although the legacy of the original Fondedile CASE 2 concept continues to influence aspects of design.

This contrast between the rates of micropile development in Europe and North America in many ways reflected the situation in piling in general. In Europe, in the immediate post-war years, there was a shortage of steel, but an abundance of cheap, highly qualified labor. Cast-in-place concrete piling therefore became popular, and in the absence of rigorous analytical expertise, industry leadership was in the hands of specialty geotechnical contractors. Designs relied heavily on the results of prior load test programs, while innovations were driven by the particular challenges posed by war damage and new urban infrastructure projects.

In North America, materials, especially steel, were generally cheaper and more readily available, although labor costs were significantly higher. Furthermore, there was no need for reconstruction programs, and the major capital works were typically outside the cities rather than inside them. This set of circumstances therefore favored the growth of the low technology, driven-pile market, not requiring specialty design/build companies.

Today the situation is similar throughout the world in terms of construction costs and technical demands. There are strong technical and academic centers and responsive and supportive public administrations. Specialty construction companies have been founded, or have been exported, globally. These factors all have helped the growth of micropiles.

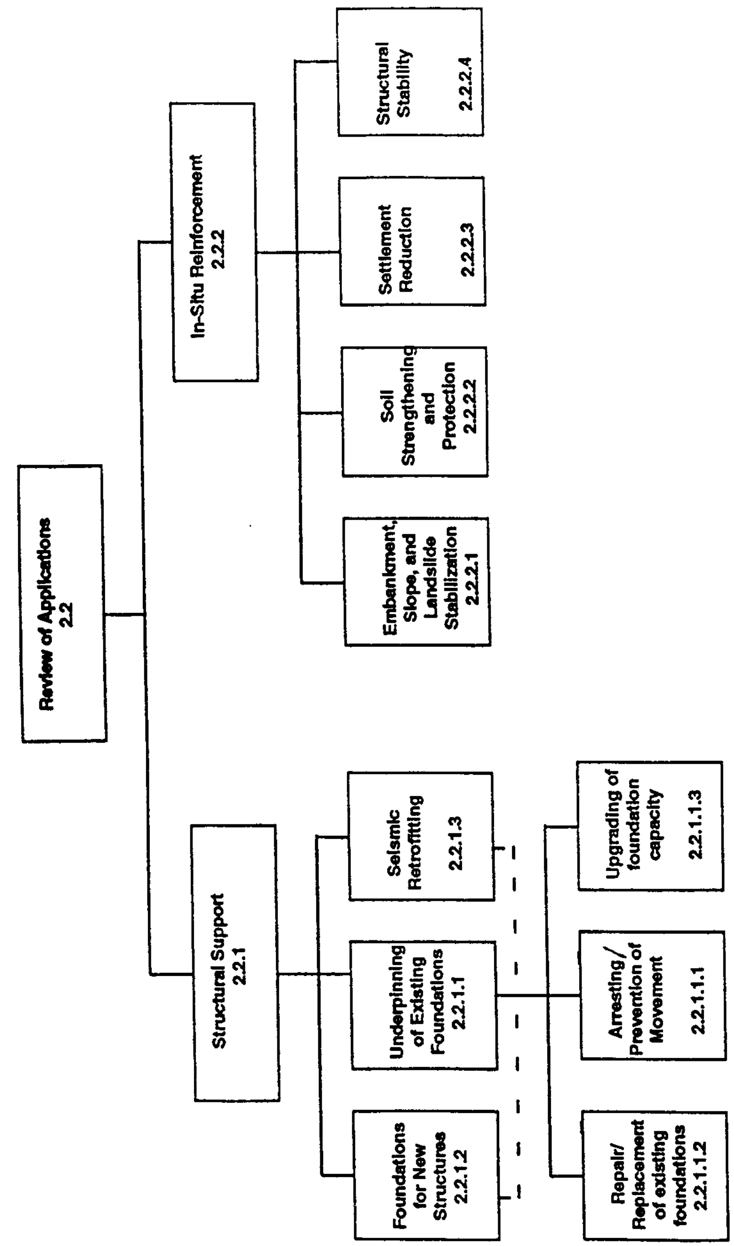
Regarding micropiles in other countries, in Canada until recently, there has been little demand and so relatively few applications. The activity level in Mexico is currently similar, although there the problem is less a shortage of applications rather than a shortage of funding. As in most other fields of specialty engineering, the potential in Mexico is considerable. Applications in South America have likewise been restricted by financial difficulties although some large CASE 2 installations have been made, such as for a landslide prevention scheme along the Santos-Sao Paulo Highway in Brazil in 1977 (Lizzi, 1978).

According to Heinz (1994) "micropiling is alive and well in South Africa", based on technologies imported by European specialty contractors working with local partners. Micropiles are regarded as a "specialized tool from the geotechnical toolbox for solving particular problems" - an observation now common internationally. Applications vary from 300-mm diameter high capacity CASE 1 piles to 75-mm diameter "simple" CASE 2 soil reinforcement, and piles of Types A, B and D have been installed in a wide variety of soil and rock conditions.

<u>Classification of Micropile Applications</u>

Micropiles are used in two basic applications: as structural support and as in-situ soil reinforcement (Figure 7). For direct structural support, groups of micropiles are designed on the CASE 1 assumptions, namely that the piles accept directly the applied loads, and so act as substitutes for, or special versions of, more traditional pile types. Such designs often demand substantial individual pile capacities and so piles of construction Types A (in rock or stiff cohesives), B and C (in most soils) are most commonly used.

For micropiles used as in-situ reinforcement, the original CASE 2 network featured low capacity Type A piles. Recent research by Pearlman et al. (1992), on groups of piles, suggests that in certain conditions and arrangements, the piles themselves are principally, directly, and locally subjected to



<u>Figure 7</u>. Classification of micropile applications (Numbers refer to Sections in FHWA State of Practice Report).

bending and shearing forces. This would, by definition, be a CASE 1 design approach. Such piles typically are highly reinforced and of Type A or B only.

Whereas CASE 1 and CASE 2 concepts alone or together can apply to slope stabilization and excavation support, generally only CASE 2 concepts apply to the other major applications of in-situ reinforcement. Little commercial work has been done in these applications (with the exception of improving the structural stability of tall towers, (Figure 3b). However, the potential is real and the subject is being actively pursued in the "FOREVER" program in France. Table 2 summarizes the link between application, classification, design concept and constructional method. It also provides an indication of how common each application appears to be world-wide.

Final Remarks

In summary, it appears that micropiles are being used throughout the world and are regarded as a reputable construction tool of real value and potential. While the underpinning of Europe's historic structures continues apace, especially in cities being impacted by new underground constructions, the newer and expanding cities of the Far East, South Africa and South America are blossoming markets as sophisticated construction continues in soft soils, with high water tables in highly congested and populous areas, often under the threat of major seismicity. The market in the United States appears to be a combination of both scenarios, given the ongoing upgrading and refurbishment of industrial, transportation, and commercial structures, especially on the coastal belts. On a somewhat cautionary note, the French "FOREVER" team sees two major research challenges, which, when met, could stimulate further micropile growth: a) there are no specific or general recommendations regarding long-term corrosion, and b) "the tools for the design, dimensioning and calculation of micropiles do not sufficiently take into account the effects of groups or networks (of piles) under a wide variety of stresses (static, cyclic, and seismic loads). Throughout their history, commercial and technological innovations have almost always preceded studies of fundamental performance and the development of design

APPLICATION	STRUCTURAL SUPPORT 2.2.1	IN-SITU EARTH REINFORCEMENT 2.2.2			
Sub-applications	Underpinning of Existing Foundations 2.2.1.1 New Foundations 2.2.1.2 Seismic Retrofitting 2.2.1.3	Slope Stabilization and Excavation Support 2.2.2.1	Soil Strengthening 2.2.2.2	Settlement Reduction 2.2.2.3	Structural Stability 2.2.2.4
Design concept	CASE 1	CASE 1 and CASE 2 with transitions	CASE 2 with minor CASE 1	CASE 2	CASE 2
Construction type	Type A (bond zones in rock or stiff clays) Type B and D in soil (Type C only in France)	Type A (CASE 1 and 2) and Type B (CASE 1) in soil	Type A and B in soil	Type A in soil	Type A in soil
Estimate of relative application	Probably 95% of total world applications	0 to 5%	Less than 1%	None known to date	Less than 1%

Table 2. Relationship between micropile application, design concept, and construction type. (Numbers refer to Sections in FHWA State of Practice Report).

methods." It is hoped that the present efforts of researchers in the United States and France will resolve these issues within the next few years.

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