

High Capacity Micropiles - Basic Principles and Case Histories

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Abstract

Small diameter, drilled, grouted-in-place micropiles have been installed throughout the world since 1952. A recent international study, funded by the U.S. Government, and summarized herein, provides new insight into design, construction and testing practices used in various countries. Two recent case histories, reflective of contemporary U.S. practice, illustrate the major innovations in theory and construction.

Background

Between 1993 and 1996, the Federal Highway Administration (FHWA) funded the single most significant and comprehensive review of global micropile practice so far conducted. This effort also underlined the desire of the FHWA to contribute to a contemporary French national research project's five-year effort named FOREVER (Fondations Renforcées Verticalement) and designed to conduct a variety of integrated experimental programs relating to micropiles. The FHWA study featured the formation of an International Advisory Panel comprising specialists from North America and Europe.

Not only did this group ensure that a comprehensive review of practice was conducted, but also they were able to resolve a number of fundamental issues regarding various aspects of the classification, design, construction and performance of micropiles.

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These issues had been a source of confusion and misunderstanding and therefore restricted the use of micropiles in certain engineering circles.

Scope

Micropiles are, generically, small-diameter, bored, grouted-in-place piles 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*, *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 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).

Characteristics and Definitions

Micropiles are a small-diameter subset of cast-in-place replacement 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. Early micropile diameters were around 100mm, but with the development of more powerful drilling equipment, diameters of up to 300mm are now considered practical. 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.

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 300mm, although in France the limit is set as 250mm), 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 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 250mm 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. It is also the case that many short piles of 75-mm diameter or less are installed routinely for residential underpinning. These typically have service loads less than 150 kN, but are often of the displacement category discussed above.

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 FHWA team concluded that a new, rigorous classification be adopted based on two criteria:

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

The first criterion dictates the basis of the overall design concepts, and the second 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 1). 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, 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,

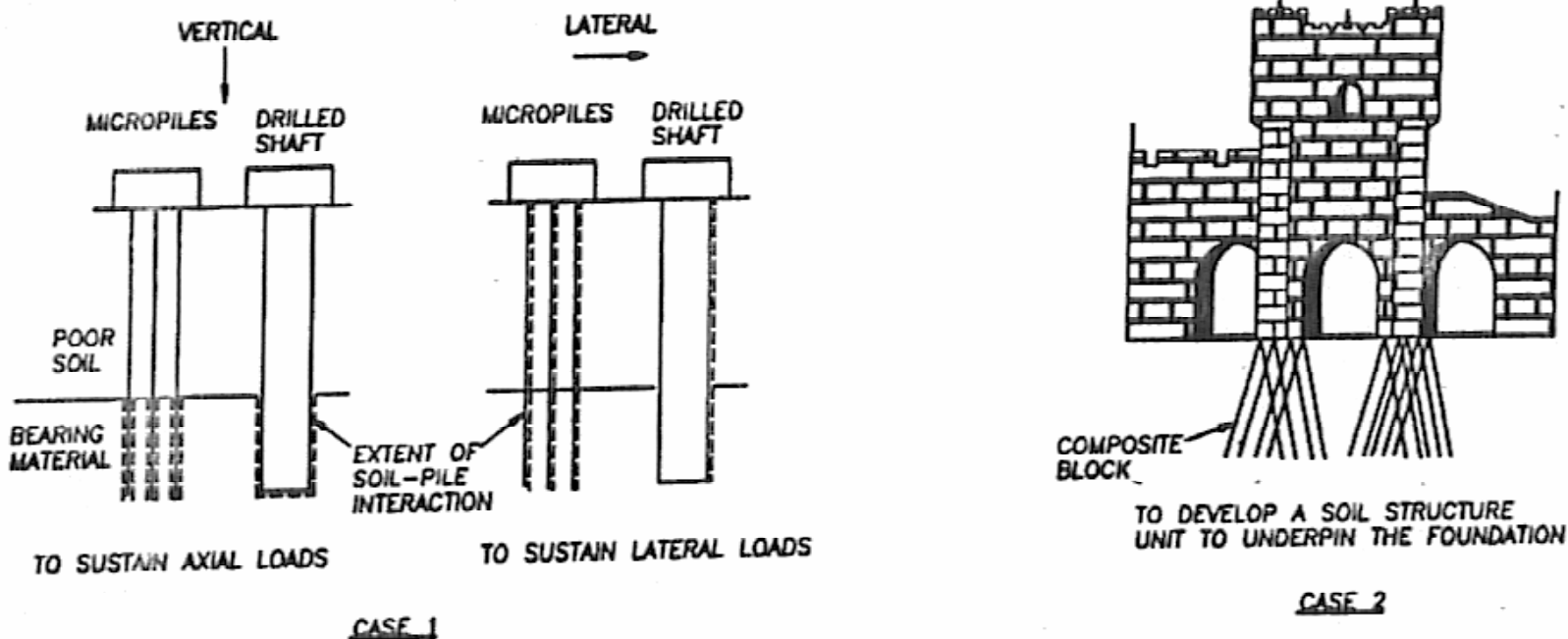


Figure 1. Classification based on design philosophy. (Bruce et al., 1995)

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 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. 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 laterally confined soil/pile composite structure that can provide underpinning, stabilization or earth retention, also as illustrated in Figure 1. 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.

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 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** is therefore adopted. It is shown schematically in Figure 2.

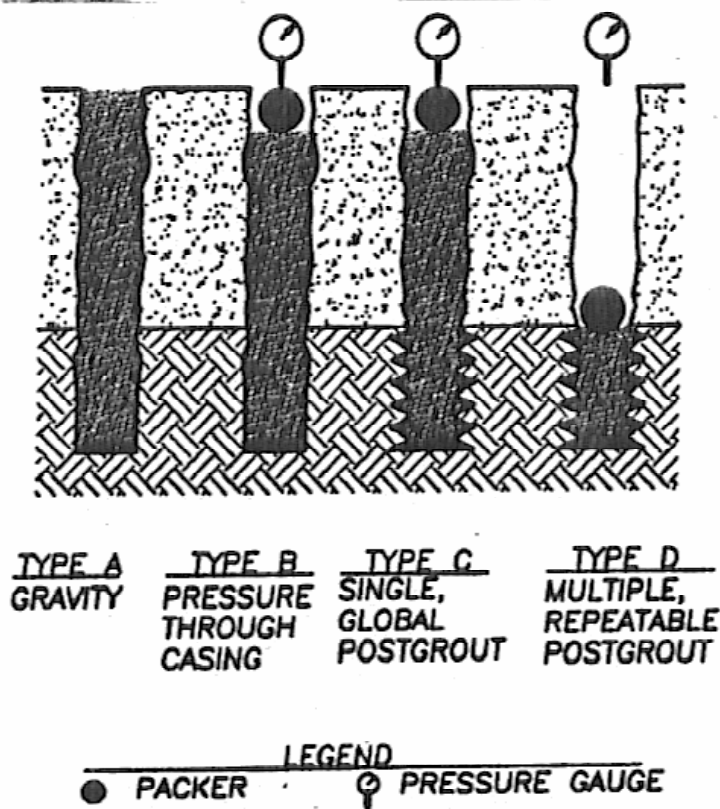


Figure 2. Classification based on construction (grouting) method (Bruce et al., 1995)

- **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 (largely 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, 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.
- **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.

Table 1 summarizes the relationships between the classification and application.

Application	Structural Support	In Situ Earth Reinforcement			
Sub-applications	Underpinning of existing foundations New foundations Seismic retrofitting	Slope stabilization and Excavation support	Soil strengthening	Settlement reduction	Structural stability
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 on application	Probably 95% of total world applications	0 to 5%	Less than 1%	None known to date	Less than 1%

Table 1. Relationship between micropile application, design concept, and construction type.

Combined Classification. Micropiles can therefore be 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. 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.

Case Histories

Brief details from two recent case histories are provided to illustrate typical current U.S. practice in the use of CASE 1 and CASE 2 micropiles respectively.

Introduction. This structure was built in 1914 and added to in 1940. It was founded primarily on Raymond step taper piles and timber piles, and is underlain by potentially liquefiable fine, silty sand. Design requirements were for 217 high capacity CASE 1B micropiles, each of service load 533kN in compression, 356kN in tension and 44kN in lateral capacity (at a maximum allowable deflection of 13mm). This is an increasingly common application of high capacity micropiles. These piles were to be installed both through existing pile caps, and in other locations where new pile caps would be later created.

Geology and Site. Under 2.4 - 3m of variable fill, the 8m thick zone of potentially liquefiable sands overlaid weathered limestone. Access for drilling equipment was difficult, given the nature of the overhead and underground obstructions (in the fill, and including the old piles and pile caps).

Design Details. To satisfy the Owner's performance requirements, each pile comprised a 244-mm o.d. steel casing socketed 0.9m into the limestone. Below this, a 200-mm diameter hole was drilled a minimum of 4.6m deep to accommodate a 60-mm diameter reinforcing bar. In addition, a 3.1-m length of 178-mm diameter steel casing was placed in the upper part of the pile to satisfy lateral load deflection characteristics.

Construction. Diesel hydraulic track rigs were used with water flush to rotary drill both overburden and rock. Pressure grouting through the drill head to a maximum pressure of 0.7 MPa was conducted with a retarded low water cement ratio Type I-II grout, produced in a high speed, high shear mixer.

Preproduction Load Tests. Load tests were conducted on a limited number of test piles prior to the production work proceeding. These tests were conducted in accordance with the relevant ASTM standards, enhanced with extra load cycles, to the criteria shown in Table 2. Results are shown in Table 3.

Final Remarks. Following the successful testing program, the remaining piles were installed during a three month period, despite severe construction impediments, including severe water rationing and ongoing building demolition. The overall structural remediation is now complete.

Compression Test	<ol style="list-style-type: none"> 1. Movement less than theoretical pile compression + 3.8mm + January 20, 1999 1% pile diameter. 2. Permanent movement after test load less than 13mm. 3. 150% of design load (801 kN) to reach limestone. 4. Maximum test load of 1068 kN to be achieved.
Tension Test	<ol style="list-style-type: none"> 1. Permanent movement after test load less than 13mm. 2. No creep at test load. 3. Maximum test load of 712 kN to be achieved.
Lateral Test	<ol style="list-style-type: none"> 1. Maximum head deflection less than 13mm at design load. 2. Design load is 44 kN, test load 88 kN.

Table 2. Acceptance Criteria for test piles, Puerto Rico.

Compression (Pile 212)	<ol style="list-style-type: none"> 1. 15.2mm 2. 5.41mm 3. Acceptable 4. Achieved 	Tension (Pile)	<ol style="list-style-type: none"> 1. 5.87mm 2. Achieved 3. Achieved 	Lateral (Pile)	<ol style="list-style-type: none"> 1. 11.4mm 2. Achieved
Conclusion	Pass		Pass		Pass

Table 3. Summary of results obtained on test piles, as judged against Table 2 criteria.

Underpinning of Machine Foundation, E. Pennsylvania (Cadden et al., 1998)

Introduction. Heavy machinery used for plastic injection molding showed signs of unacceptable movements due to its weight, the high and repeated dynamic forces exerted during its operation and the subsoil conditions. Due to overriding scheduling restrictions, the problem had to be solved with the equipment in situ, to ensure angular distortions of less than 0.13mm in 3m, and no differential settlement between the two halves of the machine.

Geology and Site. Figure 3 shows the generalized conditions under the machinery. The soil proved to be medium stiff silts and clays, and the rock was shale. The operational facility comprised a large steel framed structure providing access via roll top doors at each end. Space around the equipment was severely restricted for drilling access.

Design Details. The relatively thin and weak reinforced concrete slab was deemed unable to sustain the loads imposed by high capacity CASE 1 micropiles, and so an array of CASE 2 piles was designed (Figure 4). Each pile had a nominal service load of 200 to 400 kN, and comprised a 25-m diameter reinforcing bar in a 76-mm hole, drilled 3m into bedrock.

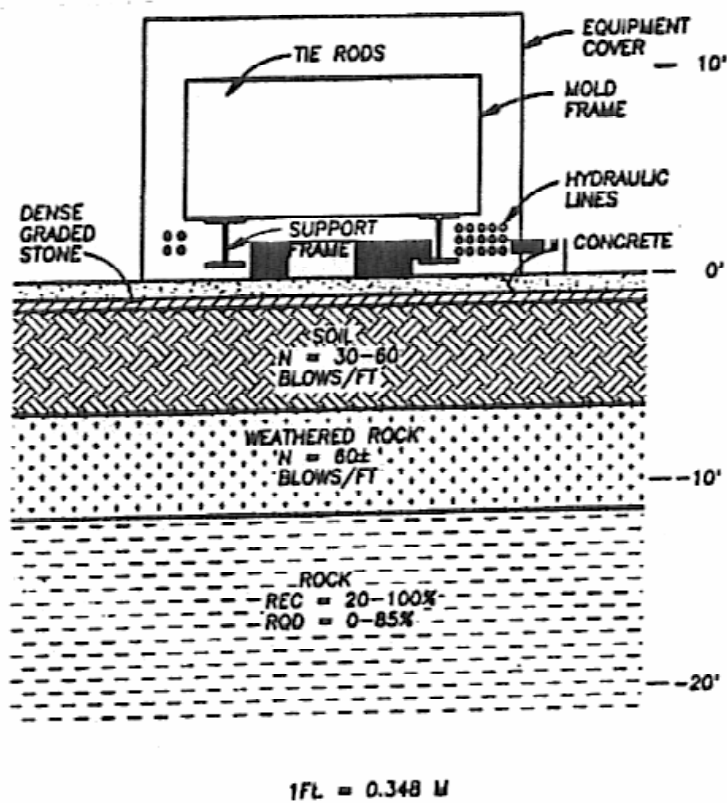


Figure 3. Simplified geologic layers beneath machinery, E. Pennsylvania (Cadden et al., 1998)

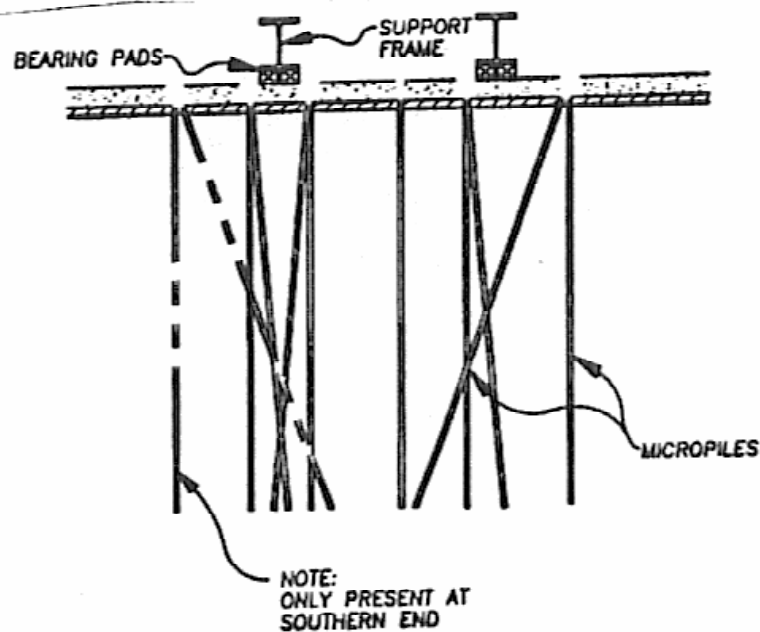


Figure 4. Micropile installation cross section, E. Pennsylvania (Cadden et al., 1998)

Construction. Special modular rotary drilling rigs were used to ensure appropriate access and hole inclination. The pile grout was designed to have low slump to facilitate clean-up in the building, while a high early strength mix was used to grout the pile reinforcement to the slab to enhance load transfer.

Performance. Following the underpinning, a uniform movement of around 0.2mm occurred, but without distortion or rocking during the transient loading applied by the machine. Within one week, no further movements were recorded, and the facility continues to operate without movement problems.

The Future

In the United States, as in the case worldwide, new geotechnical and structural challenges for both static and seismic retrofit are fostering the continuing growth of micropile technology. In particular, the demands of seismic engineering continue to provide new impetus to the study and understanding of pile performance in general, and pile networks especially.

Aided by the classification breakthrough made by FHWA, researchers in the United States, France, and Japan are poised to close the gap that still exists between the level of analytical understanding, and the excellence of the construction, testing, and performance knowledge. One consequence will be a rapid growth in the application of CASE 2 structures, optimally and rigorously designed to ensure efficient and economic solutions especially for seismic applications.

The relative ease of global information retrieval and exchange systems, coupled with the momentum established by micropile researchers in the late 1990s will ensure that developments in micropile technology will continue apace, and provide a fitting reflection of the foresight of their progenitor, Fernando Lizzi.

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