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A PRIMER ON MICROPILES

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A major international study of micropiling funded by the Federal Highway Administration provides an overview of the technology's characteristics, history and range of applications, and proposes a rigorous new system to guide micropile design and construction.

First conceived in Italy in the early 1950s and introduced in the U.S. more than two decades later, micropiling technology has advanced rapidly since the mid-1980s, spurred by micropiles' high axial load-holding performance and their ability to be installed in difficult locations and geologies. Main applications have been as foundation-support elements in static and seismic situations as well as for in situ reinforcement of slope and excavation stabilization.

Many applications are on transportation projects, and in 1993 the Federal Highway Administration (FHWA) decided to fund a major study of the technology. In part, this reflected industry's growing awareness of the potential of micropiling as a means of resolving difficult foundation and slope-stability problems. In addition, FHWA wished to cooperate with French colleagues who in 1993 had commenced a five-year project, Fondations Renforcees Verticalement (FOREVER), involving a variety of civil engineering and geotechnical organizations, other research and testing bureaus, businesses, contractors and owners.

The major tasks set for the FHWA study, which will be published in late 1995, were:

- Determine the state of the practice.
- Assess research needs.
- Coordinate with foreign programs and specialists.

The contract was awarded to Nicholson Construction Co., Bridgeville, Pa. An international advisory board was assembled that provided a blend of contractor, consultant, academic and client representatives, mirroring the French team.

CHARACTERISTICS AND DEFINITION

Small-diameter drilled and grouted piles have been used throughout the world for various purposes, under a profusion of local names, including *pali radice* and *micropali* (Italian); *pieux racines, pieux aiguilles, minipieux* and *micropieux* (French); minipiles, micropiles, pin piles, root piles and needle piles (English); *Verpresspfähle* and *Wurzelpfähle* (German); and *Estaca Raiz* (Portuguese).

This type of pile can withstand axial and/or lateral loads, and may serve as one component in a composite soil/pile mass or a small-diameter substitute for a conventional pile. Also, micropiles are installed with methods that cause minimal disturbance to structure, soil and environment. This differentiates them from related techniques that employ percussive or explosive energy (driven elements), ultrahigh flushing and/or grouting pressures (jet nails), or large-diameter drilling techniques that can cause lateral soil decompression (auger cast piles). Although soil nailing uses construction techniques similar to micropiles, in concept, design and function it was regarded to be beyond the scope of the FHWA study.

Typical overviews of bearing-pile types distinguish between displacement piles, which displace laterally the soils through which they are introduced, and replacement types, formed by creating a borehole into which the pile is then cast or placed. Micropiles are a small-diameter subset of cast-in-place replacement piles.

With conventional cast-in-place replacement piles, in which most of the load is resisted by concrete as opposed to steel, small cross-sectional area is synonymous with low structural capacity. This is not the case with micropiles, however. Innovative drilling and grouting methods permit high grout/ground bond values to be generated along the micropile's periphery. To exploit this benefit, high-capacity steel elements, occupying up to 50% 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 on, and in any event is relatively insignificant given the pile geometries involved. Early micropile diameters were around 100 mm, but with the development of more powerful drilling equipment, diameters of up to 300 mm are now considered practical. Micropiles are capable of sustaining surprisingly high loads (compressive loads of more than 5,000 kN have been recorded) or, conversely, can resist lower loads with minimal movement. Most micropiles are 100–250 mm in diameter, 20–30 m long, and 300–1,000 kN in compressive or tensile service load, although far greater depths and much

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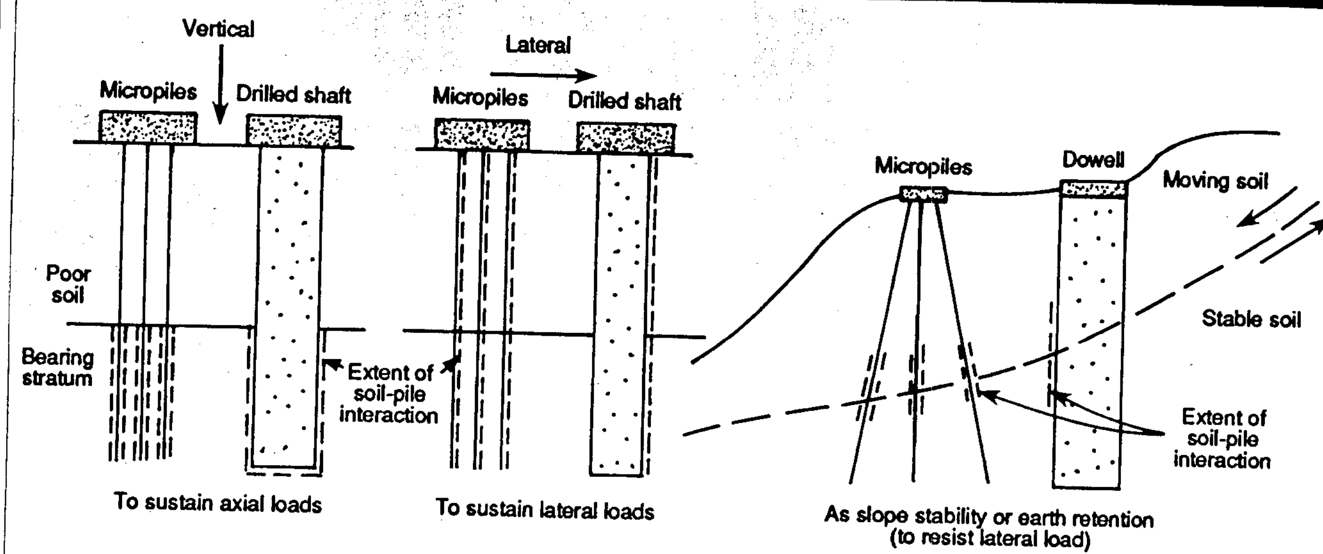
FIG. 1. CASE 1 MICROPILES



DIRECTLY LOADED PILES, WHETHER FOR AXIAL OR LATERAL LOADING CONDITIONS, COMPRISE VIRTUALLY ALL APPLICATIONS IN NORTH AMERICA AS WELL AS 90% OF ALL KNOWN INTERNATIONAL APPLICATIONS.

higher loads are common in the U.S.

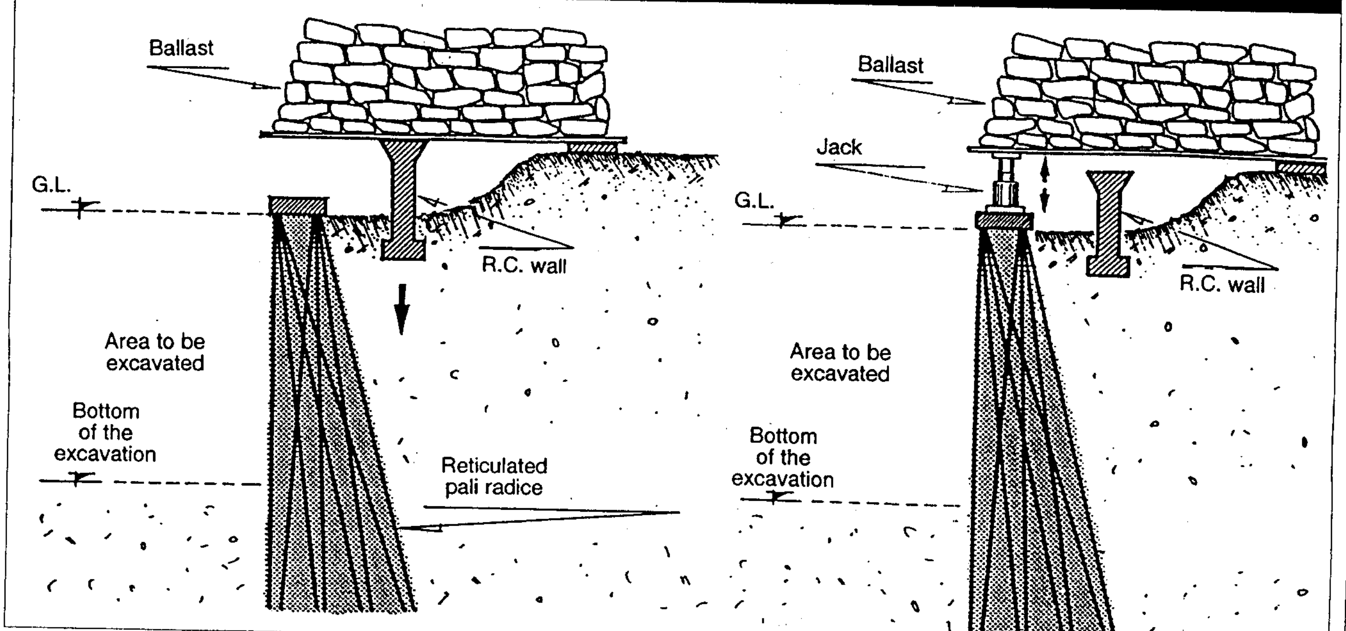
The development of highly specialized drilling equipment and methods also allows micropiles to be drilled through virtually every ground condition with minimal vibration, disturbance and noise, and at any angle below horizontal. Micropiles are used widely for underpinning existing structures, and the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

Micropiles have been subclassified according to diameter, construction process or the nature of the reinforcement. However, in the course of the FHWA study, we concluded that a new, rigorous classification should be adopted based on two criteria: the philosophy of behavior, which dictates the basis of the overall design concept; and the method of grouting, which mainly determines grout/ground bond capacity.

1. Philosophy of behavior. Micropiles are usually designed to transfer structural loads to more competent or stable strata. They act as substitutes or alternatives for other conventional pile systems. For both axially loaded piles and those used as in situ reinforcements for slope stabilization, the pile (principally the reinforcement) directly resists the applied loads. This is equally true for individual piles or groups of piles.

When axially loaded piles are designed to transfer their load only within a remote founding stratum, pile head movements will occur during loading. In this instance, the pile can be preloaded to ensure that the structure can be supported without further movements occurring. If suitably competent ground conditions exist all the way

FIG. 2. CASE 2 MICROPILES



A SMALLER GROUP OF STRUCTURES PROVIDE SUPPORT THROUGH AN INTERLOCKING THREE-DIMENSIONAL NETWORK OF RETICULATED PILES. SHOWN HERE IS AN EARLY LOAD TEST ON THE MILAN SUBWAY, CONDUCTED IN 1957.

TRACING THE ROOTS OF MICROPILES

The concept of micropiles dates back to war-damaged Italy in the early 1950s, where the search was on for innovative and reliable methods of underpinning historic buildings and monuments—specifically, for a system that could accept structural loads with minimal movements and be installed in restricted working areas and various soil types, without adversely affecting the structure being underpinned or adjacent structures. In response to this need, the Italian specialty contractor Fondedile, under the technical direction of Fernando Lizzi, developed the *palo radice* (root pile), a small-diameter, drilled, cast-in-place, lightly reinforced grouted pile ideally suited for underpinning applications.

With a diameter of around 100 mm, these piles could be constructed with small-sized rotary drill rigs able to operate in confined conditions and drill through existing structures and subsoils with minimal disturbance. Also, 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 more than 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.

The first application of root piles was for the underpinning of the A. Angiulli School in Naples, Italy. 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 attention, as did similar data from numerous sites thereafter, and the use of root piles spread quickly throughout Europe.

Fondedile introduced root piles to the U.K. in 1962, mainly to underpin historic structures threatened by decades of neglect. By 1965, similar systems had been used in then–West Germany in association with underground urban transportation schemes, and, in the same decade, root piles were used during construction of parts of the Milan, Italy subway. During this project, the Milan Subway Authority introduced the term *micropali* (micropiles), in preference to root piles because *pali radice* was proprietary. While most applications were direct underpinning, reticulated *pali radice*, first tested at full scale in 1957, were 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, which were quickly exported overseas by branches or licensees of the original European contractors.

In North America, micropiling was slower to catch on. Circumstances in the postwar years favored the growth of the low-technology, driven-pile market, not requiring specialty design-build companies. Materials, especially steel, were cheaper and more available, and labor costs were significantly higher compared with Europe. There was no need for reconstruction programs, and major capital works were typically outside the cities rather than inside.

Fondedile introduced micropiles into North America in 1973 by executing a number of underpinning jobs, principally in New England. The first reticulated structure was in 1975 to support and stabilize the abutment and pier foundation of a bridge along Interstate 55 in Jackson, Miss. In November 1977, a similar structure was completed in the Mendocino National Forest, Calif. 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 Federal Highway Administration.

By the mid-1970s, U.S. specialty contractors engaged in drilling, grouting and anchoring work began to develop their own variants. The skepticism of a traditional East Coast piling market, however, did not encourage rapid application of the technique, and, by 1984, Fondedile closed their American venture for commercial reasons. Ironically, the period from 1987 onwards saw rapid growth in 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 traditionalists.

down from below the structure, the pile can be fully bonded to the soil over its entire length; movements under equivalent loads will be smaller than in the previous case.

Such directly loaded piles (case 1), whether for axial or lateral loading conditions, comprise virtually all North American and at least 90% of international applications. There is also a smaller group of applications that provide support and stabilization by an interlocking, three-dimensional network of reticulated piles similar to the root network of a tree (case 2). This involves the creation of a laterally confined soil/pile composite structure that can work for underpinning, stabilization and earth retention. Such micropiles 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 so, to work, the soil must have a reasonable degree of competence over its entire profile.

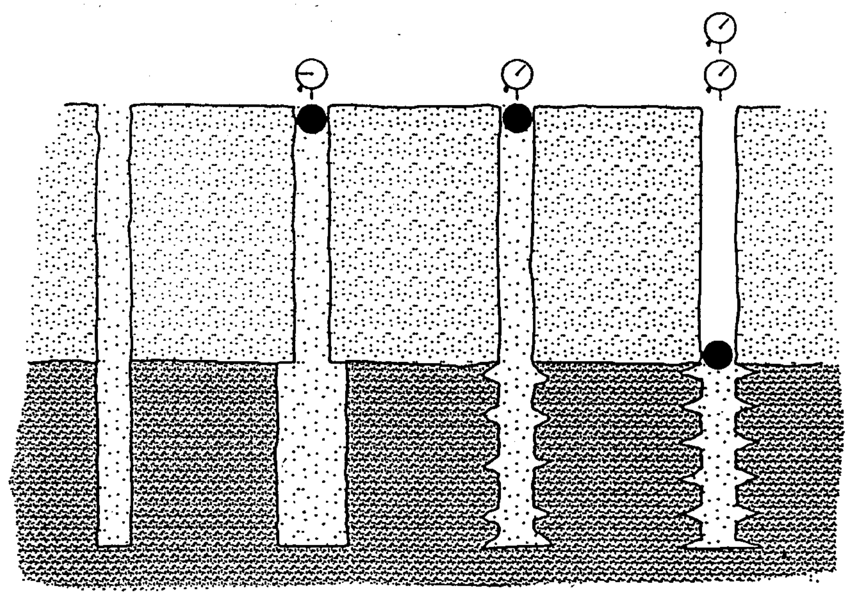
The basis of design for a case 2 network is radically different from a case 1 pile (or group of piles). However, some applications may be transitional between the two. For example, a positive group effect may be achieved in case 1 designs (although this attractive possibility is now conservatively ignored 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 transitional cases can be designed with clarity and precision.

2. Grouting method. The steps in constructing micropiles are simply: (1) drill; (2) place reinforcement; and (3) place and typically pressurize grout (usually this involves extraction of temporary steel drill casing). Overall, international practice in both micropiles and ground anchors confirms that, of these steps, the grouting is generally the most sensitive construction control over grout/ground bond development and thereby over pile capacity.

This classification of micropile type is based primarily on the type and pressure of the grouting.

- 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

FIG. 3. GROUTING METHODS



THE GROUTING METHOD IS ONE OF TWO CRITERIA INCLUDED IN A NEW CLASSIFICATION SYSTEM FOR DESIGNING MICROPILES. THE OTHER IS PHILOSOPHY OF BEHAVIOR.

drill casing or auger is withdrawn. Pressures are typically in the range of 0.3–1 MPa, limited by the ability of the soil to maintain a grout-tight "seal" around the casing during withdrawal and the need to avoid hydrofracture pressures and/or excessive grout consumptions.

- Type C: Neat cement grout is placed in the hole as for type A, but 15–25 min later—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 is common only in France, where it is known as *injection globale et unitaire*.
- Type D: Neat cement grout is placed in the hole as for type A. When this primary grout has hardened, similar grout is injected via a preplaced sleeved port 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 2–8 MPa. This is known in France as *injection repetitive et selective*, and is common worldwide.

Micropiles can 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 construction control over capacity. For example, a repeatedly postgrouted 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.

CLASSIFICATION OF APPLICATIONS

Micropiles are used in two basic applications: as structural support and as in situ soil reinforcement. 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 D (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 on groups of piles suggests that in certain conditions and arrangements, the piles themselves are principally, directly and locally subjected to 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. However, the potential is real and the subject is being actively pursued in the FOREVER program in France.

AN EXPANDING MARKET

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 with new underground constructions, the 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 U.S. market appears to be a combination of both scenarios, given the ongoing upgrade 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, if not met, could impede further micropile growth: There are no specific or general recommendations regarding long-term corrosion; and "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 methods." The present efforts of researchers in the U.S. and France may resolve these issues within the next few years.

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FEATURES

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ON THE COVER
Twin 1,040 ft suction intake pipes are being constructed using microtunneling to tap energy from cold ocean waters off Hawaii's shores. High waves were a hazard for the shaft site (see page 36). Photo courtesy Nova Group, Napa, Calif.