AMERICAN MICROPILE PRACTICE

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PREFACE

In September of 1995, the Federal Highway Administration-Western Federal Lands Highway Division, (FHWA-WFLHD), and Donald B. Murphy Contractors, Inc., (DBM), entered into a cooperative agreement for the purpose of preparing a "practitioner-oriented" micropile implementation manual. The manual contains information on micropile applications, design, construction specifications, inspection and testing procedures, cost data and contracting methods. The end product will facilitate and speed the implementation and cost effective use of micropiles on future U.S. transportation projects.

Funding for this "first of kind" project is being shared by both public and private parties. Approximately two-thirds of the funding is being equally shared by FHWA-WFLHD and FHWA-Region 10 with the remaining one-third being provided by micropile specialty contractors.

A Technical Working Group consisting of seventeen representatives selected from federal and state highway agencies and the participating micropile specialty contractors is providing guidance and direction in the preparation of the manual. The final print copy is anticipated for completion in July of this year.

Taking excerpts from the manual, this paper provides a brief overview of the history and application of micropiles, micropile classification system, American construction techniques and materials, American contracting methods and cost feasibility.

INTRODUCTION

The use of micropiles has grown significantly since their conception in the 1950□s, and in particular since the mid-1980□s. Micropiles have been used mainly as elements for foundation support to resist static and seismic loading conditions, and as in-situ reinforcements for slope and excavation stability.

In 1993, the Federal Highway Administration (FHWA) sponsored a desk study of the state-of-the-practice of micropiles. The research group for this study consisted of contractors, consultants, academics, and clients. The document produced from this study, entitled *State-of-the-Practice Review □ Drilled and Grouted Micropiles,* [1] provides a comprehensive international review and detailed analysis of available research and development results, laboratory and field testing data, design methods, construction methodologies, site observations, and monitored case studies. As part of this study, the limitations and uncertainties in the current state-of-the-practice were evaluated, and further research needs were assessed. One of the highlighted needs, voiced mainly by representatives of State Departments of Transportation, was a manual of design and construction guideline intended for use by practicing, highway agency, geotechnical and structural engineers.

In response to this need, the FHWA sponsored the development of the *Micropile Design and Construction Guidelines Implementation Manual.* Funding and development of the manual was a cooperative effort between FHWA, several U.S. micropile specialty contractors, and several state DOT's. This manual is intended to be a "practitioner-oriented" document containing sufficient

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information on micropile design, construction specifications, inspection and testing procedures, cost data, and contracting methods to facilitate and speed the implementation and cost-effective use of micropiles on United States transportation projects.

Chapter 1 provides a general definition and historic framework of micropiles. Chapter 2 describes the newly developed classifications of micropile type and application. Chapter 3 illustrates the use of micropiles for transportation applications. Chapter 4 discusses construction techniques and materials. Chapters 5 and 6 detail design methodologies for structural foundation support and slope stabilization, respectively. Chapter 7 describes pile load testing. Chapter 8 reviews construction inspection and quality control procedures. Chapter 9 discusses contracting methods for micropile applications. Chapter 10 presents feasibility and cost data. Appendix A presents sample plans and specifications for owner-controlled design and contractor design-build type contracts.

MICROPILE DEFINITION AND DESCRIPTION

Piles are divided into two general types: displacement piles and replacement piles [3]. Displacement piles are members that are driven or vibrated into the ground, thereby displacing the surrounding soil laterally during installation. Replacement piles are placed or constructed within a previously drilled borehole, thus replacing the excavated ground.

A micropile is a small-diameter (typically less than 300 mm), drilled and grouted replacement pile that is typically reinforced. A micropile is constructed by drilling a borehole, placing reinforcement, and grouting the hole as illustrated in Figure 1. Micropiles can withstand axial and/or lateral loads, and may be considered a substitute for conventional piles or as one component in a composite soil/pile mass, depending upon the design concept employed. Micropiles are installed by methods that cause minimal disturbance to adjacent structures, soil, and the environment. They can be installed in access-restrictive environments and in all soil types and ground conditions. Micropiles can be installed at any angle below the horizontal using the same type of equipment used for ground anchor and grouting projects.

Since the installation procedure causes minimal vibration and noise and can be used in conditions of low headroom, micropiles are often used to underpin existing structures. Specialized drilling equipment is often required to install the micropiles from within existing basement facilities.

Most of the applied load on conventional cast-in-place replacement piles is structurally resisted by the reinforced concrete; increased structural capacity is achieved by increased cross-sectional and surface areas. Micropile structural capacities, by comparison, rely on high-capacity steel elements to resist most or all of the applied load. These steel elements can occupy as much as one-half of the hole volume. The special drilling and grouting methods used in micropile installation allow for high grout/ground bond values along the grout/ground interface. The grout transfers the load through friction from the reinforcement to the ground in the micropile bond zone in a manner similar to that of ground anchors. Due to the small pile diameter, any end-bearing contribution in micropiles is generally neglected. The grout/ground bond strength achieved is influenced primarily by the ground type and grouting methods used, i.e., pressure grouting or gravity feed. The role of the drilling method is also influential, although less well quantified.

Historical Background

Micropiles were conceived in Italy in the early 1950□s, in response to the demand for innovative techniques for underpinning historic buildings and monuments that had sustained damage with time, and especially during World War II. A reliable underpinning system was required to support structural loads with minimal movement and for installation in access-restrictive environments with minimal disturbance to the existing structure. An Italian specialty contractor called Fondedile, for whom Dr. Fernando Lizzi was the technical director, developed the *palo radice,* or root pile, for underpinning applications. The *palo radice* is a small-diameter, drilled, cast-in-place, lightly reinforced, grouted pile. The classic arrangement of *palo radice* for underpinning is shown in Figure 2.

Although steel was in short supply in postwar Europe, labor was inexpensive, abundant, and often of high mechanical ability. Such conditions encouraged the development of these lightly reinforced, cast-in-place root pile elements, largely designed and installed by specialty contractors on a design-build basis. Load testing on these new root piles measured in excess of 400 kN, although the nominal design capacity-based on contemporary conventional bored pile design methodologies-suggested loads of less than 100 kN. Direct full-scale load tests were performed at relatively little cost, fostering the acquisition and publication of a wealth of testing information. No grout/ground bond failures were recorded during these early tests.

The use of root piles grew in Italy throughout the 1950□s. Fondedile introduced the technology in the United Kingdom in 1962 for the underpinning of several historic structures, and by 1965, it was being used in Germany on underground urban transportation schemes. For proprietary reasons, the term "micropile" replaced "root pile" at that time.

Initially, the majority of micropile applications were structural underpinning in urban environments. Starting in 1957, additional engineering demands resulted in the introduction of systems of *reticoli di pali radice* (reticulated root piles). Such systems comprise multiple vertical and inclined micropiles interlocked in a three-dimensional network, creating a laterally confined soil/pile composite structure (Figure 3). Reticulated micropile networks were applied for slope stabilization, reinforcement of quay walls, protection of buried structures, and other soil and structure support and ground reinforcement applications.

Other proprietary micropiles were developed in Switzerland and Germany, and the technologies were quickly exported overseas by branches or licensees of the originating contractors. The Far East soon became a major market.

Fondedile introduced the use of micropiles in North America in 1973 through a number of underpinning applications in the New York and Boston areas. The micropile technology did not grow rapidly in the United States, however, until the mid-1980□s, after which time an abundance of successful published case histories, consistent influence by specialty contractors, and the growing needs of consultants and owners working in old urban environments overcame the skepticism and concerns of the traditional East Coast piling market [4]. The abundance of relatively cheap labor, the shortage of steel, and the need for reconstruction programs in urban environments had all promoted the growth and use of micropiles in Europe. Conversely, the slower and later growth of micropile usage in North America is reflective of the abundance of cheap steel, relatively high labor costs, and the need for capital works projects typically outside of the cities. These circumstances fostered the growth of the comparatively low-technology, driven-pile techniques governed by prescriptive specifications. Today construction costs and technical demands are similar throughout the world and so continue to foster the growth of micropile demand, largely through geotechnical contractors with design-build capabilities.

Micropile Types in Current Use

One of the most fundamental achievements of the State-of-the-Practice Report [1] research team was development of the new classification criteria for micropiles. This is important because it resolved disagreement within the industry about fundamental differences in design and behavior of elements that are visually similar and constructed with common equipment, materials and techniques.

The State-of-the-Practice Report includes a micropile classification system based on two criteria: 1) philosophy of behavior (design) and 2) method of grouting (construction). The philosophy of behavior dictates the method employed in designing the micropile. The method of grouting defines the grout/ground bond capacity, which is generally the major constructional control-over-pile capacity. The classification system consists of a two-part designation: a *number*, which denotes the micropile behavior (design), and a *letter*, which designates the method of grouting (construction).

Design Application Classification

The design of an individual or group of micropiles differs greatly from that of a network of closely spaced reticulated micropiles. This led to the definition of CASE 1 micropile elements, which are loaded directly and where the pile reinforcement resists the majority of the applied load (Figure 4). CASE 2 micropile elements circumscribes and internally reinforces the soil to make a reinforced soil composite that resists the applied load (Figure 5) reticulated pile network.

CASE 1 micropiles can be used as substitutes for more conventional types of piles to transfer structural loads to a deeper, more competent or stable stratum. Such directly loaded piles, *whether for axial or lateral loading conditions,* are referred to as CASE 1 elements. The load is primarily resisted structurally by the steel reinforcement and geotechnically by the grout/ground bond zone of the individual piles. At least 90 percent of all international applications to date, and virtually all of the projects in North America, have involved CASE 1 micropiles. Such piles are designed to act individually, although, they may be installed in groups. Typical arrangements of CASE 1 micropiles are illustrated in Figure 6.

The remaining applications involve networks of reticulated micropiles as components of a reinforced soil mass, which is used for stabilization and support. These micropiles are referred to as CASE 2 elements. The structural loads are applied to the entire reinforced soil mass, as opposed to individual piles. CASE 2 micropiles are lightly reinforced because they are not individually loaded as CASE 1 elements. They serve to circumscribe and then to internally strengthen the reinforced soil composite. A typical network of reticulated micropiles is illustrated in Figure 7.

There are combination design philosophies between CASE 1 and CASE 2 micropiles. An example is the case of a row of micropiles installed throughout a failure plane to achieve slope stabilization. Recent research [5] suggests that pile/ground interaction only occurs near the slide plane. In this situation, the pile acts as a CASE 1 element because it directly resists the load. Above the failure plane, the pile group does add a certain degree of continuity to the reinforced soil composite structure. This behavior is of CASE 2 type. Therefore, this example is between CASE 1 and CASE 2.

This philosophy of behavior (design) of an individual CASE 1 micropile is the same as that of a group of CASE 1 micropiles. A group of CASE 1 elements is defined as a closely spaced (typically parallel) arrangement of micropiles, each of which will be loaded directly. The behavior and design approach of a group of CASE 1 elements should not be confused with those of a reticulated network, although their geometries may appear to be similar.

Construction Type Classification

The method of grouting is generally the most sensitive construction control over grout/ground bond capacity. Grout/ground bond capacity varies directly with the grouting method. The second part of the micropile classification consists of a letter designation (A though D) based primarily on the method of placement and pressure under which grouting is used during construction. The classification is shown schematically in Figure 8.

Type A: The type A classification indicates that grout is placed under gravity head only. Sand-cement mortars, as well as neat cement grouts, can be used because the grout column is not pressurized. The pile hole may be underreamed to increase tensile capacity, although this technique is not common or used with any other pile type.

Type B: Type B indicates that neat cement grout is placed into the hole under pressure as the temporary steel drill casing is withdrawn. Injection pressures typically range from 0.5 to 1 Mpa, and are limited to avoid hydrofracturing the surrounding ground or causing excessive grout takes, and to maintain a seal around the casing during its withdrawal.

Type C: Type C indicates a two-step process of grouting: 1) neat cement grout is placed under gravity head as with Type A, and 2) prior to hardening of the primary grout (after approximately 15 to 25 minutes), similar grout is injected one time via a sleeved grout pipe without the use of a packer (at the bond zone interface) at a pressure of at least 1 MPa. This pile type appears to be used only in France, and is referred to as IGU (Injection Globale et Unitaire).

Type D: Type D indicates a two-step process of grouting similar to Type C with modifications to Step 2. Neat cement grout is placed under gravity head as with Types A and C and may be pressurized as in Type B. After hardening of the initially placed grout, additional grout is injected via a sleeved grout pipe at a pressure of 2 to 8 MPa. A packer may be used inside the sleeved pipe so that specific horizons can be treated several times, if required. This pile type is used commonly worldwide, and is referred to in France as the IRS (Injection R▲ p▲ titive et S▲ lective).

Table 1 describes in more detail the micropile classification based on method of grouting (construction). Subclassifications (Numbers 1, 2, and 3) are included in the table to describe the use of drill casing and reinforcement for each method of grouting. It is emphasized that Table 1 is intended to present a classification system based on the type of micropile construction. It is not intended to be used in contract specifications.

MICROPILE APPLICATIONS

Micropiles are currently used in two general applications: for structural support and less frequently as in-situ reinforcement (Figure 9). Structural support includes new foundations, underpinning of existing foundations, seismic retrofitting application and earth retention. In-situ reinforcement is used for slope stabilization, earth retention, and ground strengthening and protection; settlement reduction; and structural stability.

For structural support, micropiles can be used a small-diameter substitutes for conventional pile types, Micropiles used for structural support are usually loaded directly and, therefore, employ a CASE 1 design philosophy. Piles typically used for these application include Type A (gravity grouted and bonded in soil or rock), Type B (pressure grouted), and Type D (postgrouted). These pile types can provide the high individual capacities typically required by structural support applications in transportation projects.

It is important to note that the in-situ reinforcement applications of slope stabilization and earth retention can employ either CASE 1 or CASE 2 design philosophies. Micropiles used for these applications are typically Type A piles (gravity grouted and fully bonded in soil or rock), because high individual pile capacities are not required due to the reinforced composite material concept of the CASE 2 approach. Recent research [5] suggest, however, that in certain conditions and for certain pile arrangements, the piles are principally, directly, and locally subjected to bending and shearing forces, specifically near the slide plane. The direct loading, by definition is CASE 1 design behavior. Micropiles under these conditions are typically heavily reinforced and of Type A or B construction.

Micropile Type and Grouting Method	Sub-type	Drill Casing	Reinforcement	Grout
Type A Gravity grout only	A1	Temporary or unlined (open hole or auger)	None, monobar, cage, tube or structural sections	Sand/Cement mortar or neat cement grout, tremied to base of hole (or casing), no excess pressure applied
	A2	Permanent, full length	Drill casing itself	
	A3	Permanent, upper shaft only	Drill casing in upper shaft, bar(s) or tube in lower shaft (may extend full length)	
Type B Pressure-grouted through the casing or augers during withdrawal	B1	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 drill casing. Excess pressure (up to 1 MPa typically) is applied to additional grout injected during withdrawal of casing.
	B2	Permanent, full length	Drill casing itself	
	B3	Permanent, upper shaft	Drill casing in upper shaft, bar(s) or tube in lower shaft (may extend full length)	
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 termied into hole (or casing/auger). Between 15 to 25 minutes later, similar grout injected through tube (or reinforcing pipe) from head, once pressure is greater than 1 MPa
	C2	Not conducted	-	
	C3	Not conducted	-	
Type D Primary grout placed under gravity head (Type A) or under pressure (Type B). Then one or more phases 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 (Type A) and/or pressurized (Type B) into hole or casing/auger. Some hours later, similar grout injected through sleeved pipe (or sleeved reinforcement) via packers, as many times as necessary to achieve bond
	D2	Possible only if regrout tube placed full-length outside casing	Drill casing itself	
	D3	Permanent, upper shaft only	Drill casing in upper shaft, bar(s) or tube in lower shaft (may extend full length)	

Table 1. Details of micropile classification based on type of grouting

Other in-situ reinforcement applications generally employ CASE 2 concepts. Little commercial work has been performed for other CASE 2 major applications beyond the stabilization of high towers in historical monuments. An example is the restoration scheme used to improve the stability of a tall, slender tower in Mosul, Iraq [6], as shown in Figure 10. This CASE 2 network of reinforced soil is attached to the structure, effectively lowering the center of gravity of the combined structure/soil system and improving stability. The potential for other in-situ reinforcement applications is being studied and pursued in other countries, especially France, Italy, Germany, Austria and Japan.

Structural Support

Micropile applications for structural support include foundations for new structures, underpinning of existing structures, scour protection, and seismic retrofitting of existing structures. Many of these applications have been used for transportation projects.

New Foundations

Micropiles are applicable in new bridge construction in areas that require deep foundation alternatives or in difficult ground (cobbles/boulders obstructions) where installation of conventional piles or drilled shafts is very difficult/expensive/ The new I-78 dual highway, designed to cross the Delaware River between Pennsylvania and New Jersey [7], is an example. All of the bridge piers were founded either on driven piles or rock, with the exception of Pier E-6. At this location, bedrock was encountered below the anticipated depth and was found to be extremely variable. Micropiles and drilled shafts were proposed as alternative foundations to solve this geological problem, and micropiles were selected based on cost, installation time, and test pile performance.

New bridges may be constructed in areas of existing overhead restrictions, and with traffic flow that must be maintained. A major improvement project was undertaken to replace the deck of the Brooklyn-Queens Expressway in the Borough of Brooklyn, New York [8]. A new center land and several new entry/exit ramps were also added. Small-diameter piles were used successfully for the new viaduct and the ramps. Major factors in the selection of micropiles were the relative lack of vibration during installation by comparison to pile-driving methods that could have affected adjacent old and sensitive structures; the variable fluvioflacial deposits; the restricted access; and the need to maintain traffic flow in the area.

Support for buildings, earth-retaining structures, and soundwalls are other micropile applications used for structural support.

Underpinning of Existing Foundations

Micropiles were originally developed for underpinning existing structures. The underpinning of existing structures may be performed for many purposes.

- To arrest and prevent structural movement;
- To upgrade load-bearing capacity of existing structures;
- To repair/replace deteriorating or inadequate foundations;
- To add scour protection for erosion-sensitive foundations;
- To raise settled foundations to their original elevation.

Micropiles can be installed through and bonded within existing structures providing direct connection with a competent underlying strata without the need for new pile caps, while at the same time reinforcing then structure internally.

Construction can be executed without reducing the existing foundation capacity. Photo 1 is of the West Emerson Street Viaduct in Seattle, Washington, where micropiles were added to five existing bents to provide additional foundation support.

Structural movements can be caused by a variety of factors, including compressible ground beneath the existing foundation, dewatering activities, groundwater elevation fluctuations, deterioration of existing foundations, and adjacent deep excavations and tunneling activities. Micropiles can mitigate this structural movement by being installed to deeper, more competent bearing strata, thus providing improved structural support.

Increased load-bearing capacity of an existing foundation may be required for several reasons. Additional vertical, lateral, or vibratory loads may be applied to the foundation due to expansion of the existing structure, increased magnitude of applied loads or the addition of vibrating machinery.

The 75-year-old Pocomoke River Bridge in Maryland was rehabilitated when the capacity of the original wooden piles of the pier foundations was compromised by exposure to river scour [9]. These micropiles were installed throughout the existing foundation and were preloaded to provide support without allowing additional settlement of this sensitive structure.

Seismic Retrofit

Micropiles are being used increasingly for seismic retrofitting of existing highway structures, especially in California. Micropiles may be economically feasible for bridge foundation retrofits having one or more of the following constraints:

- Restrictions on footing enlargements.
- Vibration and noise restrictions.
- Low headroom clearances.
- Difficult access.
- High axial load demands in both tension and compression.
- Difficult drilling/driving conditions.
- Hazardous soil sites.

Micropiles exhibit near equal tension and compression capacities, therefore optimizing the additional support elements used [10].

Micropiles were used for the California of Transportation's earthquake retrofit of the North Connector over-crossing at I-110 in Los Angeles, (Photo 2) where the use of the previously specified drilled shafts proved unsuccessful [11A]. Difficult drilling conditions, including buried concrete obstructions and water-bearing, flowing sand layers, low overhead conditions, and limited right-of-way access prohibited the use of the originally prescribed drilled shaft system.

In-Situ Reinforcement (Slope Stabilization & Earth Retention)

The concept of reticulated networks of micropiles (CASE 2) involves the use of an appropriately spaced, three-dimensional arrangement of vertical and inclined piles that encompass and reinforce the ground, and at the same time are supported by the ground. For slope stabilization, Lizzi [6] suggested that the reticulated network of micropiles creates a stable, reinforced-soil "gravity-retaining wall," in which the reinforced soil gravity mass supplies the essential resisting force, and the piles, encompassed by the soil, supply additional resistance to the tensile and shear forces acting on the "wall." For such applications, the individual piles are engaged as friction piles securing the reinforced soil composite mass in the upper soil mass, and as structural elements subject to shear and bending in the lower competent material. The function of this structure is to provide a stable block of reinforced soil to act as a coherent retaining structure, stabilizing the upper soil mass, while providing resistance to shear across the failure plane. Such an application is therefore transitional between CASE 1 and CASE 2 behavior.

Conversely, the research by Pearlman et al. [5] and Palmerton [7] suggests that groups of inclined micropiles serve to connect the moving zone (above the failure surface) to the stable zone (below the failure surface). These piles provide reinforcement to resist the shearing forces that develop along the failure surface and exhibit purely CASE 1 behavior. Typical configurations of inclined nonreticulated micropile walls for slope stabilization and earth retention are shown in Figure 11.

For rocky, stiff, or dense materials, the shear resistance of the piles across the failure surface, i.e., individual capacity, is critical (CASE 1). For loose materials, the piles and soil are mutually reinforcing and create a gravity wall, so the individual pile capacities are not as significant (CASE 2).

For example, micropiles were used to stabilize a portion of State Road 4023 (S.R. 4023) in Armstrong County, Pennsylvania [8] (Figure 12). A 75-m-long section of this road and railroad tracks located up-slope were experiencing damage from slope movements towards an adjacent river. Rock anchors and tangent caissons extending into rock were the proposed remedial techniques. A value engineering alternative of inclined CASE 1 nonreticulated micropiles was proposed and accepted, with resultant savings of approximately $1 million compared to the lowest bid for the anchored caisson wall design. The wall included four rows of Type 1A micropiles extending across the failure plane and into competent rock.

Micropiles were recently used to provide permanent earth retention along a new section of the Portland Westside Lightrail Project in Portland, Oregon [9] (Figure 13). Wall 600 extends from the east portal of the Westside Lightrail cut and cover, tunnel approximately 183 meters to just beneath the Vista Avenue Bridge. Cut heights along the retaining wall range from 4 to 9.5 meters. The wall includes CASE 1 nonreticulated micropiles installed at varying vertical and subvertical angles that were temporally exposed by excavation of the new rail alignment. An architecturally treated cast-in-place reinforced concrete facing is structurally attached to the vertical micropiles, forming the permanent wall face. The micropile wall was accepted as a contractor-proposed value engineering alternate. The original design included a counterfort concrete retaining wall supported on a driven-pile foundation. Construction of the owner-designed wall required temporary excavation support to maintain service to Jefferson Street and existing utilities. A micropile retaining wall system was the only acceptable option that could be kept within the envelop of the original counterfort structure.

An earlier example of slope stabilization using micropiles as a demonstration project involved networks of reticulated micropiles (CASE 2) used to stabilize Forest Highway 7 in Mendocino National Forest, California [7] (Figure 14 and Photo 3). This two-lane road was constructed across a landslide where slide movement was experienced due to excessive rainfall. A 94-m long section of the road was stabilized using CASE 2 micropiles to reinforce the soil mass and provide additional shear capacity. It is significant that the density of micropiles per lineal meter of wall was significantly higher than that of the CASE 1 design approach used at S.R. 4023. S.R. 4023 used 2.9 to 4.1 piles per lineal meter and FH-7 used 7.4 piles per lineal meter. Both structures have performed acceptably.

CONSTRUCTION TECHNIQUES AND MATERIALS

The construction of a micropile involves a succession of processes, the most significant of which are drilling, placing the reinforcement, and grouting. There are a large number of drilling systems available for both overburden and rock, but the particular requirements and procedures of micropile construction focus attention on a more limited range. This narrower range of drilling systems tends to be utilized worldwide as a result of the comprehensive international marketing and sales efforts of the drill rig equipment manufacturers and the ongoing exchange of data and experiences in trade and professional organizations and their related journals.

The placement of reinforcement is also a fairly standard process, although different countries use different grades, sizes, and configurations. In the United States is it common practice to leave the drill casing in place from the surface down to the top of the bond length of the pile.

It is in the process of grouting that the most extreme range of practices and preferences is evident. This consideration fosters the use of the grouting method as the basis of the micropile type classification.

The typical construction sequence for simple Type A and B micropiles (Figure 15) includes drilling the pile shaft to the required tip elevation, placing the steel reinforcement, placing the initial grout by tremie, and placing additional grout under pressure as applicable. In general, the drilling and grouting equipment and techniques used for the micropile construction are similar to those used for the installation of soil nails, ground anchors, and grout holes.

Drilling

Most of the drilling methods selected by the specialty contractor are likely to be acceptable on a particular project, provided they can form a stable hole of the required dimensions and within the stated tolerances, and without detriment to their surroundings. It is important not to exclude a particular drilling method because it does not suit a predetermined concept of how the project should be executed. On the other hand, it is equally important that the drilling contractor be aware of not only the ground conditions on the job, but also the possible wider effects of the method chosen. Drilling within a congested urban site in close proximity of older buildings or deteriorating foundations has very different restraints than drilling for new foundation on an open field site.

The act of drilling and forming the pile hole may disturb the surrounding ground for a certain time and over a certain distance. The drilling method selected by the contractor should avoid causing an unacceptable level of disturbance to the site and its facilities, while providing for installation of a pile that supports the required capacities in the most cost-effective manner. Vigorous water flushing can increase drilling rates and increase the removal of the fine components of mixed soils, enlarging the effective diameter in the bond zone and aiding in grout penetration and pile capacity. Conversely, the use of higher flush flow rates and pressures should be approached with caution, with consideration to the risks of creating voids and surface settlement, and the risks of hydrofracturing the ground, leading to heaving.

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It is typically in the best interest of pile quality that the drilling, installation of the reinforcement, and grouting of a particular pile be completed in a series of continuous processes executed as expeditiously as possible. Longer duration between completion of drilling and placing of the reinforcement and grout can be detrimental to the integrity of the surrounding soil. Some materials, such as overconsolidated clays and clay shales, can deteriorate, relax, or soften on exposure, resulting in a loss of interfacial bond capacity. In these cases, installation of a pile bond zone should be completed within one day to avoid a pile hole remaining open overnight.

Other site-specific conditions may affect selection of the drilling method and flush type. The use of a water flush can require the supply, handling, and disposal of large quantities of water. In areas where the water supply may be scarce, the setup of a series of ponds or tanks for settlement and recirculation of the water may be necessary. Requirements for cleanliness or lack of space for water handling and disposal may dictate the use of air flush or augers for hole drilling. The presence of hazardous materials in the ground and the need for careful control and disposal of the soil cuttings may also necessitate the use of augers for pile installation.

Drill Rigs

The drill rigs typically used are rotary, electrically or diesel-powered, hydraulic power units. They can be track mounted, allowing maneuverability on difficult and sloped terrain. The size of the track-mounted drills can vary greatly, as seen in Photographs 4 and 5, with the larger drill allowing use of long sections of drill rods and casing in high, overhead conditions, and the smaller drill allowing work in lower overhead and harder-to-reach locations. The drill mast can be mounted on a frame, allowing work in very limited-access and low-overhead areas, such as building basements. A frame-mounted drill, such as the one shown in Photograph 6, can be connected with long hoses to a separate hydraulic power unit. This allows placement of the power unit outside the area of work, reducing space requirements, noise in the work area, and problems with exhaust removal. The drill frame can be moved and supported with a fork lift, or moved by hand with winches and supported by bolting to a concrete floor, and/or bridge footing or bracing from a ceiling or bridge soffit.

The rotary head that turns the drill string (casing, augers, or rods) can be extremely powerful on even the smallest of rigs, allowing successful installation in the most difficult ground conditions. Shortening of the drill mast and the use of short jointed sections of drill string and pile reinforcement allows pile installation with less than 3 m of overhead. When the drilling is done against a vertical face, the pile centerline can be located as close as 0.3 m from the face of an adjacent wall; however, 0.45 m is preferred due to typical drill heads and safety/constructability concerns.

Drilling Techniques

The drilling method is chosen with the objective of causing minimal disturbance or upheaval to the ground and structure, while being the most efficient, economic, and reliable means of penetration. Micropile shafts must often be drilled through an overlying weak material to reach a more competent bearing stratum. Therefore, it typically requires the use of overburden drilling techniques to penetrate and support weak and unconsolidated soils and fills. In addition, unless the bearing stratum is a self-supporting material, such as rock or a cohesive soil, the drill hole may need temporary support for its full length, e.g. through the use of temporary casing or suitable drilling fluid. If self-supporting material is present for the full depth of the pile, the drill hole can possibly be formed by open hole techniques, i.e., without the need for temporary hole support by drill casing or hollow stem auger.

A different drilling method may be used to first penetrate through an existing structure. Concrete coring techniques may be used to provide an oversized hole in existing slabs and footings, to allow the subsequent drill casing to pass through. In some cases, conventional rock drilling methods involving rotary percussive techniques can be used to penetrate existing footings or structures with only light reinforcement Rotary percussive or rotary duplex techniques may be used to first penetrate an initial obstruction layer, such as concrete rubble, with more conventional single-tube advancement drilling used for completion of the pile shaft in the soil layers below.

Water is the most common medium for cleansing and flushing the hole during drilling, followed by air, drill slurries, and foam. Caution should be exercised while using air flush to avoid injection of the air into the surrounding ground, causing fracturing and heaving. The use of bentonite slurries to stabilize and flush holes is generally believed to impair grout /ground bond capacity by creating a skin of clay at the interface; however, this is not an uncommon choice in Italian and French practice with Type D piles. Polymer drilling muds have been used successfully in micropile construction in all types of ground. This slurry type reduces concern for impairment of the bond capacity, and allows for easier cleanup and disposal versus bentonite slurry.

Overburden Drilling Techniques

There is a large number of proprietary overburden drilling systems sold by drilling equipment suppliers worldwide. In addition, specialty contractors often develop their own variations in response to local conditions and demands. The result is apotentially bewildering array of systems and methods, which does, however, contain many that are of limited application, and many that are either obsolete or virtually experimental. Closer examination of this array further confirms that there are essentially sixgeneric methods in use internationally in the field of specialty geotechnical construction (i.e., diameters less than 300 mm, depths less than 60 m). The following is a brief discussion of these six methods. These six methods are also summarized in Table 2, and simply represented in Figure 16.

	Drilling Method	Principle	Common Diameters and Depths	Notes
1	Single-tube advancement: a) Drive drilling b) External flush	Casing with "lost point" percussed without flush. Casing, with shoe, rotated with strong water flush.	50-100 mm to 30 m 100-250 mm to 60m	Obstructions or very dense soil problematical. Very common for anchor installation. Needs high torque head and powerful flush pump.
2	Rotary duplex	Simultaneous rotation and advancement of casing plus internal rod, carrying flush.	110-220 mm to 70 m	Used only in very sensitive soil/site conditions. Needs positive flush return. Needs high torques. (Internal flushing only)
3	Rotary percussive concentric duplex	As 2, above, except casing and rods percussed as well as rotated.	89-175 mm to 40 m	Useful in obstructed/rocky conditions. Needs powerful top rotary percussive hammer.
4	Rotary percussive eccentric duplex	As 2, except eccentric bit on rod cuts oversized hole to ease casing advance.	89-200 mm to 60 m	Expensive and difficult system for difficult overburden.
5	"Double head" duplex	As 2 or 3, except casing and rods may rotate in opposite directions.	100-150 mm to 60 m	Powerful, new system for fast, straight drilling in very difficult ground. Needs significant hydraulic power.
6	Hollow-stem auger	Auger rotated to depth to permit subsequent introduction of grout and/or reinforcement through stem.	100-400 mm to 30 m	Obstructions problematical; care must be exercised in cohesionless soils. Prevents application in higher grout pressures.

Table 2. Overburden Drilling Methods

Note: Drive drilling, being purely a percussive method, is not described in the text as it has no application in micropile construction.

Single-tube advancement - external flush (wash boring): By this method, the toe of the drill casing is fitted with an open crown or bit, and the casing is advanced into the ground by rotation of the drill head. Water flush is pumped continuously through the casing, which washes debris out and away from the crown. The water-borne debris typically escapes to the surface around the outside of the casing, but may be lost into especially loose and permeable upper horizons. Care must be exercised below sensitive structures in order that uncontrolled washing does not damage the structure by causing cavitation.

Air flush is not normally used with this system due to the danger of accidentally overpressurizing the ground in an uncontrolled manner, which can cause ground disturbance. Conversely, experience has shown that polymer drill flush additives can be very advantageous in certain ground conditions, in place of water alone [16]. These do not appear to detrimentally affect grout-to-soil bond development as may be the case with bentonite slurries.

Rotary Duplex: With the rotary duplex technique, drill rod with a suitable drill bit is placed inside the drill casing. It is attached to the same rotary head as the casing, allowing simultaneous rotation and advancement of the combined drill and casing string. The flushing fluid, usually water or polymer flush, is pumped through the head down through the central drill rod to exit from the flushing ports of the drill bit. The flush-borne debris from the drilling then rises to the surface along the annulus between the drill rod and the casing. At the surface, the flush exits through ports in the drill head. Although any danger with duplex drilling is less than when using the single-tube-method, air flush must be used with caution because blockages within the annulus can allow high air pressures and volumes to develop at the drill bit and cause ground disturbance.

Rotary Percussive Duplex (Concentric): Rotary percussive duplex systems are a development of rotary duplex methods, whereby the drill rods and casings are simultaneously percussed, rotated, and advanced. The percussion is provided by a top-drive rotary percussive drill head. This method requires a drill head of substantial rotary and percussive energy.

Rotary Percussive Duplex (Eccentric or Lost Crown): Originally sold as the Overburden Drilling Eccentric (ODEX), System, this method involves the use of a rotary percussive drilling combined with an eccentric underreaming bit. The eccentric bit undercuts the drill casing, which therefore can be pushed into the oversized drill hole with much less rotational energy or thrust than is required with the concentric method just described. In addition, the drill casing does not require an expensive cutting shoe and suffers less wear and abrasion.

The larger diameter options, of more than 127 mm in diameter, involve the use of a down-the-hole hammer acting on a drive shoe at the toe of the casing, so that the casing is effectively pulled into the borehole as opposed to being pushed by a top hammer.

Most recently, systems similar to ODEX, which is now sold as TUBEX, have appeared from European and Japanese sources. Some are merely mechanically simpler versions of TUBEX. Each variant, however, is a percussive duplex method in which a fully retractable bit creates an oversized hole to ease subsequent casing advancement.

Double Head Duplex: With the double head duplex method, a development of conventional rotary duplex techniques, the rods and casings are rotated by separate drill heads mounted one above the other on the same carriage. These heads provide high torque (and so enhanced soil-and obstruction-cutting potential), but at the penalty of low rotational speed. However, the heads are geared such that the lower one (rotating the outer casing), and the upper one (rotating the inner drill string) turn in opposite directions. The resulting aggressive cutting and shearing action at the bit permits high penetration rates, while the counter-rotation also discourages blockage of the casing/rod annulus by debris carried in the exiting drill flush. In addition, the inner rods may operate by either purely rotary techniques or rotary percussion using top-drive or down-the-hole hammers. The counter-rotation feature promotes exceptional hole straightness, and provides a guarantee of penetrability, even in the most difficult ground conditions.

Hollow-Stem Auger: Hollow-stem augers are continuous flight auger systems with a central hollow core, similar to those commonly used in auger-cast piling or for ground investigation. These are installed by purely rotary heads. When drilling down, the hollow core is closed off by a cap on the drill bit. When the hole has been drilled to depth, the cap is knocked off or blown off by grout pressure, permitting the pile to be formed as the auger is withdrawn. Such augers are used mainly for drilling cohesive materials or very soft rocks.

Various forms of cutting shoes or drill bits can be attached to the lead auger, but heavy obstructions, such as old foundations and cobble and boulder soil conditions, are difficult to penetrate economically with this system. In addition, great care must be exercised when using augers: uncontrolled penetration rates or excessive "hole cleaning" may lead to excessive spoil removal, thereby risking soil loosening or cavitation in certain circumstances.

Open-Hole Drilling Techniques

When the micropile can be formed in stable and free-standing conditions, the advancement of casing may be suspended and the hole continued to final depth by open-hole drilling techniques. There is a balance in cost between the time lost in changing to a less-expensive open-hole system and continuing with a more expensive overburden drilling system for the full hole depth. *Contractors need to be cautious with open-hole drilling operations. The micropile installation contractor is ultimately responsible for selection and proper performance of the drilling and installation method(s).* Open-hole drilling techniques may be classified as follows:

Rotary Percussive Drilling: Particularly for rocks of high compressive strength, rotary percussive techniques using either top-drive or down-the-hole hammers are utilized. For the small hole diameters used for micropiles down-the-hole techniques are the most economical and common. Air, air/water mist, or foam is used as the flush.

Top-drive systems can also use air, water, or other flushing systems, but have limited diameter and depth capacities, are relatively noisy, and may cause damage to the structure or foundation through excessive vibration.

Solid Core Continuous Flight Auger: In stiff to hard clays without boulders and in some weak rocks, drilling may be conducted with a continuous flight auger. Such drilling techniques are rapid, quiet, and do not require the introduction of a flushing medium to remove the spoil. They avoid the problems of soil softening and interface smear associated with the use of rotary techniques with water flush, although there may be the risk of lateral decompression or wall remolding, either of which may adversely affect grout/soil bond. Such augers are used in conditions where the careful collection and disposal of drill spoils are particularly important environmentally.

Underreaming: Various devices have been developed to enlarge or underream open holes in cohesive soils or soft sediments, especially when the piles are to act in tension (e.g., for transmission towers). These tools can be mechanically or hydraulically activated and will cut or abrade single or multiple underreams or "bells". However, this is a time-consuming process, and it is rarely possible or convenient to verify its effectiveness. In addition, the cleaning of the underreams is often difficult; water is the best cleaning medium, but may cause softening of the ground. For all these reasons, it is rare to find underreaming conducted in contemporary micropile practice. Increases in load-holding capacity are usually achieved by pressure grouting techniques.

Grouting

The grouting operations have a major impact on subsequent micropile capacity and form the most fundamental construction basis for micropile classification. Details of each type of grouting vary somewhat throughout the world, depending on the origins of the practice and the quality of the local resources. However, as general observations, it may be noted that:

- Grouts are designed to provide high strength and stability, but must also be pumpable. As shown in Figure 17, this implies typical water/cement (w/c) ratios in the range of 0.45 to 0.50 by weight for micropile grout.
- Grouts are produced with potable water, to reduce the danger of reinforcement corrosion.
- Type I/II cement conforming to ASTM C150/AASHTO M85 is used, supplied either in bagged or bulk form depending on site condition, job size, local availability, and cost.
- Most grouting is conducted with neat cement-water mixes, although sand is a common additive in certain countries (e.g., Italy, Britain). Bentonite (which reduces grout strength) is used in primary mixes only with extreme caution, while additives are restricted only to those that improve pumpability over long distances and/or in hot conditions (e.g., high-range water reducers).
- Design compressive strengths of 28 to 35 MPa can reasonably be attained with properly produced neat cement grouts.

The critical importance of the grouting operation is underlined by the fact that the placed grout is required to serve a number of purposes:

- It transfers the imposed loads between the reinforcement and the surrounding ground.
- It may form part of the load-bearing cross section of the pile.
- It serves to protect the steel reinforcement from corrosion.
- Its effects may extend beyond the confines of the drill hole by permeation, densification, and/or fissuring.

The grout, therefore, needs to have adequate properties of fluidity, strength, stability, and durability. The need for grout fluidity can mistakingly lead to the increase in water content; this has a negative impact on the other three properties. Of all the factors that influence grout fluidity and set properties, the water/cement ratio is the dominant. Again, Figure 17 illustrates why this ratio is limited to a range of 0.45 to 0.50, although even then, additives may be necessary to ensure adequate pumpability for ratios less than 0.40.

It is essential to the integrity of the pile that on completion of the grouting operation there is no significant loss of grout from any part of the pile that will be relied upon for load bearing or corrosion protection. This can be achieved by grouting to refusal during pile formation. Problems with grout loss may necessitate the use of a filler such as sand for plugging the permeable layer, or may require grouting the hole and redrilling and regrouting after set of the initial grout.

For a Type B pile, it may not always be possible to attain the desired pressures during grouting; the soil seal around the casing may not always be adequate to contain the pressurized grout. This may occur after partial pressure grouting of the bond length. If it occurs, the grout should be pumped until the level reaches the top of pile, at which time grouting is discontinued.

Maintaining grout pressures at a reasonable level (0.70 MPa or less) will help prevent this from occurring. If the bond lengths of the test piles that verified the geotechnical capacity are grouted full length with the desired pressure, questions may be raised as to the adequacy of the piles grouted under partial pressure. One benefit of conducting pile tests to a high load (150 to 200 percent design load) or to bond failure is that it helps determine if the piles have excess geotechnical capacity, relaxing this concern. Production proof tests may be conducted on the suspect piling.

Because the grout is such a vital component of the micropile, close attention must be paid to the control and quality of the product. A grout quality control plan, which at the minimum should include cube compression testing and grout density (water/ cement ratio) testing, is recommended.

Comprehensive guides to cement grout mix design, performance, and equipment in general are provided by Littlejohn (1982), Gourlay and Carson (1982), and Houlsby (1990). Similar issues relating solely to the similar demands of prestressed ground anchors are summarized by Littlejohn and Bruce (1977).

Grout Equipment

As a general statement, any plant suitable for the mixing and pumping of fluid cementitious grouts may be used for the grouting of micropiles. The best quality grouts, in terms of both fluid and set properties, are produced by high-speed, high-gear colloidal mixers (Figure 18) as opposed to low-speed, low-energy mixers, such as those that depend on paddles (Figure 19). Mixing equipment can be driven by air, diesel, or electricity, and is available in a wide range of capacities and sizes from many manufacturers.

For grout placement, lower pressure injection (say, to 1 MPa) is usually completed using constant pressure, rotary-screw type pumps (Moyno pumps), while higher pressure grouting, such as for Type C or D micropiles, usually requires a fluctuating pressure piston or ram pump.

Grout Mixing

The measured volume of water is usually added to the mixer first, followed by cement and then aggregate or filler if applicable. It is generally recommended that grout be mixed for a minimum of two minutes and that thereafter the grout be kept in continuous slow agitation in a holding tank prior to being pumped to the pile. Only in extreme cases- for example, where exceptionally large takes are anticipated- should ready- mix grout supply be required. The grout should be injected within a certain maximum time after mixing. This safe workability time should be determined on the basis of on- site tests, as it is the product of many factors, but is typically not in excess of one hour.

The water is typically batched into the mixer by means of a calibrated tank or flow meter. Cement is typically batched by weight, either in bags or by bulk from a silo. Sand or fillers are also batched by weight from premeasured bags or more commonly, by using a gagebox that has previously been checked and weighed. For bulk material, some method must be provided for controlling the quantities of components (Volume or weight measurement) added to the mix. Admixtures are usually provided ready proportioned to a single bag of cement, or the dosage can be adjusted by the mixer operator.

Grout Placement Techniques

Four classifications of grouting methodology have been established earlier in this paper. These methods are described in further detail as follows.

Gravity Fill Techniques (Type A Micropiles):

Once the hole has been drilled to depth, it is filled with grout and the reinforcement is placed. Grout should always be introduced into the drill hole through a tremie pipe exiting at the bottom of the hole. Grout is pumped into the bottom of the hole until grout of similar quality to that being injected is freely flowing from the mouth of the borehole. No excess pressure is applied. Steps are taken to ensure that the quality of grout is maintained for the full length of the borehole. This type and phase of grouting is referred to as the *primary treatment.*

The grout usually comprises a neat cement mix with w/c ratio between 0.45 and 0.50 by weight. Additionally, sanded mixes of up to 1:1 or 2:1 sand:cement ratio have been used in European practice, but they are becoming less common due to a growingtrend towards use of higher pressure micropiles requiring neat cement grouts. Gravity fill techniques tend to be used now only when the pile is founded in rock, or when low-capacity piles are being installed in stiff or hard cohesive soils, and pressure grouting is unnecessary [18]. For sanded mixes, the w/c ratio is often extended to 0.60, assuming the resultant mix remains stable [19].

Pressure Grouting Through the Casing (Type B Micropiles):

Additional grout is injected under pressure after the primary grout has been tremied, and as the temporary casing is being withdrawn. The aim is to enhance subsequent grout/soil bond characteristics. This operation can be limited to the load transfer length within the design-bearing stratum, or may be extended to the full length of the pile where appropriate.

Pressure grouting is usually conducted by attaching a pressure cap to the top of the drill casing (this is often the drilling head itself) and injecting additional grout into the casing under controlled pressure. In the early days, pressurization of the grout was achieved by applying compressed air through the grout line, since contemporary drill head details and grout pump technology could not accommodate the relatively viscous, sand-cement mortars. This method has now been rendered obsolete by the developments in pump capabilities, combined with the trend to use stable, neat cement grouts without sand.

Grout pressures are measured as close to the point of injection as possible, to account for line losses between pump and hole. Commonly, a pressure gauge is mounted on the drill rig and monitored by the driller as a guide to rate of casing withdrawal during the pressurization phase. Alternatively, if a grouting cap is used and the casing is being extracted by means other than the drill rig (e.g., by hydraulic jacks), it is common to find a pressure gauge mounted on the cap itself. Practitioners acknowledge that there will be line losses in the system, but typically record the pressure indicated on the pressure gauge without the correction, reasoning that such losses are compensated by the extra pressure exerted by the grout column due to its weight in the borehole.

American practice is to inject additional grout at a typical average pressure between 0.5 to 1 MPa with the aim of reinstating lateral soil pressures that may have been reduced by the drilling process and achieving permeation into coarser grained granular soils or fractured rocks. The injection pressures (typically 20 kPa per meter of depth in loose soils and 40 kPa per meter of depth in dense soils) are dictated by the following factors:

- The need to avoid ground heave or uncontrolled loss of grout.
- The nature of the drilling system (permissible pressures are lower for augers due to leakage at joints and around the flights).
- The ability of the ground to form a seal around the casing during its extraction and pressure grouting.
- The need to avoid seizing the casing by flash setting of the grout due to excessive pressure, preventing proper completion of the pile.
- The groutability of the ground.
- The required grout/ground bond capacity.
- Total pile depth.

The injection of grout under pressure is aimed at improving grout/ground skin friction, thus enhancing the load-carrying capacity of the micropile. Extensive experience with ground anchors has confirmed the effect of pressure grouting on ultimate load-holding capacity.

When pressure grouting in granular soils, a certain amount of permeation and replacement of loosened soils takes place. Additionally, a phenomenon known as pressure filtration occurs, wherein the applied grout pressure forces some of the integral mixing water out of the cement suspension and into the surrounding soil. This process leaves behind a grout of lower water content than was injected and is thus quicker setting and of higher strength. It also causes the formation of cake-like cement paste along the grout/soil interface that improves bond. In cohesive soils, some lateral displacement, compaction, or localized improvement of the soil can occur around the bond zone, although the improvement is generally less well marked than for cohesionless soils.

Pressure grouting also appears to cause a recompaction or redensification of the soil around the borehole and increases the effective diameter of the pile in the bond zone. These mechanisms effectively enhance grout/soil contact, leading to higher skin friction values and improved load/displacement performance. Such pressure grouting may also mechanically improve the soil between piles. This is an interesting concept within the CASE 2 pile application but is, as yet, untested.

Postgrouting (Type C and D Micropiles):

It may not be possible to exert sufficiently high grout pressures during the casing removal stage. For example, there may be ground hydrafracture or leakage around the casing. Alternatively, some micropile construction methods may not use or need a temporary drill casing, and so pressure grouting of the Type B method is not feasible. These circumstances have led to the development of post-grouting techniques, whereby additional grout can be injected via special grout tubes some time after the placing of the primary grout. Such grouts are always neat cement-water mixes (for the ease of pumpability) and may therefore have higher water contents than the primary grout, being in the range of 0.50 to 0.75 by weight. It is reasoned that excess water from these mixes is expelled by pressure filtration during passage into the soil, and so the actual placed grout has a lower water content (and therefore higher strength).

As described in the following paragraphs, high postgrouting pressures are typically applied, locally, for quite restricted periods; it may only take a few minutes to inject a sleeve. Herbst [1] noted that the required aim of providing higher grout/ground bond capacity may, in fact, be more efficiently achieved in Type B micropiles, where grouting pressures are lower but are exerted over a larger area and a much longer period. This has yet to be evaluated.

The construction-based classification method identified two types of postgrouted piles, namely Type C and Type D.

Type C: Neat cement grout is placed in the hole as done for Type A. Between 15 and 25 minutes later, and so before hardening of this primary grout, similar grout is injected once from the head of the hole without a packer, via a 38- to 50-mm diameter preplaced sleeved grout pipe (or the reinforcement) at a pressure of at least 1 MPa.

Type D: Neat cement grout is placed in the hole as done for Type A. Several hours later, when this primary grout has hardened, similar grout is injected via a preplaced sleeved grout pipe. Several phases of such injection are possible at selected horizons and it is typical to record pressures of 2 to 8 MPa, especially at the beginning of each sleeve treatment when the surrounding primary grout must be ruptured for the first time. There is usually an interval of at least 24 hours before successive phases. Three of four phases of injection are not uncommon, contributing additional grout volumes of as much as 50 percent of the primary volume.

Variations on the technique exist. The postgrout tube can be a separate 25- or 38-mm diameter sleeved plastic pipe (tube à manchette) placed together with the steel reinforcement (Figure 20), or it can be the reinforcement tube itself, suitably sleeved (Figure 21). In each of these cases, a double packer is used to grout through the tubes from the bottom sleeve upwards.

Alternatively, this pressure grouting can be conducted from the surface via a circulating-loop arrangement. By this method, grout is pumped around the system and the pressure increased steadily by closing the pressurization value on the outlet side. At the critical "break out" pressure, dictated by the lateral resistance provided by the adjacent grout, the grout begins to flow out of the tube through one or more sleeves and enters the ground at that horizon. When using the loop method, it is assumed that with each successive phase of injection, different sleeves open, so ultimately ensuring treatment over the entire sleeved length (a feature guaranteed by the tube à manchette method using double packers.)

A slight cautionary note against the use of postgrouting was raised by Dr. Lizzi, who was concerned about leaving "foreign materials" (e.g., the postgrouting tubes) in the pile, and about contractors being tempted to use low-strength bentonite primary grouts to reduce "break out" pressures. Consideration should be given to these issues if the pile structural design places dependency on the compressive strength of the grout.

Top-Off (Secondary) Grouting:

Due to slow grout seepage, bleed, or shrinkage, it is common to find that the grout level drops a little prior to stiffening and hardening. In ground anchorage practice, this is simply rectified by topping off the hole with the lowest water-content grout practical, at some later phase. However, in micropile practice where a permanent casing for reinforcement of the upper pile length is not used, such a cold joint is best avoided, since the grout column should be continuous for load holding and corrosion protection reasons. Topping off is therefore best conducted during the stiffening phase to ensure integrity. Where particularly high interfacial bond stresses must be resisted between the pile and an existing structure, the use of a high-strength non-shrink grout may be considered.

REINFORCING STEEL

The amount of steel reinforcement placed in a micropile is determined by the loading it supports and the stiffness required to limit the elastic displacement. Reinforcement may consist of a single reinforcing bar, a group of reinforcing bars, and/or a steel pipe.

Placement of Reinforcement

Reinforcement may be placed either prior to grouting, or placed into the grout-filled borehole before the temporary casing is withdrawn. It must be clean of deleterious substances such as surface soil and mud that may contaminate the grout or coat the reinforcement, impairing bond development. Suitable centralizers should be firmly fixed to maintain the specified grout cover. Pile cages and reinforcement groups, if used, must be sufficiently robust to withstand the installation and grouting process and the rotation and withdrawal of the temporary casing.

Reinforcement Types

Further description of the various types of reinforcement follows.

Concrete Reinforcing Steel Bars (rebar): Standard reinforcing steel, conforming to ASTM A615/AASHTO M31and ASTM A706, with yield strengths of 420 and 520 MPa, is typically used. Bar sizes range in diameter from 25 mm to 63 mm. A single bar is typically used, but a group of bars is possible. For a group, the individual bars are separated by the use of spacers or ties to the helical reinforcement, to provide area for grout to flow between the bars and ensure adequate bonding between the bars and grout.

For low overhead conditions where placement of full-length bars is not feasible, mechanical couplers can be used. Field adjustment of individual bar lengths can be difficult if the coupler type requires shop fabrication.

Continuous-Thread Steel Bars: Steel reinforcing bars that have a continuous full-length thread, such as Dywidag Systems International (DSI) Threadbar or the Williams All-Thread Bar.

The DSI Threadbar system, which is also named a GEWI pile, is a common choice throughout the world for micropile reinforcement. The bar has a coarse pitch, continuous ribbed thread rolled on during production. It is available in diameters ranging from 19 mm to 63 mm in steel conforming to ASTM A615/AASHTO M 31, with yield strengths of 420 and 520 MPa. The size range of 45 mm to 63 mm is most commonly used. Higher strength bars of steel conforming to ASTM A722/AASHTO M 275 with an ultimate strength of 1,035 MPa are also available, in diameters of 26, 32, and 36 mm.

The Williams All-Thread Bar is available in diameters ranging from 26 mmto 45 mm in steel conforming to ASTM A722/AASHTO M 275, with an ultimate strength of 1,035 MPa. The bar has a finer thread than used on the DSI bar.

The thread on the bars not only ensures grout-to-steel bond, but also allows the bar to be cut at any point and joined with a coupler to restore full tension/compression capacity. The continuous thread also simplifies pile-to-structure connections where the bar is connected to a anchor plate. A hex nut is used to connect the plate, with the continuous thread allowing easy adjustment of the plate location.

Continuous-Thread Hollow-Core Steel Bars: Steel reinforcing bars that have a hollow core and a continuous full-length thread include the MAI Anchor System and Ischebeck Titan Micropile System. These bar types offer the advantages of the continuous thread, and the hollow core allows the bar to be used to drill the pilehole. A drill bit is mounted on the tip of the bar, and the bar is drilled in with grout flush pumped to the bit through the hollow core of the bar. Alternately, an air or water flush can be used, with the grout placed through the bar after drilling to the final depth.

The continuous thread allows the bar to be cut to length and coupled, and allows the use of a hex nut for the pile top connection. The main drawback of this type of reinforcement is the higher cost. *(Caution to designers: Currently these type of bar systems are manufactured outside of the United States and might not be allowed on contracts containing Buy America or Buy American Provisions.)*

Steel Pipe Casing: With the trend toward micropiles that can support higher loading with low displacements and for the requirement to sustain lateral load and bending and shear stresses from lateral displacements, the use of a steel-pipe reinforcement has become more common. Pipe reinforcement can provide significant steel area for support of high loading and contribution to the pile stiffness, while providing high shear and reasonable bending capacity.

Pipe reinforcement is placed by either using the drill casing as permanent reinforcement, or by placing a smaller diameter permanent pipe inside the drill casing. Use of the drill casing for full-length reinforcement is typical only for micropiles founded in rock, where extraction of the casing for pressure grouting is not necessary. The length of the pipe sections used is dictated by the length of the drill mast and by the available overhead clearance. Casing sections are typically joined by a threaded connection, which is machined into the pipe. The reduced area of the threaded joint should be considered in the structural design of the pile, particularly for the capacity in tension and bending. Methods exist for reinforcement of the threaded joints that can provide a strength equivalent to the full casing section.

Pipe in the sizes typically used for micropile construction are available in steel conforming to ASTM A53, A519, and A106 with a typical yield strength of 241 Mpa. Availability of the desired pipe size may determine the grade of steel used. The main drawbacks of using these pipe grades is the relatively low yield strength and a very high unit cost per linear meter.

As an alternative, API N-80 casing may be used. The high yield strength of 551 Mpa greatly aids the micropiles ability to support high loads, and improves the strength of threaded joints that machined into the pipe wall. The pipe is also readily available in the form of mill secondary material at a reasonable unit cost. The use of this pipe source requires verification of steel quality through tensile and chemical testing of sampled steel rather than through mill certification, which is typically not available.

Due to the high strength of the API N-80 casing, weldability of the casing is an issue. Prior to welding the N-80 casing, welding procedures must be submitted to the owner for approval.

Composite Reinforcement

For micropiles founded in soil where pressure grouting is desirable with partial extraction of the permanent drill casing necessary for the pressure grouting, the use of a steel bar for reinforcement of the bottom portion of the pile is common, resulting in a composite reinforced pile (Figure 22). The reinforcing bar may be extended to the top of the micropile for support of tension loading. The use of varying reinforcement adds complexity to the pile structural analysis, with particular attention needed for the location of reinforcement transition.

Reinforcement Corrosion Protection

Traditionally, with the exception of permanent tension piles in aggressive ground conditions, little corrosion protection other than the surrounding cement grout has been provided to the reinforcement in most countries.

The various levels of corrosion protection that can be applied to reinforcing bars follow.

Grout Protection Only - Reinforcing Bar: Centralizers are applied along the length of the bar to ensure adequate cover of grout between the bar and the side of the borehole. Centering of the reinforcement in the grout is also structurally desirable for compression piles. Internationally, various codes require minimum grout cover of 20 to 30 mm. Alternative approaches regarding this level of protection include geometric corrosion protection, which relates to the concept that a progressive loss of section with time is allowable, and typical rates are widely quoted [20]. Corrosive potential of the existing ground, magnitude of the tension loading, and the structural detailing of the pile must all be considered for this level of protection.

Protective Barriers - Reinforcing Bar: Additional protection may be required in those cases where a continuous grout cover of adequate thickness cannot be guaranteed, where the pile is installed in aggressive ground conditions, or the reinforcement may cause tension cracking of the grout, providing a corrosion path to the steel. Options for protective barriers include providing a coating on the bar, such as an epoxy coating, or providing a encasing sheath (encapsulation), such as corrugated plastic, with the annulus between the bar and the sheath filled with grout The use of a grout-filled corrugated sheath is a common feature of permanent anchor tendons and the DSI threadbar and GEWI Bar, and is referred to as *double corrosion protection.*

For micropiles with composite reinforcement (bar and pipe), the permanent grout-filled pipe provides protection in a manner similar to the encapsulation method for the upper portion of the bar encased by the pipe. Protection may still be necessary for the uncased portion of the pile.

Sacrificial Steel – Casing: Corrosion protection of pipe reinforcement can be more difficult, particularly if the drill casing has been used as the reinforcement. The various levels of corrosion protection that can be applied to permanent casings follow. According to AASHTO section 4.3.4.2.2, for concrete-filled pipe piles in installations, where corrosion may be expected, 1.6 mm shall be deducted from the shell thickness to allow for reduction in the section due to corrosion.

The French code CCTG (1993) recommends adoption of the minimum dimensions of shell thickness to be sacrificed as corrosion protection in the absence of specific studies as summarized in Table 3. The effect on pile strength and stiffness should be included in the consideration of sacrificial steel as corrosion protection.

	Service Life (years)			
Soil Type	**25**	**50**	**75**	**100**
Not Aggressive	0.25	0.60	0.70	0.80
Barely Aggressive	1.00	1.60	2.00	2.50
Very Aggressive	2.50	4.00	5.00	6.00

Table 3. Minimum dimensions (in mm) of shell thickness as corrosion protection (From CCTG, 1993)

Grout Cover – Casing: The pile shaft annulus around a drill casing can vary typically from 10 to 75 mm, depending on the soil conditions and methods of drilling and grouting. Grout cover may not be present in this annulus if the soil seal contains the grout in the lower bond length during pressure grouting, preventing it from filling in around the upper portion of the pile. This may not be a concern in cohesive soil or rock conditions. The method to ensure a minimum grout cover around pipe reinforcement, particularly in granular soil conditions, may be to place a separate permanent pipe and completely retract the drill casing.

Protective Barriers – Casing: The use of a coating such as an epoxy paint where the drill casing provides permanent reinforcement is not desirable, due to the abrasive action of the soil on the outer casing wall and probable resulting damage to or wearing off of the coating. An encasing sheath in the form of an additional outer casing provides very effective corrosion protection, but at considerable additional cost.

CONTRACTING METHODS

To date, methods of design, specification, and installation of micropile systems in the United States have been developed by specialty geotechnical contractors. Most public agencies and consulting engineers presently have little or no knowledge regarding micropiles and their application. The goal of this manual is to provide guidelines that will help owners and engineers implement the most technically and economically feasible application of micropile technology in everyday use.

Preparation and enforcement of the contract documents are important steps in the introduction of new technologies. For innovation to flourish, there must be a need and a reward for those who take the risk of funding and implementing the technology. One of the biggest constraints on this is our most commonly used delivery system for construction projects, the traditional "low-bid" owner-designed system. This process limits innovation, promotes the use of unqualified contractors and poor quality, may result in an increase in end-product costs, and retards the implementation of new technology. With this in mind, the implementation of project specifications incorporating the use of alternative contracting methods is vital to the adoption of micropile technology.

In order to insure quality micropile construction, it is strongly recommended that projects utilizing micropiles be specified to place a large amount of responsibility on the specialty geotechnical contractor. This is the basis for the remaining portions of this chapter. Alternative contracting methods are described and compared to provide guidelines for owners and consulting engineers when specifying micropiles. Also, information to be included on the contract plans and the specialty contractor working plan submittal is discussed.

Specifications

As most specialty geotechnical work is performed in the public sector, fair contracting practices are always an issue. The U.S. construction industry is very strongly geared to the owner- designed low-bid contracting process to promote these fair contracting practices. Owners are reluctant to move away from this system, for fear of potential litigation caused by unfair contracting. There are alternative contracting means that can be used to encourage good quality innovation and better protect the owners' interest, even within the confines of the traditional low-bid system.

The specifications can be used to mandate methodology or provide alternative design constraints. The degree of detail will be based on the designer's experience with micropile installations, owner confidence with the prequalified micropile contractors, and the critical nature of the application. An important note to always remember when preparing the plans, specifications, and cost estimate for micropile projects is that the specialty contractor installing the micropiles is often a subcontractor on the project. Support services are necessary from the general contractor and will have to be included in the micropile pricing (e.g., access, spoils handling, footing excavation and backfill, etc.).

Recommended specification methods for micropile applications are divided into two categories: **Owner-Controlled Design** and **Contractor Design/Build**. As stated earlier in this chapter, micropile specifications must place a large amount of responsibility on the specialty geotechnical contractor. With this in mind, prequalification of micropile contractors is highly recommended for both owner-controlled design and contractor design/build specifications. It is not the intent of this document to develop a prequalification system for every project owner, but it is recommended that the prequalification process be performed prior to contract advertisement. The prequalified micropile contractors (minimum of two) can be listed in the contract specifications. If the micropile work is a subcontracted item, each general contractor must be required to provide the name of its micropile subcontractors with the bid submittal.

Minimum prequalification requirements are as follows for each micropile contractor recommended.

1. The company and personnel's previous successful experience of at least three years -evidenced by owner references-in the design and installation of micropiles of similar scope to those proposed for the application project. Documentation shall include at least five successful projects performed in the last five years.
2. The micropile contractor's project engineer must be a full-time employee with at least three years of micropile design and construction experience, and must be a registered professional engineer.
3. Micropile contractor must have previous drilling experience in soil/rock similar to project conditions. Contractor must submit at least three successful load-test reports from different projects of similar scope to project.
4. Project superintendents and drill operators responsible for installation of micropile system must have at least three years of micropile installation experience.

Alternative specifications for both owner controlled design and contractor design/build projects are described in the following sections. *(Note: All specification recommendations assume prequalified micropile contractors are listed in the contract documents.)*

Owner-Controlled Design Methods

Owner-controlled design specifications vary in the amounts of the design to be performed by the owner's design engineer and the micropile contractor. The owner typically establishes the following:

- Scope of work.
- Micropile design loadings.
- Footing details.
- Size/location of slope stabilization structure.
- Corrosion protection.
- Micropile testing procedures and requirements.
- Instrumentation requirements.
- Special design consideration (e.g., scour and liquefaction potential).
- Performance criteria

The micropile contractor specifies the following:

- Micropile construction process.
- Micropile type.
- Micropile design.
- Pile top footing connection design.

This division of work allows the prequalified specialty contractors to provide an economical micropile design, while satisfying the owner's engineer's design requirements. This method also allows responsibility for the work to be shared between the owner and the micropile contractor. While this is slightly more restrictive than the contractor design/build specification method, it is still flexible enough to allow for some innovation and cost savings. Various types of owner-controlled design specifications include the following.

Standard Design

The contract documents for the Standard Design Type are prepared to allow for various prequalified micropile designs. The owner's engineer provides the micropile design loadings, footing design, and pile layout for foundation support projects. For micropile slope stabilization projects, the owner provides the existing slope stability design and minimum static and seismic factors of safety required to stabilize the slope. In addition, the owner provides the following:

- Geotechnical reports and data.
- Micropile design parameters, including (foundation support projects only)
    Maximum pile sizes,
    Axial pile loads,
    Displacement requirements, and
    Ductility requirements.
- Existing utility plans.
- Site limitations, including
    Right of way,
    Scour,
    Liquefaction,
    Noise requirements,
    Vibration requirements, and
    Hazardous/contaminated soils.
- Contractor working drawing/design submittal and review requirements, including
    Time frame, and Penalties.
- Material specifications.
- Testing requirements.
- Instrumentation requirements (if any).
- Acceptance criteria.
- Method of measurement and payment.

It is recommended that micropile measurement and payment be performed on a unit-per-micropile basis separately for furnished and installed production piles, verification testing, and proof testing.

During the bidding process, the prequalified micropile contractors prepare a preliminary design and a firm cost proposal based on the owner's plans and specifications. If the project is to be subcontracted, general contractors will receive bids from each prequalified specialty subcontractor and includes the best offer in the proposal. The name of the recommended micropile subcontractor are included in the general contractor's bid, which is then submitted. Once the contract has been awarded, the selected specialty contractor prepares his working drawings and design calculations and submits them to the engineer for review and approval. After acceptance of the design, construction begins.

Alternate Design

The contract documents for the Alternate Design Type are also prepared to allow for various prequalified micropile designs. The major difference in this method is the owner provides a design in the contract documents utilizing a more traditional foundation support system. The contract documents allow alternate micropile designs to be submitted by the listed specialty contractors on a one-for-one pile replacement of the owner-designed pile system. The information described under Standard Design Type is also required.

Typically, micropiles are not competitive with more traditional piling systems in a one-for-one pile replacement. Therefore, this specification method is rarely used.

An attractive option to this one-for-one pile replacement method is where the owner provides three alternative pile-supported footing designs in the contract documents. Alternate 1 would be one-for-one pile replacement, Alternate 2 could be one-for-two pile replacement, and Alternate 3 could be one-for-one-and-one-half pile replacement. This allows the prequalified micropile contractor to provide fewer higher capacity micropiles than the conventional pile footing design requires, and allows the owner's engineer to maintain control of the footing design.

The information necessary in the contract documents is similar to that previously mentioned, except the owner provides two to three alternative pile footing designs on the plans with the associated pile design and load criteria.

Cost Reduction Incentative Proposal (Value Engineering)

The Cost Reduction Incentative proposal is another long-established form of alternate proposal used in the United States. Although more progressive in concept, it has limited use in specialty geotechnical contracting.

When Cost Reduction Incentive Proposals are permitted, it is important that the owner specify any additional restrictions that may apply, such as right-of-way restrictions. Most general contractors are hesitant to entertain value engineering proposals viewing them as high-risk options with too little reward. This proposal is more appropriate for slope stabilization projects. Foundation support elements are usually the first order of work, so the approval time required for the value engineering proposal often eliminates it as a viable option.

Contractor Design/Build Methods

According to the owner-controlled design specification method, when the use of micropiles is stipulated for a project, the owner's engineer defines the scope of work and shares responsibility in the design and installation of the micropile system. With the design/build method, by contrast, the owner outlines the project's ultimate needs and the specialty contractor is responsible for the micropile system detailed design and installation. The owner's engineer defines the performance criteria and objectives. Based upon specified limitations and requirements, a design/build proposal is submitted, either before the bid advertisement (prebid), or after contract award (post-bid). Measurement and payment is typically made on a lump-sum basis.

In design/build construction, the owner is committed to a team approach whereby the specialty contractor becomes an important part of the team, contributing to all foundation and ground-support aspects of the project. Risk sharing is integral: the micropile contractor is responsible for the adequacy of the design and its construction, the owner is responsible for the accuracy of the information upon which the design is based. Costs are reduced, as the contractor includes fewer contingencies. Innovation is encouraged, since the contractor is rewarded for economies of design and installation. Lastly, quality is enhanced due to prequalified contractors working with the project owner in a partnering approach. The two recommended types of contractor design/build specifications follow.

Postbid

The contract documents for the postbid design/build method are prepared to allow for various prequalified-contractor-designed alternatives. The owner's engineer provides the design and detailing of ancillary structures, and the performance criteria and objectives necessary for the micropile system design and installation. This information includes, as a minimum, the following:

- Geotechnical reports and data.
- Existing utility drawings.
- Design criteria and parameters.
- Site limitations (e.g., right of way).
- Design and details of ancillary structures.
- Contractor working drawing/design submittal and review requirements.
- Acceptance criteria.
-

During the bidding process, the prequalified micropile contractors prepare a preliminary design and a firm cost proposal based on the owner's plans and specifications. For subcontracted items, general contractors will receive bids from each prequalified specialty subcontractor and include the best cost proposals in their bids. The name of the recommended micropile subcontractors are included in the general contractor's bid, which is then submitted. Once the contract has been awarded, the selected specialty contractor prepares his detailed design calculations and working drawing and submits them to the engineer for review and approval. After acceptance of the design, construction begins.

Prebid

The contract documents for the prebid design/build method are also prepared to allow for prequalified-contractor-designed micropiling alternatives. The major difference in this method is the timing of the design and the bidding. Performance criteria and necessary project design information are usually made available 60 to 90 days prior to the contract advertisement date. Prequalified micropile contractors prepare and submit final design calculations and working drawings for the owner's review and approval. Once the designs (typically two to three total) are approved, a list of prequalified specialty contractors with approved designs are included in the contract documents. Often the specialty contractors' proprietary working drawings are included in the contract bid documents. These drawings illustrate the proposed construction and assist the general contractors in understanding and coordinating their other project tasks with the proposed micropile construction. General contractors then receive bids from each prequalified subcontractor, bidding only on their own proprietary design, and include the best cost proposals in their bids. The names of the recommended micropile subcontractors are included in the general contractors' bids, which are then submitted. Once the contract is awarded, the selected specialty contractor is prepared to begin the work immediately.

Other Methods

Technical and Cost Proposals

Weighted technical cost proposals require the contractor to submit two very detailed documents, one for the price to perform the work and the other for the proposed work plan. Each is independently assessed. The first portion is a plan of how the contractor proposes to perform the work. This portion contains the contractor's design and construction experience, proposed scope of work and work plan, preliminary design and construction schedule, preliminary design calculations and drawings and proposed quality control and safety plans. This document is evaluated for technical competence, personnel, and corporate experience and safety. The second portion is a lump-sum cost proposal. Each element is given a rating; 70/30 or 60/40 for the technical-to-price ratio is not unusual. The contract award is made to the contractor who provides the best overall proposal to the owner.

This two-pronged contracting procedure is slowly gaining popularity with Federal and State agencies. In the technical cost proposal process as with the value engineering process, bidding contractors incur a lot of time and expense. This fact alone, however, will defer all but the most serious contractors. This process also involves considerable effort by the owner, and so is really viable only for particularly large and/or complex projects.

Contract Plans

For all of the specification methods mentioned, the contract plans must include the necessary bid information in order to protect the owner's best interests. They also need to describe the owner's objectives in enough detail that the micropile contractor can provide an adequate design and bid. It is recommended that the contract plans be prepared in a three-line format for both owner-controlled design and contractor design/build specification methods. Concept-only plans are provided for the contractor design/build method.

The quality of the subsurface information, existing utility plan, and micropile design criteria are very important for a mutually successful project. Inadequate subsurface information and conservative pile design criteria may create expensive contractor contingencies and higher pile prices and increase claim potential.

COST

Micropile costs are the product of many factors:

1. Physical access and environmental conditions.
2. Subsurface conditions.
3. Mobilization/demobilization.
4. Project location.
5. Pile quantity.
6. Pile capacities.
7. Pile length.
8. Pile inclination.
9. Pile testing requirements.
10. Pile installation schedule.
11. Local labor regulations.
12. Contractor overhead and margin percentages.
13. Risk assessment.
14. Contractual arrangement.

Because of these many cost factors, micropile pricing varies widely on every project. As a guideline, however, and assuming the below listed constraints, the contract bid price range for micropiles in the United States is typically $150.00 to $300.00 per lineal meter of pile (1996 costs). To take it a step further, the various cost factors must be analyzed in a "best case vs. worst case scenario" to determine a realistic micropile contract price range. Table 4 illustrates this cost analysis.

For example price constraints may include the following factors:

1. No physical, environmental, or access restrictions.
2. No unusual subsurface conditions.
3. Average pile load capacities and lengths (1,000 kN, 15m).
4. Average pile quantity (50 piles).
5. One verification pile load test and proof testing 5 percent of the production piles.
6. One mobilization/demobilization.
7. Continuous pile drilling operations.
8. Prevailing labor rates.
9. Typical contractor overhead and margin percentages.

Cost Factor	**Influence Range**	**Cost Influence (%)**
Physical and access conditions	Very easy to very difficult	0% to +100%
Geology/soil conditions	Very easy to very difficult	0% to + 50%
Pile capacity	Very low to very high	-30% to + 30%
Pile lengths	Very short to very long	-25% to + 25%
Pile quantities	Very high to very low	-50% to +100%
Testing requirements	Very low to very high	-10% to + 10%
Mobilization/demobilization	One to multiple	0% to + 10%
Continuous drilling operations	Continuous to not continuous	0% to + 25%
Union agreements	Nonunion to very strong	-15% to + 30%
O/H and profit margins (risk evaluation)	Very low to very high	-10% to + 10%

Table 4. Micropile cost influence analysis

Measurement and Payment

There are several methods of measuring and paying for micropiles. Table 5 lists recommendation for both owner-controlled and contractor design/build specification methods.

	Measurement/Payment Unit	
Item	**Owner-Controlled Design**	**Contractor Design/Build**
Mobilization/demobilization	Per Each	Lump Sum
Pile load testing	Per Each	Lump Sum
Furnish and install piles (foundation support)	Per Each	Lump Sum
Furnish and install micropile slope stabilization	Per lineal meter of structure	Lump Sum

Table 5. Micropile measurement and payment units

Proportioning the micropile unit costs (furnish and install only) typically results in the following breakdown:

- Labor-----------------30-50 percent
- Equipment-----------20-30 percent
- Materials-------------25-30 percent

CONCLUSION

Micropiles are used for structural support of foundations and in-situ earth reinforcement. Micropiles are practical in any soil, fill or rock condition and can be installed at any angle. They can accommodate restrictive access and environmental problems, and have wide application both for new construction and rehabilitation of existing structures and/or marginally stable or failing slopes.

Technology-selection criteria for each foundation support and slope stabilization project must be site specific. Besides price, some standard criteria issues include environmental concerns, settlement sensitivity, soil disturbance, scheduling, physical access, noise sensitivity, pile tension, compression, and positioning capabilities. Sometimes micropiles are the only alternative. Other times, extenuating circumstances make them more economical than the more traditional systems.

The unit price of micropiles usually exceeds that of conventional piles, especially driven piles. However, under certain combinations of circumstances, such as difficult ground conditions, site access constraints, low headroom/limited work area, etc., micropiles are cost effective and occasionally, represent the only technically feasible option.

Owners and engineers in the United States are gaining confidence with the development and implementation process of micropile technology. The American transportation construction industry must continue to build from the success of past research and project installations. It must continue to improve micropile design and installation methodologies and contracting methods to achieve the most optional foundation and ground support solutions.

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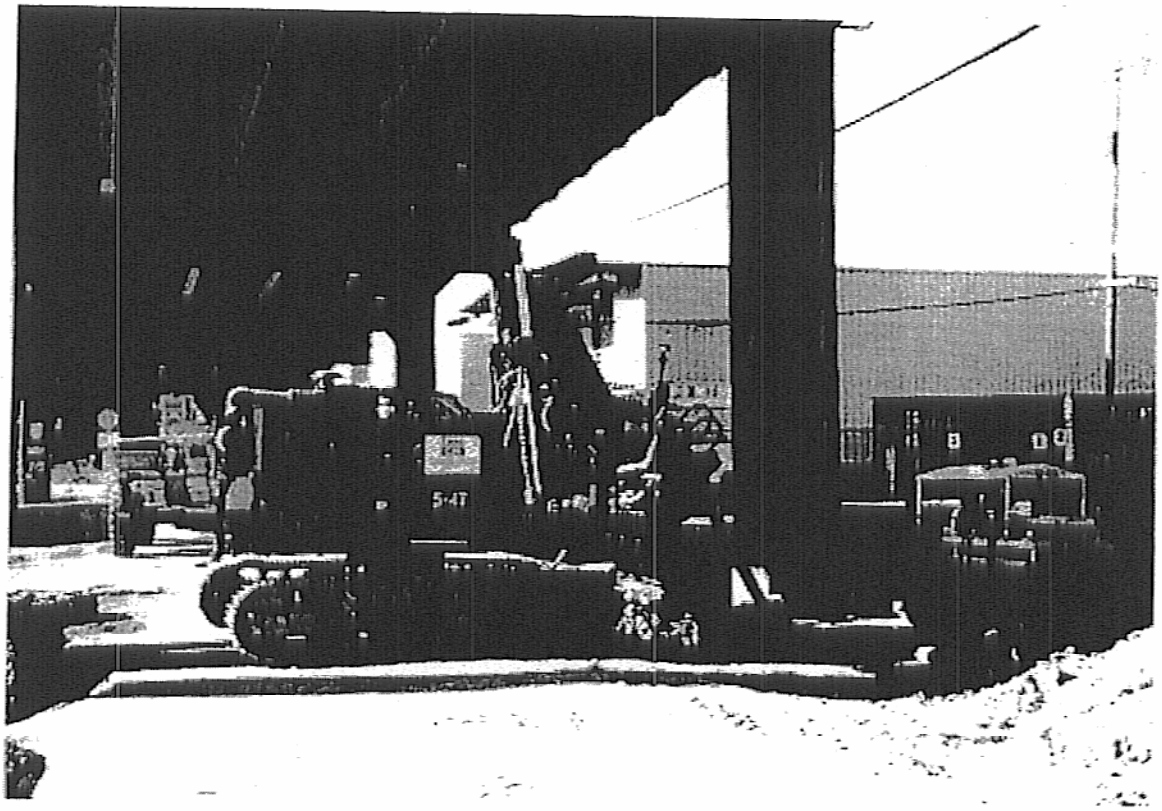
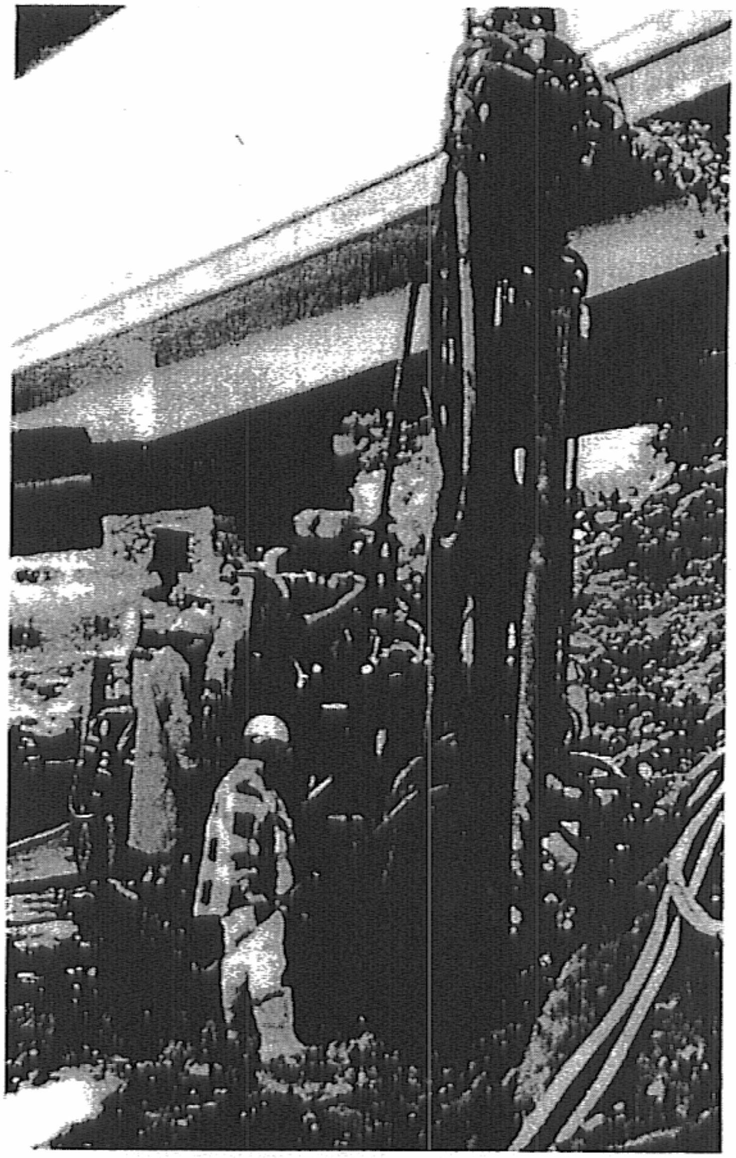
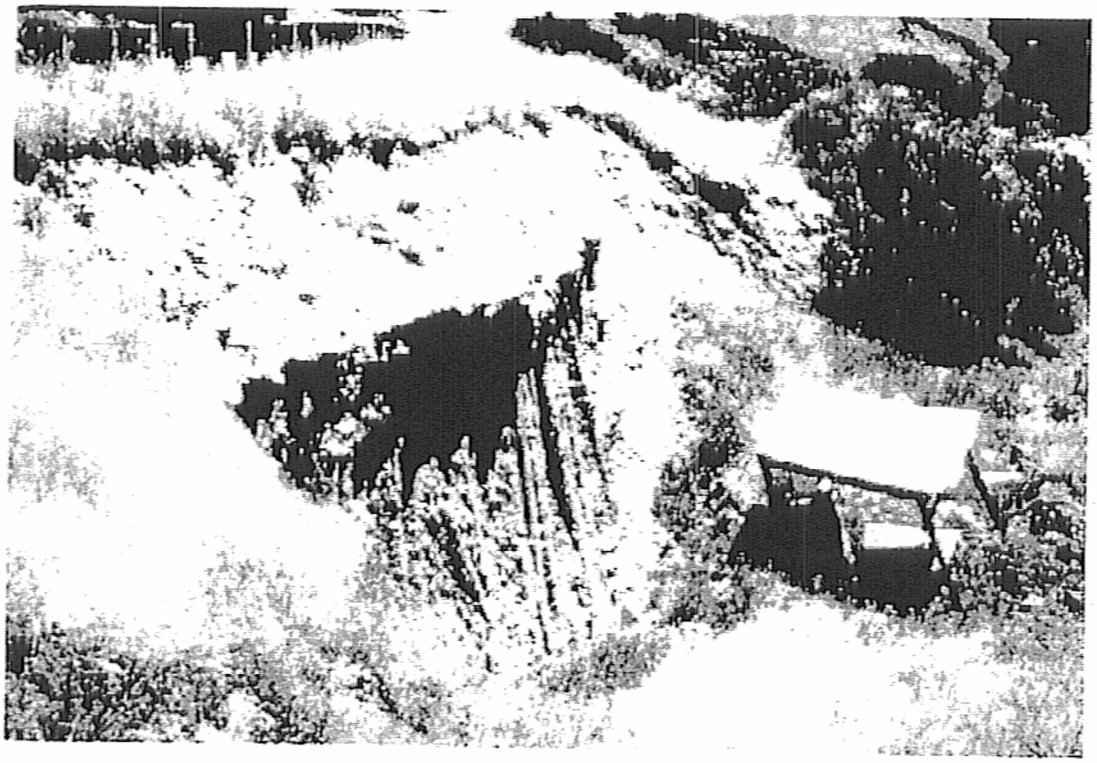


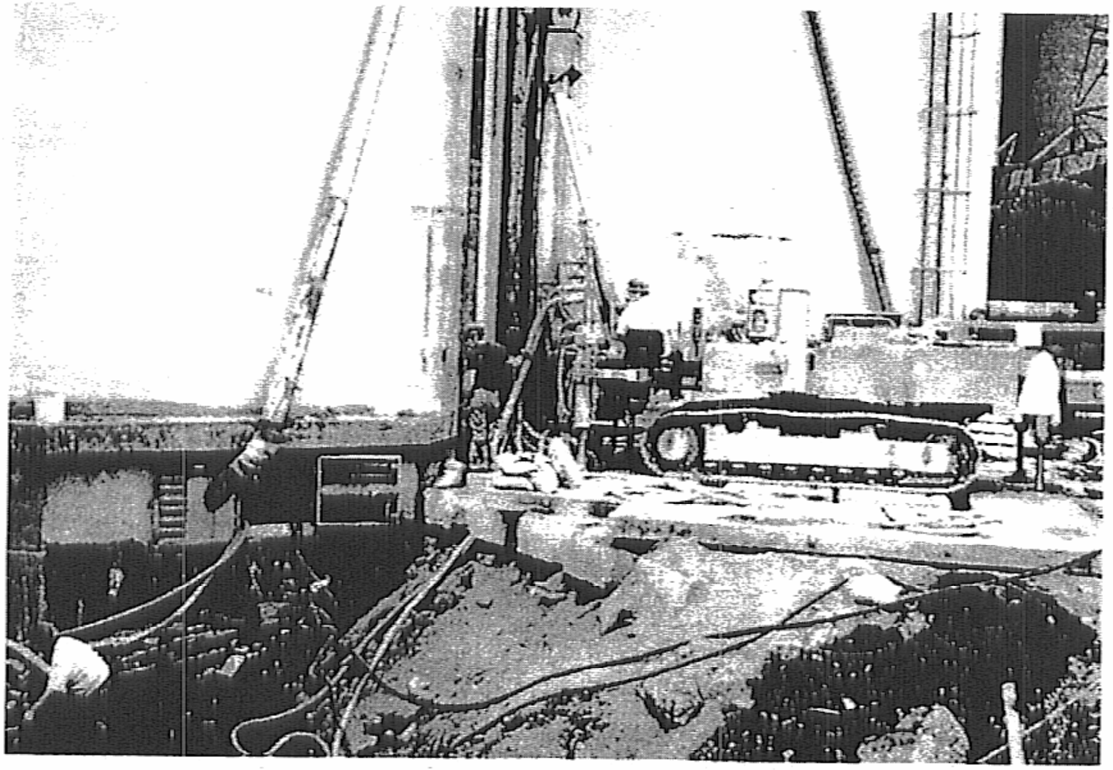
Photograph 1. Underpinning of West Emerson Street Viaduct, Seattle, Washington



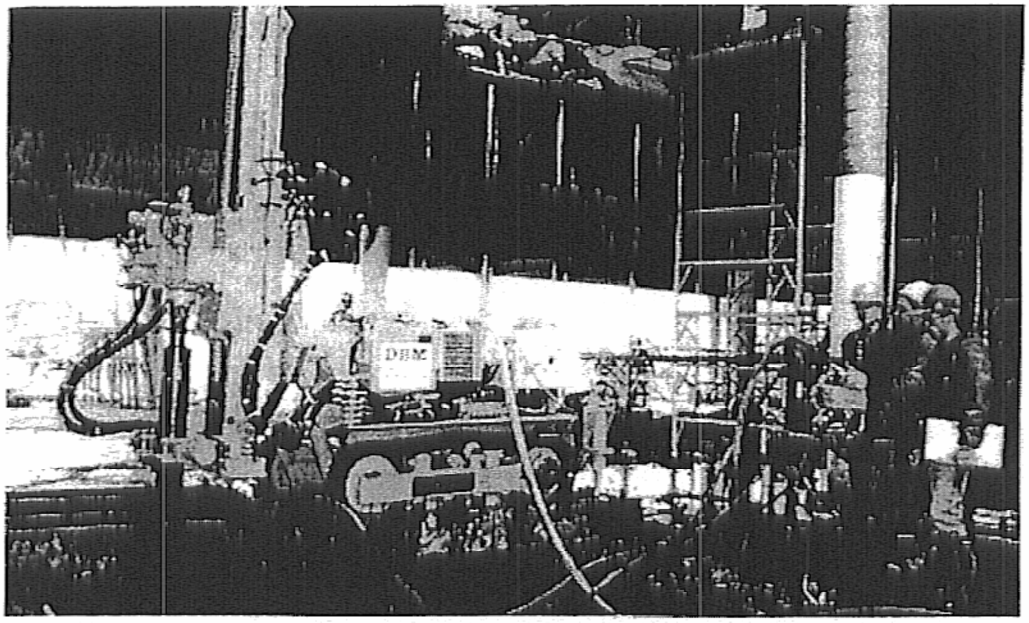
Photograph 2. Seismic Retrofit of I-110, North Connector
Los Angeles, California



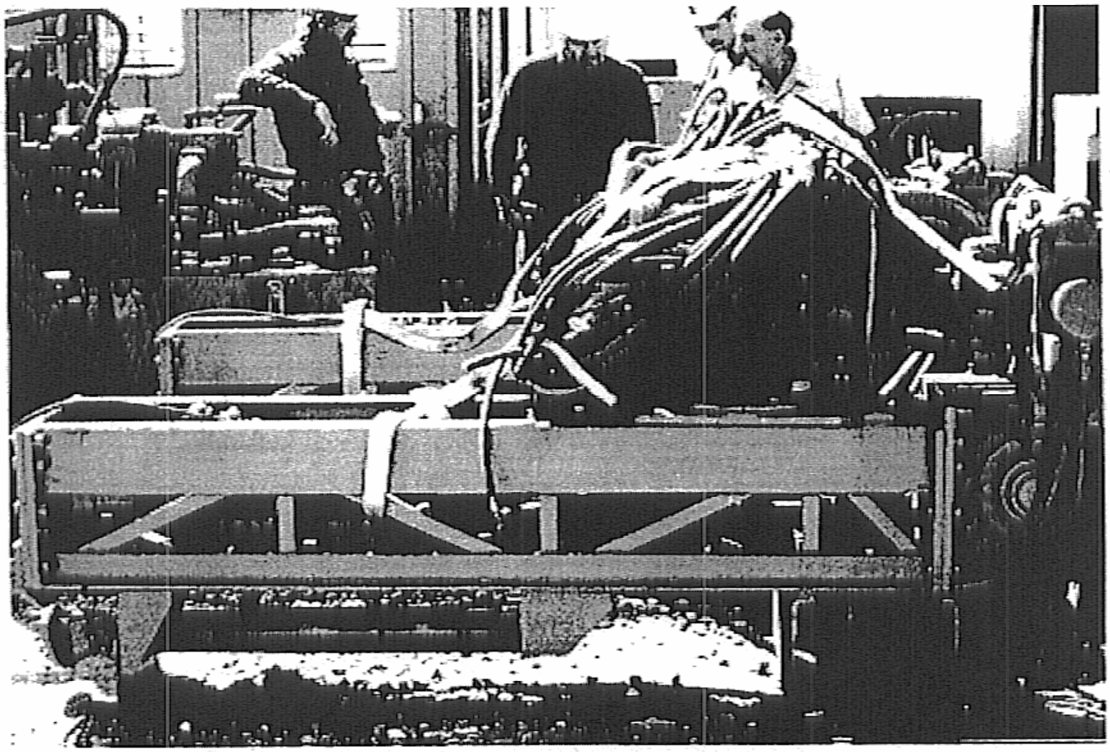
Photograph 3. FH-7, Mendocino National Forest, California (Slope Stabilization)



Photograph 4. Large Track-mounted Rotary Hydraulic Drill Rig



Photograph 5. Small Track-mounted Rotary Hydraulic Drill Rig



Photograph 6. Small Frame-mounted Rotary Hydraulic Drill Rig