Recent Advances in the Selection and Use of Drilled Foundations

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ABSTRACT: The construction and design of drilled foundations in recent years has been most significantly affected by developments in drilling techniques related to materials, equipment, and generally improved capabilities in construction. In addition, advancements in technology for testing and QC/QA have resulted in improvements in performance, reliability and design. This paper describes some of the most significant developments affecting drilled foundations, including large diameter drilled shafts, continuous flight auger piles, drilled displacement piles, and small diameter micropiles.

INTRODUCTION

The drilled foundation options available in current practice include an incredible range of available technology, from very small diameter micropiles only a few inches in diameter to large drilled shafts that may be as large as 4m (13ft) in diameter. These foundations share a common feature in that the foundation is constructed by drilling a hole into the bearing formation and constructing the foundation into that hole by placing a cementitious material such as grout or concrete. This critical part of the structure is thus cast *in-situ* rather than prefabricated and installed into the ground as with a driven pile. (note: although helical anchors might also be considered "drilled" foundations, these will not be included as this paper already covers enough ground just dealing with cast-in-place drilled foundations!).

The differences between types of drilled foundations relate mostly to the method of installation and how the casting operation for the pile is completed, although this relates directly to the equipment used to construct the foundation. This paper will discuss the state of practice of drilled foundations in a way that is consistent with each particular drilled foundation type, as follows.

Micropiles are most often 30cm (12in) or less in diameter and often selected for use because of the advantages provided by the lightweight and maneuverable equipment available to install these piles. The distinguishing feature from a design perspective is that the pile itself is typically designed as a steel member such as a bar or tube which is bonded to the bearing stratum with a cement grout. Micropiles are most effectively used where the bearing materials allow effective utilization of the high strength of the steel. Granular soils or rock often provide suitable bearing formations and micropiles are often used in rock or in highly variable conditions where difficult drilling may be encountered.

Continuous Flight Auger Piles (CFA piles) are typically 30 to 100 cm (12 to 40 in) diameter and most often selected for use because of the advantages provided by the speed and cost-effectiveness of the installation method and equipment. Often called "augered cast-in-place (ACIP)" or "augercast" piles in U.S. practice, the distinguishing feature of the construction of these piles is the fact that the concrete (sometimes a sand-cement mix) is placed through the hollow center of the continuous flight auger drill string as the augers are withdrawn and then the reinforcement is placed into the wet fluid mix after the casting operation is complete. The pile is thus a reinforced concrete structural element and designed accordingly. CFA piles are usually most cost effective when used at lengths of 10 to 30 m (30 to 100 ft) and constructed entirely in soils, although occasionally these piles are used in weak rocks. Because of the speed with which the pile can be drilled and completed, it is not uncommon for a constructor to install several piles within a single hour of work.

Drilled Displacement Piles are constructed using a technique similar to CFA piles, but using tooling and more powerful equipment such that the drill tool is advanced while displacing the soil to form the hole rather than extracting the soil. These piles provide the obvious advantages that ground improvement is achieved during installation in some types of soils, and the handling and removal of spoils (which may include contaminants in some situations) is avoided. With the controls and monitoring equipment available on modern drill rigs used for these piles, there has also been progress in relating the torque and crowd pressures to the stratigraphy so that the performance of a specific pile can be related to installation measurements.

Drilled Shafts are most often 1 m (3ft) or more in diameter and constructed by excavating and stabilizing a hole into the bearing formation (often with drilling fluid and/or steel casing) followed by placement of reinforcement and then concrete. In this way, large diameter foundations are constructed which can transfer forces to deep, competent bearing strata and provide very large axial and lateral resistance. With the capabilities of modern equipment to install large drilled shafts and the improved testing capabilities for verification of structural integrity and geotechnical performance, the use of a single drilled shaft to support a single column is often used to maximize the foundation capacity in the smallest possible footprint.

This paper describes some of the most significant developments in the last 20 years affecting the selection and design of each of these types of drilled foundations. Selected examples from the author's experience are included to illustrate the capabilities and use of modern drilled foundations, along with the factors influencing the selection of a specific drilled foundation type.

MICROPILES

The most significant advancement related to the use of micropiles for foundations and stabilization within the last 20 years has been the development and acceptance of practical design and construction guidelines, which in turn has lead to the adoption of micropiles in building codes and public works projects. The use of these foundations has grown dramatically during this period, and the popularity of this type of drilled foundation is largely the result of the versatility of the equipment (as shown in Figure 1) used to install them. Micropiles are used for applications including underpinning and seismic retrofitting and in locations and ground conditions where more conventional deep foundations would be difficult or impossible to construct.

a) Foothills Bridge, East Tennessee b) World Trade Center, New York City

Figure 1 Micropile Drill Rigs in Restricted Access Locations

Besides the ability to overcome difficult site access, micropiles can be drilled to provide good foundation support into materials which are impossible to penetrate with driven piling or which represent extremely difficult drilling conditions with larger diameter drilled foundations. Examples include piles through boulders, fills including rubble or other hard debris, and karstic formations in hard limestone. The micropiles may be advanced through porous layers with casing until a substantial thickness of sound material is penetrated, and then the casing partially withdrawn to form a permanently casing through the pervious strata and allow the pile to be grouted into the sound layer.

In a recent example, micropiles were installed to underpin a building for an industrial facility in Alabama. The single story building had been supported on steel H piles which had been driven to refusal on limestone layers within a zone of epikarst (weathered limestone) which had subsequently settled during a period of extreme drought that resulted in a drop in groundwater. Micropiles were used to penetrate into the underlying limestone, through karst solution features.

Micropile Design Details

Typical micropiles incorporate a tubular steel element or solid bar (sometimes multiple bars) which is grouted into rock or strong soil bearing stratum with a permanent steel casing extending through the overlying weak soils. Corrosion protection of the interior steel is provided by the grout and casing, and epoxy or galvanized coatings may be used in aggressive environments. In extreme cases, PVC or HDPE sheathing may be included to provide double corrosion protection as for an anchor. The micropile grout is typically a mixture of water and Portland cement that may be simply tremie-placed under gravity only, or may be pressure grouted during or after installation. Micropiles are often designed to support axial service loads of 1 MN (225k) or less per pile, but higher loads per pile can be achieved and there have been successful load tests of micropiles to loads in excess of 6 MN (1350k).

In a typical application, the structural loads dictate the size of the steel element and then the embedded length is determined to provide the geotechnical resistance necessary for the transfer of load from the steel through the grout to the soil or rock. The transfer of axial load is typically accomplished through side resistance in the portion of the pile below the casing (the bond zone), with no reliance upon side resistance in the permanently cased zone or in end bearing.

The unit side resistance in the bond zone is not only affected by the type of soil or rock, but may be strongly affected by the type of construction practice used for drilling and for grouting. As a result, the average nominal unit grout-to-ground bond strength is usually estimated empirically and verified through site-specific load testing, with the final micropile geotechnical design performed by the specialty contractor. By working in this way with either performance-based specifications or a design-build type of contract, the contractor has the ability and responsibility to select the most appropriate and cost-effective drilling and grouting techniques. The constructor thus typically has some design responsibility and incentive to improve geotechnical performance, and static load tests are routinely employed to provide verification of axial resistance.

A major factor in the broad acceptance and increased use of micropiles within the last 15 years has been the work of industry groups to develop and promote standards, share knowledge and expertise, and transform the technology into a more universally accepted foundation option. The practice in the U.S. has been shaped by the joint micropile committee of the Deep Foundations Institute and ADSC: The International Association of Foundation Drilling, whose members have worked with the Federal Highway Administration and the National Highway Institute to produce design and construction guidelines and training materials. An FHWA reference manual was published in 2000 (Armour, et al, 2000) and subsequently updated (Sabatini, et al, 2005), which provides a widely used reference for the design and construction of micropiles. Micropiles were only recently incorporated into the AASHTO Bridge Design Specifications in 2007 and the International Building Code (IBC) in 2006.

Example Applications of Micropile Foundations

The micropile design for the Foothills Parkway Bridge shown in the photo in Figure 1a, was part of a design-build project for the U.S. National Park Service. The bridge is constructed on a steep mountainside location in an environmentally sensitive area, with natural slopes approaching 1:1. Micropiles were used to support both a temporary work bridge and the piers for the permanent structure, and were drilled through residual overburden of decomposed rock to bear in the underlying metasandstone and metaconglomerate as illustrated in Figure 2. Anchors were incorporated into the foundation to resist passive earth pressures from the overburden soils which have marginal stability against downslope creep.

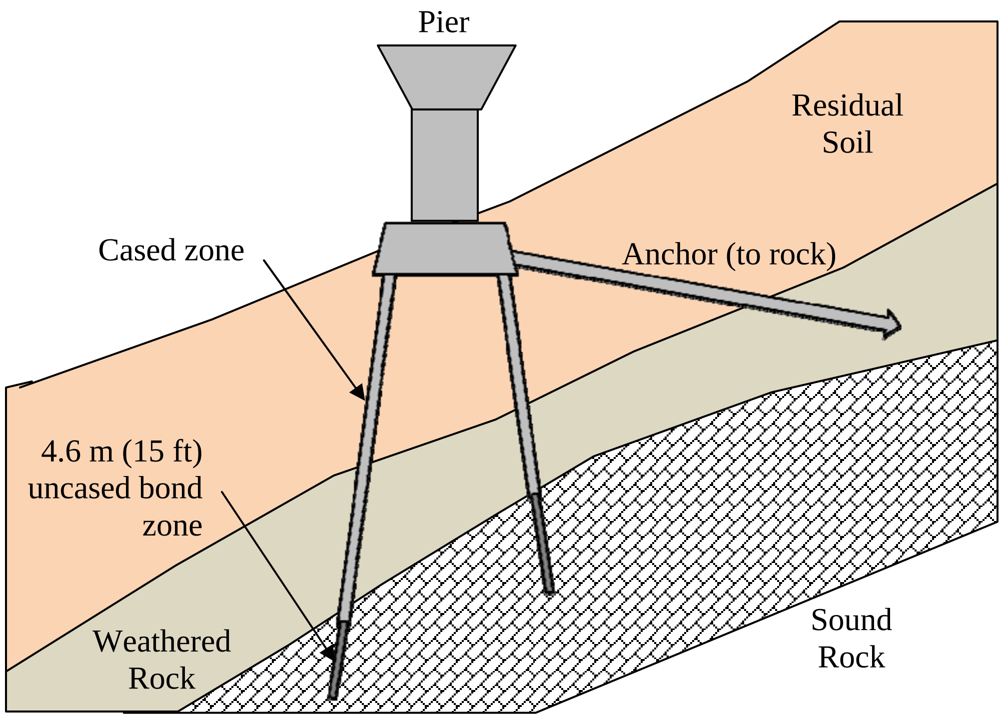


Figure 2 Micropile Foundation Design for a Typical Pier, Foothills Parkway Bridge No. 2

Analyses of the pile group foundation for bridge foundation loads from the pier were used to determine shear, moment, and axial demands on the individual piles and the design completed in accordance with the AASHTO 2007 LRFD guidelines. The shear and moment demand is resisted by the grout-filled permanent casing, which is 244 mm (9-5/8 inch) diameter, 12 mm (0.472 inch) wall thickness, 550 MPa (80 ksi) yield strength, and extends through the overburden soils and weathered rock zone. The casing was also installed so that no joint was located within 2.4 m (8 ft) of the top of the pile beneath the footing. The piles include a No. 18 center bar (57 mm, or 2-1/4 inch diameter) with 414 MPa (60 ksi) yield strength.

The maximum factored axial load demand of 1380 kN (310 kips) is resisted by the 203 mm (8 in.) diameter uncased portion of the pile which extends 4.6 m (15 ft) into the rock. This socket is designed for a nominal unit side resistance of 690 kPa (100 psi) and a resistance factor of 0.7. The axial resistance was confirmed by load tests.

The key factor in utilizing micropiles for the Foothills Bridge was the ability to position a small rig into place to install piles (shown in Figure 1a) with a minimum impact on the rugged and environmentally sensitive site. A tubular steel work trestle was installed atop the temporary micropiles, allowing construction of the permanent foundations and the remainder of the bridge from above ground. This type of solution requires a collaborative effort from both the designer and the constructor, as is facilitated by the design-build system for project delivery.

The photos in Figures 3 and 4 show another typical application where micropiles have been used for a foundation of a pedestrian bridge in Nashville, Tennessee. This foundation was installed as a part of a value-engineered alternate which was used because of the difficult access and unstable slope at this foundation location. The piles were drilled through boulder-filled debris using 24 cm (9-5/8 inch) O.D. permanent casing to facilitate drilling and casting through this zone, with a bond zone below the casing into an underlying limestone formation. The micropiles were constructed using a single threaded bar in each pile which extends into the reinforcement for the pile cap and utilizes plates threaded onto the bar to facilitate this connection. A load test was performed to a proof load of 4 MN (900 kips) with only 12 mm (½ inch) of elastic deformation observed during the test.

Figure 3 Micropiles Cased Through Boulder Fill for the Cumberland River Pedestrian Bridge, Nashville, TN

Figure 4 Completed Micropile and Connection to Footing

Micropiles in Slope Stabilization

The last 20 years has seen increased use of micropiles for problems of slope stability, whereby micropiles are utilized to transfer axial and shear forces across a sliding surface to provide restraining forces into an unstable soil mass. Brown and Loehr, (2007) document a rational but simple method to compute mobilized axial and shear forces across a failure surface and incorporate these into a limit equilibrium approach for estimating the contribution of micropiles to stability. This methodology is compared with measurements from the few available instrumented case histories in a research report sponsored by the aforementioned joint DFI/ADSC micropile committee (Loehr and Brown, 2008). One such example is the slide on U.S. 43 near Littleville, Alabama (Brown and Chancellor, 1997) which includes measurements of bending and axial forces in the micropiles. These piles were installed through a guide wall as shown in Figure 5 in an "A" configuration through fill and colluvium to restrain a soil mass sliding atop a weathered shale. The measurements documented the behavior of the piles to provide combined shear and axial tension or compression to restrain the failure, and this approach has now been employed on a number of slide repair projects across North America, e.g. Hasenkamp and Turner (2000).

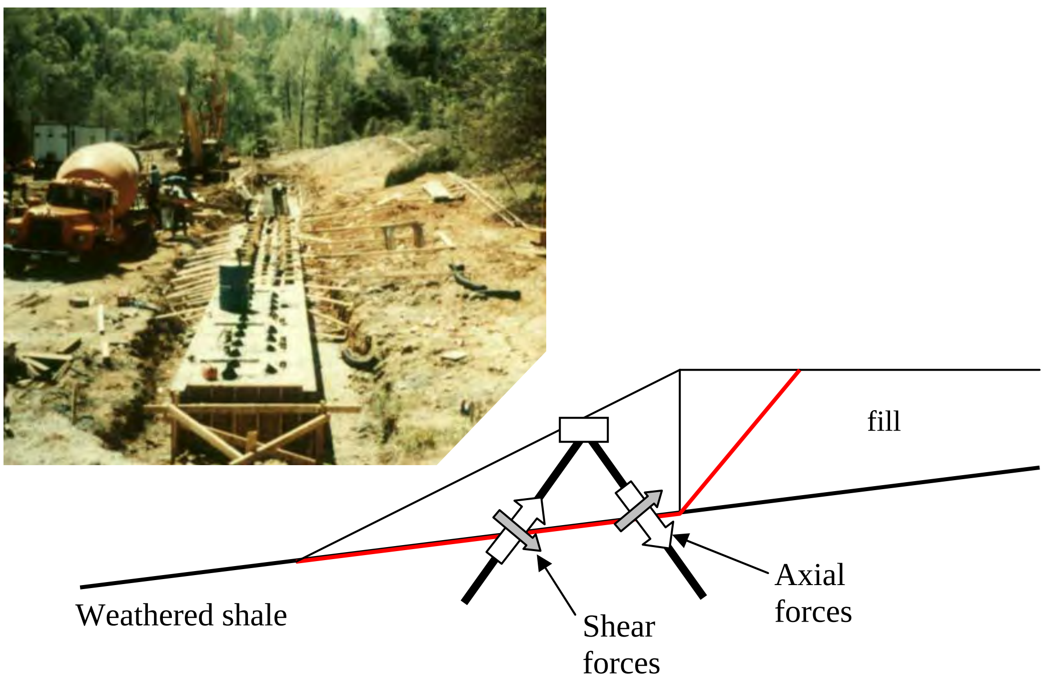


Figure 5 Micropile Slide Repair at Littleville, Alabama

Advancements in Micropile Drilling

Advancements in drilling technology and increases in load carrying capacity have been significant. The standardization of the flush joint threaded casing commonly used with micropiles has improved cost-effectiveness and the reliability of the flexural strength and structural performance of micropiles. Other advances and efficiencies are related to the combined use of the pile element as part of the drilling tool, for example with hollow bars or sacrificial drill pipe.

An example of innovation in drilling and grouting is illustrated in Figure 6 by the use of grout placement through a reverse circulation percussion drill tool, described by Atlaee et al (2010) for the construction of the micropiles for the Bronx-Whitestone Bridge in New York. The 35 cm (14 inch) diameter micropile foundations for the replacement of the Bronx approach structure for this bridge were constructed to bear in gneiss bedrock beneath overburden soils ranging from soft silts and peat to dense sand and glacial till including boulders. The reverse circulation percussion drilled flushed cuttings up through the drill rods and through the swivel atop the rods and into a discharge hose. Upon completion of drilling, grout was pumped down through the drill rods as the drill was extracted from the hole. The single #18 GR75 bar was installed into the grout-filled hole after the drill rods were removed. This innovative approach allowed the contractor to advance the drill rods to the bottom of the hole through the wide range of materials without the necessity to stop and replace tooling, and then accomplish the grouting without withdrawal of the drilling tools.

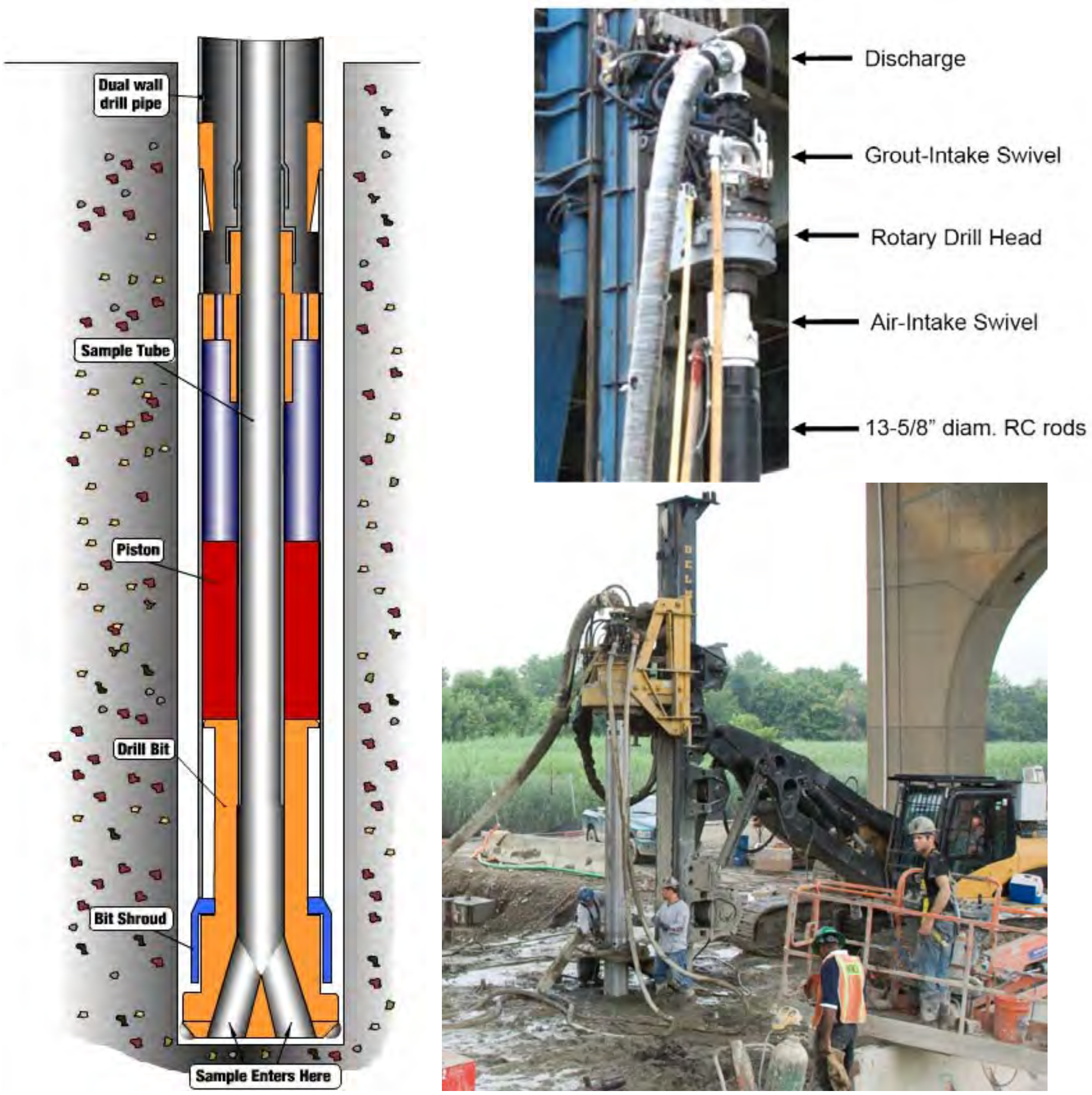


Figure 6 Hammer Grout Piles at the Bronx Whitestone Bridge

Another example of innovation in drilling and grouting is described by Szynakiewicz and Boehm (2008), whereby an office building in Houston, Texas was underpinned using micropile construction. The site of the project was composed of highly plastic clay soils, ground conditions that are generally not favorable to micropiles because of the low bond strength. However, the need for underpinning in a low headroom environment was most conducive to the small, versatile equipment used to install these piles. The underpinning was completed while the building remained occupied by constructing jet-grout columns within the deeper and more stable soils, and then installing micropiles into the jet-grout columns to provide load transfer from the building into the column. Low headroom drills were used for construction of both the columns and the micropiles. Load testing confirmed the load capacity of this hybrid pile, which transfers load from the micropile into the jet-grout column and then from the column into the clay soil.

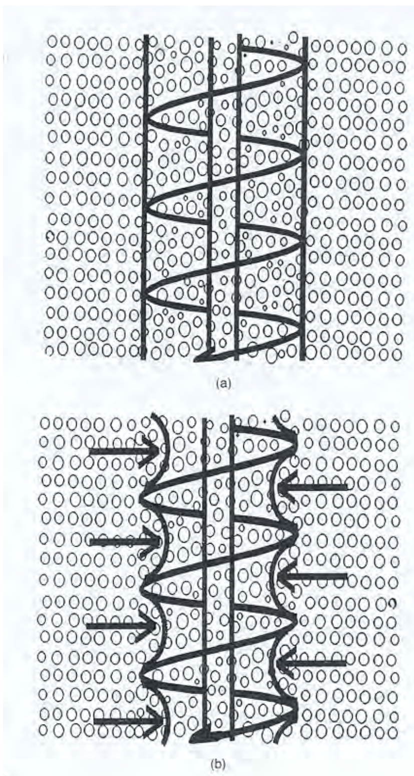
CONTINUOUS FLIGHT AUGER (CFA) PILES

The use of continuous flight auger piles or "ACIP" piles has been commonly performed in the U.S. since the 1970's, mostly using crane attached drills with a top-drive gearbox. Current practice includes the widespread use of this type of equipment as well as the adoption of many European practices. The current practices for design and construction of CFA and Drilled Displacement Piles in the U.S. is described in an FHWA reference manual by Brown, et al (2007).

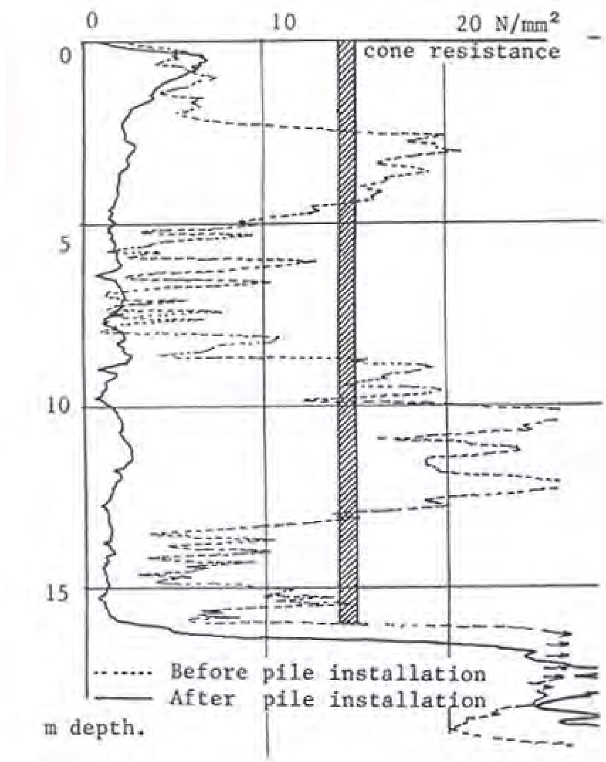
The major advancements in the last 20 years have resulted primarily from two broad areas: 1) electronic controls for monitoring and guiding the drilling and casting process, and 2) more powerful drilling equipment with improved capabilities. The use of electronic monitoring equipment provides the drill operator with the feedback needed to ensure that each pile is constructed in a reliable and repeatable way, and the measurements provide the verification that the pile has been constructed properly. The use of more powerful fixed mast hydraulic-powered rigs provides greater torque and crowd or lifting capacity on the drill tooling, and promoted the use of larger diameter CFA piles.

Control of Drilling Process

The first key component is the control of the drilling process, in which the continuous flight auger drill must be advanced at the optimum rate. The drill is typically rotated at a constant rate and if the drill is allowed or forced to penetrate too quickly it can corkscrew into the soil and become "hung", i.e., the torque required to continue advancing exceeds the torque capacity of the rig. For this reason, the rate of advance must often be restrained to ensure that the soil is cut and loosened, but not so much that the augers are not kept charged full of soil to provide stability to the hole. The rate of advance of the drill must allow conveyance of enough material up the flights to allow for the volume of the drill itself and the bulking action of the soil as it is cut and remolded by the auger. If the soils have sufficient cohesion and/or arching action to stand vertically without the lateral support of the soil-filled auger, then the rate of penetration can be restrained to ensure easy drilling since conveyance of soils up the flights is not a significant issue. However, in loose sands below the groundwater or soft clays, excessive rotation of the drill without advancement will convey soils up the auger flights like a screw pump, the lateral stress around the pile is reduced, and the soil around the hole will side-load the auger resulting in loosening and ground subsidence around the pile. These effects have been described by Fleming (1995), and the effects on soil disturbance and pile behavior measured and described by Van Weel (1988) and Mondolini, et al (2002) (Figure 7). Observations of ground subsidence around CFA pile construction in sands and soft soils have been noted on numerous projects, for example as described by Esrig, et al (1994).



a) Side loading the auger due to excessive rotation (from Fleming, 1995)



b) Effect of soil loosening due to excessive rotation of CFA measured by CPT (from Van Weel, 1988)

Figure 7 Effects of Excessive Rotation of CFA Auger

Control of the Casting Process

The second key component in the construction of CFA piling is the control of the withdrawal of the auger during concrete or grout placement, and the need to synchronize this process with pumping so that:

a) positive pumping pressure is maintained at the point of discharge at the bottom of the augers,
b) a structural defect or neck in the pile does not result from pulling the auger string too fast, and
c) wasteful pumping of excess concrete or grout does not occur, particularly in soft soils where overconsumption would provide little or no benefit.

Automated Monitoring and Controls

Through much of the history of the use of CFA piles, the skill of an experienced drill rig operator has been recognized as a critical component, because the “feel” of the operator was always so important to both advance the drill effectively and withdraw the drill during concreting in the correct way. The use of modern electronic controls, shown in the photos of Figure 8, provides the operator with direct feedback measurements on the critical parameters and also the ability to document that the pile has been constructed in accordance with good practices. Many of today’s rig operators, having grown up playing electronic games, are quite comfortable operating a joystick and using a graphical electronic display. For the constructor, the monitoring can also provide a measure of productivity, since some systems provide a minute-by-minute log of the activity of the drill rig. Equipment maintenance requirements represent another common function that may be included as a part of the on-board computer system.

a) Controls on a hydraulic system **b) Controls on a crane-mounted rig**

Figure 8 Automated Monitoring Systems in Use with CFA Pile Construction

The most important control parameters include the rate of penetration and sometimes the applied torque and crowd (down force) on the tools, rotation rate, the concrete or grout pressures, and the volume of concrete or grout pumped as a function of the elevation of the auger tip and the theoretical volume required to that point. When these parameters are calibrated to site-specific load testing, the use of automated monitoring provides a high level of quality control and quality assurance. The monitored parameters are recorded and documented in a production log that provides a record of the successful completion of each pile.

Although not yet common in North American practice, there are available capabilities for the on-board computer to take over the casting process, automatically matching the rate of withdrawal of the auger to the rate of delivery of grout as measured through an in-line flowmeter while maintaining a specified delivery pressure in the pump line at the top of the auger string.

DRILLED DISPLACEMENT PILES

The use of more powerful fixed mast hydraulic-powered rigs provides greater torque and crowd on the drill, and promoted the use of drilled displacement piles. The drill tooling for these piles includes a feature that displaces rather than extracts the soil, as illustrated by a few of the different types of tools in use in the photos of Figure 9. These tools are characterized by a displacing body which is typically around 1.5 to 2 m (5 to 7ft) above the tip of the auger, with sometimes occasional reverse flights at various intervals above the displacing body. The short length of auger below the displacing body helps advance the tool by screwing into the soil below the displacing body and pulling it downward. Various types of cutting shoes on the bottom may be employed, depending on the type of soil to be penetrated. The photo on the left is from the construction of the Georgia Aquarium in Atlanta and shows a tool extracted from the soil upon completion of casting. The lack of spoils associated with the construction of this pile points to one of the advantages of this technique, i.e., spoil removal and the mess associated with CFA piles is avoided.

Figure 9 Drilled Displacement Tools

The torque and crowd required to construct a drilled displacement pile is substantial, and the modern fixed-mast hydraulic drill rigs are typically used for these piles. Because the pile fully displaces the soil, there are no issues related to over-rotation of the auger and potential loosening of the soil as described for CFA pile construction. The energy required to install the pile is related to the resistance of the soil to the displacement, and so the piles are often installed to a depth that is controlled by the capabilities of the drilling rig. The potential effect of lateral displacement or heaving on nearby structures may also be a consideration.

With the monitoring equipment capabilities described previously for CFA piles, it stands to reason that the measure of torque and crowd as a function of penetration might logically be related to the axial resistance of the completed pile in a manner similar to a CPT sounding. Variations in stratigraphy are readily detected, i.e., the penetration into a denser stratum is immediately evident by the measured torque and crowd required to maintain penetration. Although a broad methodology is not yet in widespread use, work is ongoing to develop site-specific correlations between "installation effort" (NeSmith and NeSmith, 2009) and load test results. Each individual drilled displacement pile is then installed to achieve a specific criterion based on the measurements of torque and crowd using the automated monitoring system. These advances offer improved efficiency as well as quality control and quality assurance.

Another advantage of the drilled displacement pile is the ground improvement that is naturally accomplished as the displacement tool densifies cohesionless soils and increases the in-situ stresses in the ground. In this way, the construction of multiple displacement piles in a group actually enhances the capacity of nearby piles, as demonstrated by Brown and Drew (2000). The ground improvement associated with the installation of displacement piles has been demonstrated by CPT soundings before and after installation, reported by Siegel, et al (2007) for a number of sites composed of sandy soils. Examples of these data are provided on Figure 10.

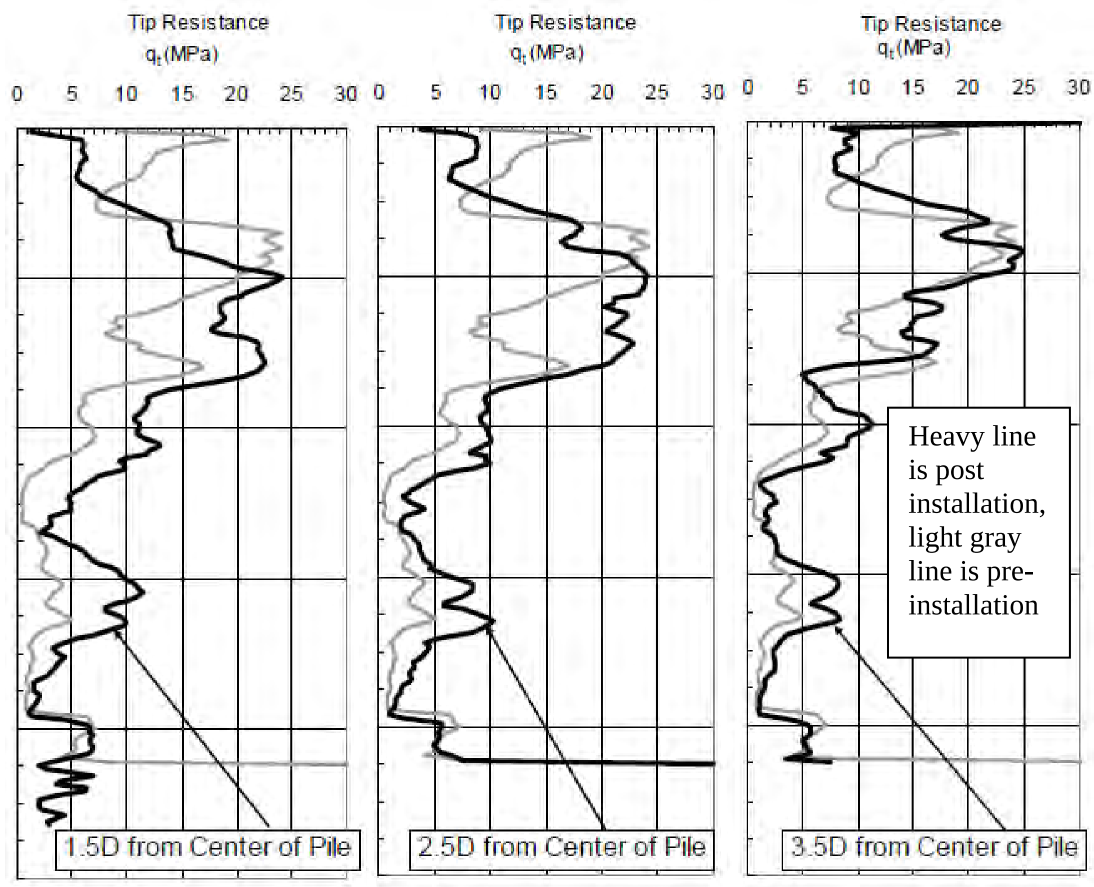


Figure 10 Effect of Drilled Displacement Pile Installation on Cone Tip Resistance in a Sandy Soil (from Siegel et al, 2007)

As a result of the ground improvement benefits with drilled displacement pile equipment, these piles are popular for construction of pile raft foundations. The delineation between what is to be called a "pile" as opposed to a "rigid inclusion" or "column" in terms of ground improvement technology has become obscured and the terminology used may often reflect the design approach with respect to building code requirements. When used primarily as a ground improvement technique, the structure may in fact be designed to bear on spread footings that are not connected to the installed pile elements (or columns, since they are not really used as piles), and the columns may even be constructed of lower strength, unreinforced concrete.

An example of the use of drilled displacement pile construction techniques to achieve ground improvement is described by Siegel and NeSmith (2011) for a site composed of loose silty sand for a hospital in Kentucky. The technique was used to provide liquefaction mitigation and to increase subgrade stiffness so that the structure was founded on shallow footings bearing on the composite ground. The project included load tests on 3 m by 3m (10 ft by 10 ft) test foundations to applied bearing pressures of 335 kPa (7 ksf) to verify the performance. Photos of the footing construction and testing are shown on Figure 11, along with a plot of the results of the three load tests. The three tests were performed on nearly identical column layout in three different areas of the site. Instrumentation on the columns and on the subgrade between columns suggests that at the maximum bearing pressure the load was distributed about 40% to the columns and about 60% to the soil subgrade directly beneath the footing.

Figure 11 Load Tests of Drilled Displacement Columns Supporting a Conventional Spread Foundation

DRILLED SHAFTS

The major advancements in the use of drilled shaft foundations come from improvements in equipment and construction methods and improvements in testing and verification of performance. Drilled shafts can now be used with greater diameters and depths than ever before, a trend which opens opportunities for applications for foundation and geotechnical engineers to employ drilled shafts in new and creative ways. Methods of construction such as the use of base grouting and the use of polymer drilling fluids have been shown to provide improvements in performance of drilled shafts. Testing technology has also evolved to a point of routine use for verification of structural integrity and measurement of axial and lateral resistance to extremely large loads. Current practices for construction, design, and testing of drilled shaft foundations are provided by Brown, et al (2010).

Equipment for Larger and Deeper Drilled Shafts

The drilled shaft construction industry has evolved from a relatively small group of subcontractors to a much broader industry with a wide array of specialized equipment used for construction. Although it is still largely a craft performed by specialty subcontractors, a larger number of general contractors are self-performing this work and many subcontractors are concentrating on specialized types of drilled shaft and other specialty drilled construction techniques. The increased availability of specialized equipment which is focused on a particular construction technique contributes to this trend. On large or complex projects, drilled shafts have been employed with diameters of up to 4 m (13 ft) and depths of up to 80 m (260 ft).

One trend in recent years is a much increased use of oscillator or rotator equipment to install full length segmental casing. This type of equipment has been used to construct drilled shafts with diameter of up to 3.6 m (12 ft), and offers particular advantages in potentially caving ground conditions. The machines use hydraulic-powered jaws to clamp onto and twist the casing, and also pull or push the casing in the vertical direction. The oscillator machines twist the casing back and forth through a range of about 25° whereas the rotator provides the ability to twist the casing continuously through 360° and effectively use the casing as a full length coring tool. Photos of oscillator and rotator machines are provided in Figure 12.

One of the advantages of these machines is that drilled shafts can be installed in caving ground conditions with improved ability to stabilize the hole during excavation and concrete placement. The Benetia-Martinez bridge in the San Francisco Bay area is an example of a project with very challenging ground conditions composed of steeply bedded siltstone and shale with interbedded layers of soft and hard rock. After great difficulties with open hole drilling into this formation, the project was successfully completed using the rotator equipment shown in Figure 12b. The rock was removed from within the casing using a drop chisel to break the rock and a hammer-grab to extract it.

The installation of the casing by twisting it into place allows the casing to advance ahead of the excavation without the vibrations associated with the use of a vibratory hammer. Therefore the system allows installation of large diameter drilled shaft foundations in close proximity to existing structures with minimal risk of impact on the existing structure. Oscillator equipment was used to install 3.6 m (12ft) diameter drilled shafts for the Gilmerton Bridge in Chesapeake, Virginia in close proximity to two bascule bridges that remained operational during construction. The lack of vibrations adjacent to the drilled shaft construction was a primary feature in the selection of this method, and the use of large diameter drilled shafts minimized the size of the foundation footprint under each individual column for the new structure. Similar very large oscillator-installed drilled shafts were used on the Doyle Drive approach structures to the Golden Gate Bridge in San Francisco (Faust, 2011).

a) Drill-Mounted Oscillator **b) Rotator Attached to Crane**

Figure 12 Oscillator and Rotator Machines

The presence of a fully cased hole also provides a reduced risk of soil caving during concrete placement, and therefore improved reliability for construction in applications such as bridge foundations where flexural demands require the use of large diameter drilled shafts. Where artesian groundwater conditions are present, the casing can be readily maintained at an elevation well above the ground surface to provide sufficient head within the shaft excavation to counterbalance the artesian condition.

Katzenbach, et al (2007) reviewed available load test information on drilled shafts constructed using the oscillator and rotator segmental casing method and report that the results are comparable and in some cases favorable to other installation techniques. One factor that favors the performance of drilled shafts constructed using this method is the fact that the teeth that are used on the cutting shoe at the bottom of the casing tend to produce a roughened surface at the concrete/soil interface as the casing is extracted. An opportunity to examine the surface of drilled shafts constructed using this construction method was provided recently at the Huey Long Bridge in New Orleans (Brown et al, 2010). The 2.8 m (9 ft) diameter drilled shafts were exposed within the sheet pile cofferdam after placement of the seal slab and during construction of the footing. These foundations were constructed prior to excavation of the cofferdam, with a corrugated metal pipe used as a temporary form above the top of the drilled shafts. The photo in Figure 13 shows the herringbone pattern left at the surface of the drilled shaft concrete due to the action of the teeth on the soil as the casing is extracted.

Another advantage is the control on verticality provided by the increased stiffness of the drilling system. While verticality is not often a critical factor for foundations, this aspect is important for applications in which drilled shafts are used near underground structures or to construct secant or tangent pile walls. Typical specifications for verticality of drilled shaft foundations using conventional construction techniques are 1.5% in soil and 2% in rock (Brown, et al, 2010). However, recent experiences in a test installation for the TransBay Terminal in San Francisco suggest that oscillator/rotator equipment is capable of maintaining verticality on the order of 0.35% to 0.5% for foundations as deep as 73 m (240 ft).

Figure 13 Exposed Texture on the Drilled Shaft Surface, Huey P. Long Bridge

Reverse-circulation drilling is another technique that has been increasingly used in recent years to construct drilled shafts to large diameters and depths. This drilling technique provides full face rotary cutting at the base of the excavation with the drilling fluid used to remove cuttings via air-lift pumping up through the center of the drill pipe. This closed system avoids the need to cycle in and out of the hole to remove cuttings from an auger and can also be very effective in excavating rock.

The photos on Figure 14 illustrate the equipment used with this technique. The system in Figure 14a is mounted onto a casing that was installed with a rotator, and is working in the space beneath an existing bridge on I-90 in Connecticut to install 2.8 m (9 ft) diameter drilled shaft foundations into the bedrock for the replacement bridge structure prior to demolition of the old one. The drill removes the cuttings by pumping the cuttings and fluid up through the center drill pipe, through the swivel at the top, and on to a spoil container via the discharge hose in the foreground. Drilling fluid is simultaneously pumped into the top of the excavation through a return line. An example of a full face rotary cutting tool is shown in Figure 14b. This tool was used on the Walter F. George Dam in Alabama to construct a cutoff wall into limestone. The bottom of the air-lift pipe is located slightly off-center so that this pipe moves around and suctions the cuttings across the face as the tool rotates.

a) Restricted Headroom Drilling **b) Full Face Drilling Tool**

Figure 14 Reverse Circulation Drilling

The Wolf Creek Dam project in Kentucky is an example of the advancement of drilled shaft equipment and technology to overcome challenges in a way that was not possible years ago. Seepage through the underlying limestone bedrock below has threatened the stability of the earth dam that retains Lake Cumberland, the largest reservoir east of the Mississippi. A previous cutoff wall had been constructed into the bedrock in the late 1970's using the best available technology at that time, and the seepage problem was not successfully resolved by that effort. Seepage has found new paths under and around the wall, leading to sinkholes and soft wet areas downstream as well as high measured pore water pressures in the embankment. The Wolf Creek Dam was in critical need of remediation to correct the problem.

The key component of the repair to the dam is the construction of a secant pile cutoff wall, and the construction of this wall utilizes reverse circulation drilling to construct drilled shafts to very great depths. After lowering the reservoir and completing an initial grouting program, the cutoff wall is constructed through the dam from a bench on the upstream face, as shown in the photo of Figure 15.

First, a 1.8 m (6 ft) wide concrete diaphragm wall is constructed through the embankment to the top of rock at a depth of around 25 to 30 m (80 to 100 ft). The secant pile wall is then constructed to depths of up to 84 m (275 ft) through the concrete diaphragm wall and the karstic limestone and into a sound limestone layer. The secant pile excavation is started using conventional drills with rock augers to open a hole to a depth of around 15 m (50 ft) into the diaphragm wall, and then completed using reverse circulation drilling as illustrated in the photos of Figure 16.

In order to maintain the alignment on such deep drilled shafts and ensure that the secant piles overlap to form a water-tight cutoff wall, a pilot hole is first installed using directional drilling techniques. The reverse circulation drill is equipped with a "stinger" to follow the pilot hole and maintain the alignment during drilling.

Construction of the cutoff wall is ongoing, with anticipated completion in 2013.

Figure 15 Work Platform at Wolf Creek Dam

Figure 15 Reverse Circulation Drilling for Secant Pile Cutoff Wall

Base Grouting

Base grouting to enhance the axial resistance of drilled shaft foundations is a technology that has been around for decades, but research in Tampa by Mullins et al (2000) has spawned a renewed interest in this technology in North American practice. Base grouting is a form of compaction grouting at the toe of a drilled shaft which compresses and preloads the soil below the toe, increases the state of stress in the ground, and can significantly increase the axial base resistance of drilled shafts which are founded in granular soils (Mullins, et al, 2006). There is also benefit from base grouting in that the grouting mitigates the effect of any loose granular material which might remain as a result of imperfect cleaning of the base of the drilled shaft excavation. The technique provides relatively little benefit in rock, cohesive soils, or strongly cemented materials. Another limitation to the improvements achieved with base grouting is that the available side resistance of the drilled shaft limits the magnitude of the pressure which can be applied.

The photos in Figure 16 illustrate some aspects of base grouting. Figure 16a) shows a typical base grouting apparatus attached to the base of the reinforcement cage. The photo in Figure 16b) shows a 1 m (3.5 ft) diameter and 8 m (25 ft) long drilled shaft at the Auburn University National Geotechnical Experimentation Site. This shaft was base grouted and subsequently exhumed to reveal the effects of base grouting in a very silty and medium dense soil. A relatively large volume of approximately 0.3 m^3 (10 ft^3) of grout was injected at the base of this shaft, representing a volume equal to about 30 cm (1 ft) length of shaft. The grout can be seen to have produced a bulge at the base and also to have migrated up along the side wall of the drilled shaft over the lower one to two diameters. The drilled shaft in the background of this photo was not base grouted.

a) Sleeve Port System for Grouting **b) Exhumed Base-Grouted Shaft**

Figure 16 Base Grouting for Drilled Shaft Foundations

An example of the use of this technique on a major project is described by Dapp and Brown (2010) for the John James Audubon Bridge over the Mississippi River in Louisiana, which utilized drilled shafts founded in dense alluvial sand. Each of the two pylon foundations for the cable-stayed bridge included 21 drilled shafts which were 2.3 m (7.5 ft) diameter and approximately 60 m (200 ft) deep. The base grouting was accomplished via a sleeve-port system (tubes-a-manchette) that utilized the crosshole sonic logging tubes. The eight tubes were connected in pairs across the base of the drilled shaft to form four separate U-shaped circuits, as shown in the photo of Figure 16a).

The project included load tests using the Osterberg cell (O-cell) at the base of both grouted and ungrouted drilled shafts to provide a comparison of performance for full scale foundations. The data provided in Figure 17 illustrates the improvement in base resistance achieved by base grouting to a pressure of approximately 5 MPa (750 psi). The data shown are measured load at the base of the drilled shaft from base grouted shafts except the curve test T3. Shaft T3 was constructed in an identical way to the others but was not grouted and did not include the base grouting system.

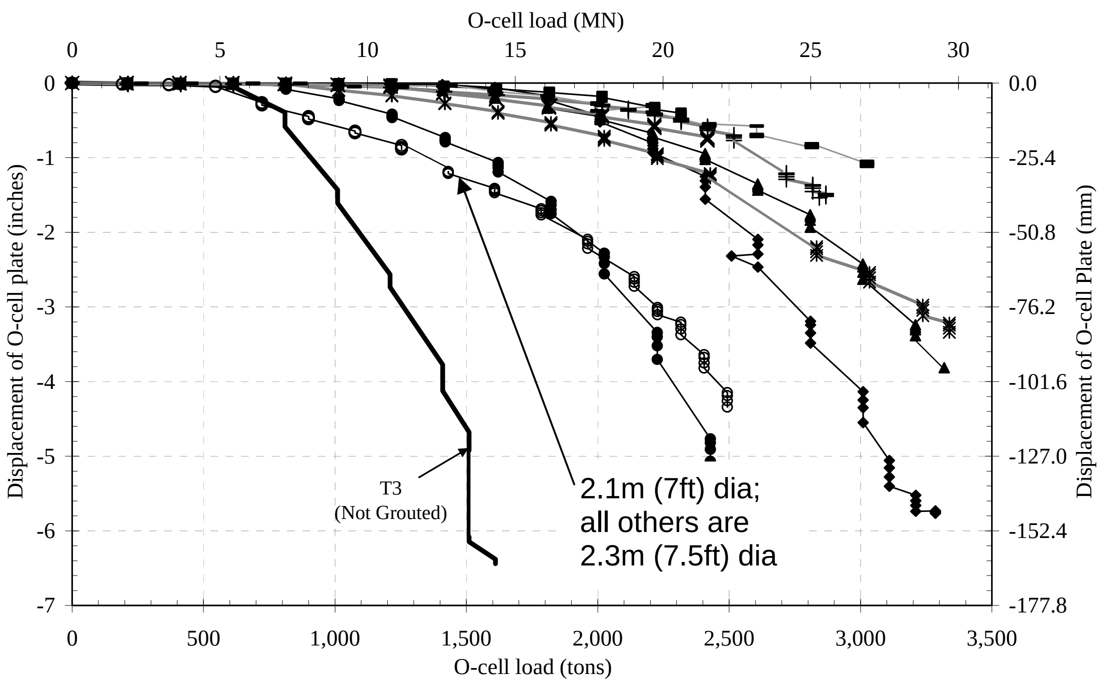
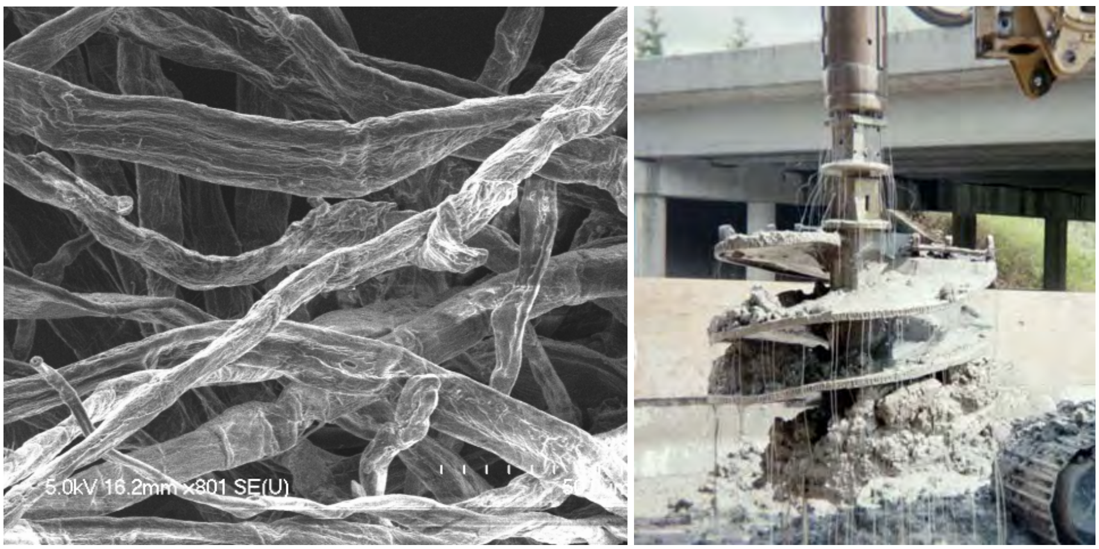


Figure 17 Measured Base Resistance from the Base-Grouted Drilled Shafts at the John James Audubon Bridge, Louisiana

Polymer Drilling Slurry

Although the versatility of drilled shaft construction emerged using mineral slurry (mostly bentonite) for drilling fluids, in recent years the use of polymer-based drilling fluids has become the prevalent practice where wet-hole techniques are used for construction. Polymers have several advantages over conventional bentonite for constructors, because it is more easily mixed, de-sanded, and disposed. The long-chain polymers (shown in Figure 18) mix easily with water and increase the viscosity of the fluid, and increased viscosity reduces the fluid loss into the surrounding soil and provides a stabilizing fluid pressure when a positive head is maintained within the drilled shaft excavation.

Unlike bentonite, polymers do not create a filter cake on the borehole wall, and therefore fluid loss tends to be a greater than with bentonite slurry. Also, the density of polymer slurry tends to be lower than bentonite fluids, and cannot be easily increased as with the addition of barite to bentonite fluids. In coarse or gravelly sand or areas with very high or artesian groundwater levels, these aspects may result in less effective performance with respect to borehole stability. If the fluid head in the shaft excavation is not actively maintained at a level higher than the groundwater level, the fluid level in the excavation will eventually fall and the supporting pressure may be lost. On the other hand, the lack of a filter cake mitigates one of the major design concerns associated with the use of bentonite slurry for drilled shaft construction, namely that excessive filter cake buildup will be detrimental to the bond at the soil/concrete interface and therefore reduce the available side resistance of the foundation.



a) Scanning Electron Micrograph, 800x **b) Polymer Slurry in Use**

Figure 18 Polymer Drilling Fluids (photo at left courtesy of Likos, Loehr, and Akunuri, Univ. of Missouri)

Specifications for polymer slurry construction often have evolved from those used for bentonite, but the differences in performance of polymers require several modifications. Experiences with polymer slurry construction indicate that designers should be aware of several factors that affect practice.

The upper limits on viscosity used for bentonite are too restrictive for polymer; there is a need to limit the viscosity of bentonite to avoid excessive filter cake buildup, but polymers can utilize significantly higher viscosity in order to provide effective stabilization.

Unlike bentonite slurry, the density of polymer slurry will not be much higher than that of water, and so where groundwater levels are very near the top of the drilled shaft it is critical that a positive head of 2 m or more is maintained at all times. Where groundwater levels are near or above the ground surface, it will be necessary that the contractor extend the casing above grade to provide this head, plus additional distance to allow for fluctuations and working freeboard within the casing.

Because there is no bentonite filter cake, it is not necessary to limit the exposure time of the soil to slurry and/or require agitation of the sidewall. There is also substantial evidence that drilled shafts constructed using polymer slurry result in higher values of unit side resistance in sands and silts than similar foundations constructed using bentonite (Brown et al, 2002; Brown, 2002; Meyers, 1996).

Even where natural clays or shales are encountered in the soil, the polymers as shown in Figure 18b tend to stabilize these soils and prevent mixing of the clay with the drilling fluid. Many contractors like to employ a small amount of polymer slurry when drilling through clay because it reduces the tendency for clay to stick to the auger. There is also evidence that polymer drilling fluids may reduce wetting of some shales and thereby reduce the tendency for degradation of shale when the excavation is open. This behavior can result in improved side resistance for drilled shafts socketed into shale, especially for large drilled shafts where several days may be required to complete construction.

Axtell et al (2009) describe a case history for a bridge project in Kansas City where 3.2 m (10.5 ft) diameter rock sockets were constructed into a shale, and even though the polymer slurry filled hole was open for four days, load test measurements determined that the unit side resistance in the socket was a relatively favorable value 720 kPa (15 ksf). The polymer slurry was perceived to provide benefits with respect to preserving the integrity of the shale and was used for construction even though casing extended to the rock and slurry was not required to stabilize the hole. Slake durability tests of the shale with both river water and polymer slurry are summarized in Table 1. The higher slake durability index and durability rating of the rock specimens tested in polymer slurry indicates that the shale was subject to less significant degradation in the presence of polymer slurry compared to that observed when the rock was exposed to plain river water.

Table 1: Slake Durability Test Results.

Sample	Natural Moisture Content	Slake Durability Index		Durability Rating Based on Shear Strength Loss	
	(%)	Type	$I_d(2)$ (%)	Type	DR_s
River Water	8.3	II	72.2	Intermediate	61.9
Polymer Slurry	8.3	II	98.2	Hard, more durable	78.6

Where fine sands and silts are present, polymer slurry can present a challenge from the standpoint of cleaning the slurry. These sands and silts will not stay in suspension and will tend to settle out slowly after completion of excavation. The de-sanding units used with bentonite slurry construction do not work with polymer because the polymer molecules would be destroyed by the shearing process in the de-sander and polymers will also tend to clog the screens. De-sanding of polymer is normally accomplished by adding flocculants to help promote the settling of solids, a process that requires that the slurry be maintained in a calm environment so that the sands can settle out. Flocculation can occur either in the borehole (followed by pumping from the base of the hole to remove solids) or in a weir tank after removal and replacement of the fluid in the hole with clean slurry. In a very deep drilled shaft excavation filled with sand-contaminated polymer, solids can rain out of suspension for days and if left untreated could result in contamination of concrete during placement. Although flocculants can be used in the borehole to accelerate the process, the most reliable approach is to fully exchange the fluid by pumping slurry from the base of the shaft to a holding tank while adding clean slurry into the top of the excavation.

Verification Testing

Only within the last 20 years has integrity testing and load testing of drilled shaft foundations become commonplace, and the availability and use of these technologies has greatly improved the efficiency of designs and the reliability of the constructed foundations.

The vast majority of integrity testing performed in North America uses crosshole sonic logging (CSL) to verify the integrity of the concrete within the drilled shaft. CSL testing relies upon the measurement of compression waves between pairs of tubes that are typically attached to the reinforcement. The tubes are filled with water so that acoustic transponders and receivers can be used to perform measurements through the water, tube, and concrete between tube pairs at intervals of every few inches. By using multiple tubes, measurements can be performed at various angles and directions across the drilled shaft diameter and around the perimeter. There is some use of gamma-gamma testing (largely by Caltrans) to measure density of the concrete in the vicinity around embedded PVC tubes, although CSL testing is used as a backup if anomalies are detected. Recently, a promising new method called Thermal Integrity Profiling has been developed by Mullins (2010) based on thermal measurements; the heat of hydration is measured via downhole tubes and correlated with the presence of good concrete. This thermal technique offers the promise to verify integrity before the concrete has fully hardened.

CSL testing and other measures of integrity testing through downhole access tubes offer the potential to detect even relatively minor inclusions of soil, laitance, low strength concrete, or other deleterious material. Besides improving the reliability of the constructed foundation, the accountability provided by these test measurements provide quantifiable verification of an effective contractor’s work plan and quality control for concrete placement. Effective construction methods are apparent because of the successful integrity test measurements; ineffective methods or poor controls are quickly detected. This accountability has had the effect of significantly improving the quality of construction on public works projects where CSL testing is routinely employed.

On the other hand, there is a distinct need for engineers and designers to recognize that perfection is not achievable in this challenging construction environment, and that drilled shaft designs should be relatively tolerant of minor imperfections. An example is illustrated in Figure 19 from an experimental drilled shaft at Lumber River, SC that was exhumed as a part of research (Brown et al, 2005). The source of an anomaly in the CSL measurement was exposed when the exhumed shaft was saw-cut at precisely the elevation revealed by the anomaly. The flaw was a small pocket of segregated concrete that was lodged against the CSL tube and was approximately the size of a tennis ball.

An imperfection detected as a result of integrity testing does not necessarily constitute a deficiency in the drilled shaft. The size of the flaw exposed in Figure 19 should not be of serious concern because the structural design of the drilled shaft must include adequate tolerance for such small imperfections. The magnitude of a potential flaw detected by CSL tests can usually be quantified by close examination of various signal paths across the cross section of the shaft and even by using tomography techniques if needed. If a potential imperfection is detected it may be at a location where the drilled shaft is not subject to the maximum flexural demands, and so a greater tolerance may exist. An engineering evaluation of the structural and geotechnical performance requirements at the elevation in question is required to determine if a deficiency exists in a drilled shaft with an imperfection.

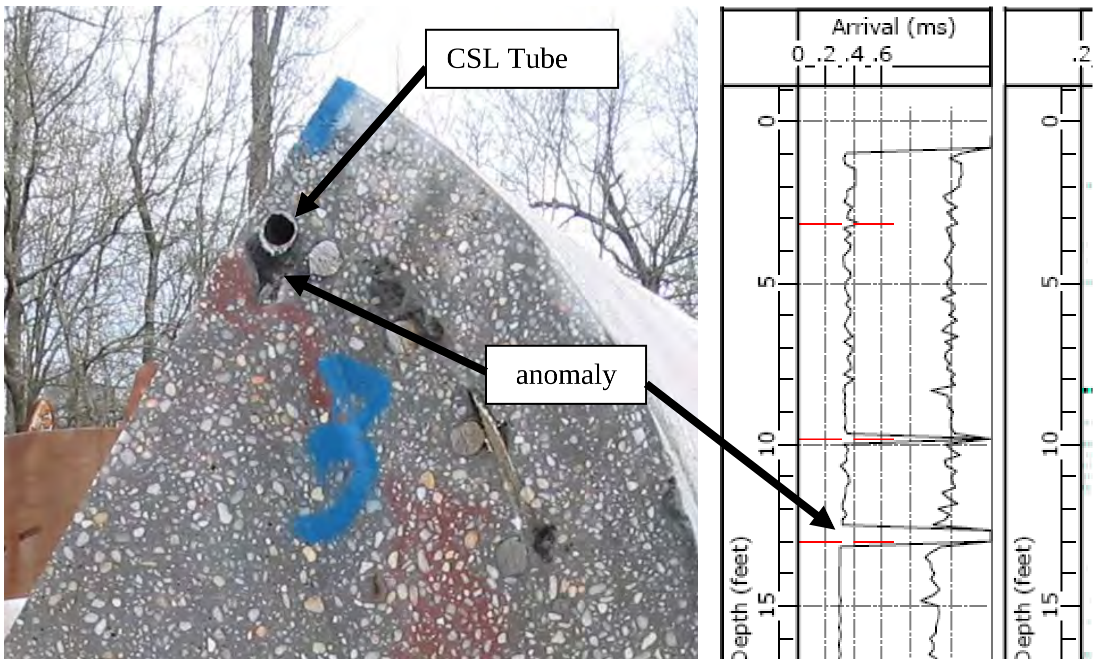


Figure 19 Exposure of an Imperfection and CSL Anomaly

Another consideration is that sometimes an anomaly in the signal occurs as a result of non-uniform concrete curing, tube debonding, or other artifacts of the test measurements. For these reasons, an anomaly in the integrity test measurement should typically be verified with coring or other means before expensive corrective action is warranted. An independent evaluation of the anomaly may be necessary to determine if a real imperfection exists and if any such imperfection is sufficient to constitute a deficiency.

The majority of load testing performed on drilled shafts in North America utilizes bi-directional embedded loading jacks, also known as the Osterberg Cell® (O-cell). The O-cell is embedded within the drilled shaft to engage the portion above the cell as a reaction against the portion of the shaft below the cell, with measured pressure in the cell calibrated to load and independent measurements of displacement of the two separate portions of the drilled shaft. This load testing technology has allowed the measurement of extremely large axial resistance because of the inherent simplicity in the test and the lack of need for a reaction system.

Conventional static top down load tests are still occasionally used with drilled shafts, and load tests of up to 50 MN (11,000 kips) have been performed with static reaction systems. Other advancements with drilled shaft load testing include the use of rapid load testing and high strain dynamic testing with signal matching, as would be performed on a driven pile. The rapid load testing method is most often employed using the Statnamic® device, which launches a reaction mass upward with about 20g of acceleration resulting in a downward thrust onto the drilled shaft. This test method offers a relatively economical means of verifying axial resistance from the top down without the need for a reaction system, and can often be performed on production foundations. The equipment available to perform rapid load testing is currently limited to a maximum applied force of around 45 MN (10,000 kips), and the maximum static resistance which can be mobilized is slightly lower due to inertial and rate-of-load effects.

The major implications of the advancements in testing for high capacity drilled shaft foundations are:

- Designers now have the means to obtain measurements that will provide the feedback necessary to improve design practices.
- Alternative forms of project delivery such as design-build can now include performance measurements for verification, and the availability of such testing can allow for performance-based specifications to be employed in the design-build process.

An example of the use of load testing for verification in design-build is the Honolulu Transit project currently under construction. The first phase of this project includes approximately 10 km (6 miles) of elevated guideway to be constructed in a tight space within existing right-of-way. A single drilled shaft foundation at each pier provides maximum support in the minimum footprint. Eight load tests using the O-cell method have been performed along the alignment in order to evaluate both the range of ground conditions encountered and the range of construction methods used.

Another example is provided by the New Mississippi River Bridge project in St. Louis, where load tests were used to verify a contractor-proposed “alternative technical concept” or ATC (Brown et al, 2011). This project utilized a conventional bid-build contract, but bidders were encouraged to submit confidential ATC’s for review and possible approval during the pre-bid period. A bidder with an approved ATC could bid the project including the ATC in lieu of the base design for that portion of the work. The winning bidder submitted an alternative foundation design which included heavily loaded drilled shaft foundations and a plan for load testing to verify the axial resistance. The use load testing in the ATC design allowed the use of higher resistance factors in the LRFD design methodology and potential savings in foundation costs. The investment in load testing and increased performance risk to the contractor was considered as economically advantageous because of the potential savings.

Each of the two pylon foundations for this cable-stayed bridge is composed of a 2 x 3 group of drilled shafts, with permanent casing down to rock. Each shaft is supported entirely by the limestone bearing stratum through a 3.4 m (11 ft) diameter rock socket with depths into rock ranging from 5 m (16.5 ft) to 6.7 m (22 ft). The photos in Figure 20 show the excavation of the very hard limestone, which typically had compressive strength of around 140 MPa (20,000 psi), but included thin seams of weaker material. The load test successfully demonstrated a total axial resistance of 320 MN (72,000 kips), a value which exceeded the requirement for the ATC design.

Figure 20 Load Test Shaft for the Mississippi River Bridge, St. Louis

SUMMARY AND CONCLUSIONS

Today's engineers have a phenomenal variety of drilled foundation alternatives at their disposal. The tools that can be employed to solve deep foundation problems range from small diameter micropiles that can be installed in tight spaces using lightweight and portable rigs, to large diameter drilled shafts capable of supporting enormous loads. Reliability is enhanced by technology ranging from on-board rig monitoring and controls as well as post-construction integrity and load testing.

Innovative applications of micropiles have been described which exploit the capabilities of this technology, along with some new and innovative techniques for installing micropiles. The use of these drilled foundations is now becoming mainstream in North American practice, with published design guidelines by agencies such as FHWA and with micropiles now incorporated into building codes such as IBC and AASHTO.

The construction of CFA piles has matured so that these piles are recognized and more widely accepted, and the use and reliability of these economical piles is greatly improved by the use of onboard computer monitoring and control.

The advances in drilling equipment have lead to increased use of drilled displacement piles, a technology which offers advantages from the inherent ground improvement that is achieved. Displacement during drilling provides increased axial resistance and reliability in granular soils compared to CFA piles and the elimination of most excavated materials from the piling operations.

The capabilities of the equipment and methods for installing drilled shaft foundations has lead to larger and deeper drilled shafts so that effective solutions are provided for projects like the Wolf Creek Dam and the John James Audubon Bridge. Integrity and load testing provides reliability for improved design and construction as well as accountability for innovative project delivery methods such as design-build and the use of contractor-developed alternative technical concepts.

The capabilities of the equipment and drilling techniques present opportunities for engineers, as well as challenges. The opportunities are present because the work is more sophisticated than ever, and engineers who are in a position to utilize the available technology can provide value and efficiency to complex foundation engineering projects. The challenges are posed by the requirement to understand the complexities of new drilled foundation techniques and the impact of construction on the performance.

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO) (2008). "AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 4th Ed., Section 10, 'Foundations'", Washington, D.C.

Armour, T., Groneck, P., Keeley, J., and Sharma, S. (2000). "Micropile Design and Construction Guidelines Implementation Manual" Report No. FHWA-SA-97-070, June, 376 p.

Atlaee, A., Burns, A. and Shah, H. (2010). "Hammer-Grout Piles at the Bronx-Whitestone Bridge," Proceedings of the Deep Foundations Institute 35th Annual Conference, Hollywood, CA, 11p.

Axtell, P., Thompson, R., and Brown, D. 2009. "Drilled Shaft Foundations for the kciCON Missouri River Bridge." Proceedings of the Deep Foundation Inst. 34th Annual Meeting, Kansas City, 10p.

Brown, D. (2002). "The Effect of Construction on Axial Capacity of Drilled Foundations in Piedmont Soils," *J. of Geotechnical and Geoenvironmental Engineering*, 128(12), pp 967-973.

Brown, D., Axtell, P., and Kelly, J, (2011). "The Alternate Technical Concept Process for Foundations at the New Mississippi River Bridge, St. Louis," Proceedings of the Deep Foundation Institute 36th Annual Conference, Boston, pp. 169-178.

Brown, D., Bailey, J. and Schindler, A., (2005). "The Use of Self-Consolidating Concrete for Drilled Shaft Construction: Preliminary Observations from the Lumber River Bridge Field Trials," Proceedings of the GEC3 Conference, Dallas, TX, pp. 437-448.

Brown, D. and Chancellor, K. (1997). "Instrumentation, Monitoring and Analysis of the Performance of a Type-A INSERT Wall – Littleville, Alabama", Final Report RP 930-335, Highway Research Center, Auburn University, 105p.

Brown, D., Dapp, S., Thompson, R. and Lazarte, C. (2007). "Design and Construction of Continuous Flight Auger Piles," Geotechnical Engineering Circular No. 8, Federal Highway Administration Office of Technology Application, Office of Engineering/Bridge Division, 294p.

Brown, D.A. and Drew, C., (2000). "Axial Capacity of Augered Displacement Piles at Auburn University." Geotechnical Special Publication No. 100, ASCE, pp 397-403.

Brown, D., Faust, P., and Santos, J. (2010). "Construction of the Drilled Shaft Foundations for the Huey P. Long Mississippi River Bridge, New Orleans," Proceedings of the Deep Foundation Inst. 35th Annual Meeting, Hollywood, CA, 8p.

Brown, D. and Loehr, E. (2007). "A Simple Solution for Slope Stabilization Using Micropiles" Proc. of the 32nd Annual Conf. on Deep Foundations, Deep Foundations Inst. Oct., pp. 93-104.

Brown, D., Muchard, M., and Khouri, B. (2002). "The Effect of Drilling Fluid on Axial Capacity, Cape Fear River, NC." Proceedings of the Deep Foundation Inst. 27th Annual Meeting, San Diego, 5p.

Brown, D., Turner, J., and Castelli, R. (2010). "Drilled Shafts: Construction Procedures and LRFD Design Methods," FHWA/NHI Publication 10-016, Reference Manual and Participants Guide for National Highway Inst. Course 132014, 972p.

Dapp, S. and Brown, D. (2010). "Evaluation of Base Grouted Drilled Shafts at the Audubon Bridge." Geotechnical Special Publication 199, Advances in Analysis, Modeling and Design, ASCE, 10p.

Esrig, M.I., Leznicki, J.K.,and Gaibrois, R.G., (1994). "Managing the Installation of Augered Cast-in-Place Piles," Transportation Research Record 1447, Transportation Research Board, pp 27-29.

Faust, P. (2011). "Doyle Drive – Extreme Pile Installation," Proceedings of the Deep Foundation Institute 36th Annual Conference, Boston, pp. 179-188.

Fleming, W.G.K. (1995). "The understanding of continuous flight auger piling, its monitoring and control," Proceedings, Institution of Civil Engineers Geotechnical Engineering, Vol. 113, July, pp. 157 – 165. Discussion by R. Smyth-Osbourne and reply, Vol. 119, Oct., 1996, p. 237.

Hasenkamp, R.N, and Turner J.P., (2000) "Micropile and Ground Anchor Retaining Structures for Stabilization of the Blue Trail Landslide", *FHWA-WY-00/04F*, Federal Highway Administration and Wyoming Transportation Department, Cheyenne, WY, June, 97p.

International Building Code (2006). International Code Council, Inc.

Katzenbach, R., Hoffmann, H., Vogler, M., O'Neill, M. and Turner, J. (2007). "Load Transfer and Capacity of Drilled Shafts with Full-Depth Casing," Proc. of the 32nd Annual Conf. on Deep Foundations, Deep Foundations Inst. Oct., pp. 165-175.

Loehr, E. and Brown, D. 2008. "A Method for Predicting Mobilization of Resistance for Micropiles Used in Slope Stabilization Applications." Report to the joint ADSC/DFI Micropile Committee, 69p.

Mandolini, A., Ramondini, M., Russo, G., and Viggiani, C. (2002). "Full-Scale Loading Tests on Instrumented Continuous Flight Auger (CFA) Piles," Geotechnical Special Publication No. 116, Ed. by M. W. O'Neill and F. C. Townsend, American Society of Civil Engineers, February, Vol. 2, pp. 1088 - 1097.

Meyers, B (1996). "A Comparison of Two Shafts: Between Polymer and Bentonite Slurry Construction and Between Conventional and Osterberg Cell Load Testing," Paper Presented at the Southwest Regional FHWA Geotechnical Conf., Little Rock, April.

Mullins, G. (2010). "Thermal Integrity Profiling of Drilled Shafts," Journal of the Deep Foundations Institute, Vol. 4, No. 2, Dec., pp 54-64.

Mullins, G., Dapp, S., and Lai, P. (2000), "Pressure-Grouting Drilled Shaft Tips in Sand," Geotechnical Special Publication No. 100, ASCE, pp 1-17.

Mullins, A.G., Winters, D., and Dapp, S.D., (2006) "Predicting End Bearing Capacity of Post-Grouted Drilled Shaft in Cohesionless Soils" J. Geotech. and Geoenvir. Engrg., Volume 132, Issue 4, pp. 478-487.

NeSmith, W. M. and NeSmith, W.M (2009). "Advancements in Data Acquisition-Based Design for Drilled Displacement Piles." Geotechnical Special Publication No. 185, Ed. by M. Iskander, D.F. Laefer and M.H. Hussein, American Society of Civil Engineers, March, pp. 447-455.

Ryan, P. (2010). "Prototype Test Program and Monitoring During Construction of Drilled Shafts, Transbay Transit Center," Final Report from Arup, May.

Sabatini, P., Tanyu, B, Armour, T., Groneck, P, and Keeley, J. (2005). "Micropile Design and Construction" Report No. FHWA-NHI-05-039, December, 436 p.

Siegel, T.C., NeSmith, W.M., NeSmith, W.M., and Cargill, P.E. (2007). "Ground Improvement Resulting from Installation of Drilled Displacement Piles." Proceedings of the Deep Foundations Institute 32nd Annual Conference, Colorado Springs, CO, pp. 131-138.

Siegel, T.C. and NeSmith, W.M. (2011). "Confirmation of Composite Ground Design Using Field Plate Tests," Proceedings of the Deep Foundations Institute 36th Annual Conference, Boston, pp. 301-312.

Szynakiewicz, T. and Boehm, D. (2008). "Limited Access Underpinning and Re-Leveling of a Six-Story Office Building using Jet Grouted Micropiles," Proceedings of the Deep Foundations Institute 33rd Annual Conference, New York, pp. 131-142.

Van Weel, A.F. (1988). "Cast-in-situ piles – Installation methods, soil disturbance and resulting pile behaviour" *Proc., 1st Int'l Geotech Seminar on Deep Foundations on Bored and Auger Piles*, (Ghent, Belgium) Van Impe, ed, Balkema, Rotterdam, 219-226.