Quality and Quantification in Small Hole Drilling

Donald A. Bruce[1] and John P. Davis[2]

Abstract

The quality of the drilling process is fundamental to the successful and timely execution of micropile, anchor and soil nail projects. Guidelines are provided as to choice and classification of drilling systems and basic performance requirements. The use of Measurement While Drilling (MWD) principles is described as an excellent tool for enhancing the geotechnical value of every production hole in a quantitative way. The use of sonic drilling for difficult overburden drilling situations and in environmentally restrictive conditions is described.

Introduction

Micropile, anchor and soil nail works will require the drilling of holes through fill, overburden, concrete, and/or rock. Such holes may be required for purposes of exploration, verification and monitoring, as well as for structural element emplacement and grouting. Holes are typically 75 to 300 mm in diameter and are rarely more than 100 m deep. They may range in inclination from vertically upwards to vertically downwards, although most holes are within 20º of vertical and horizontal. Whereas rock and concrete masses are naturally and somewhat variable in terms of strength and structure, overburden and fill materials can pose far greater difficulties to the drilling contractor. Such materials may range from soft and loose to hard and dense, and from dry to saturated. They may contain alien and/or atypical inclusions or horizons which will be problematical to penetrate.

This natural variability in site and ground conditions will pose difficulties to the drilling contractor who will naturally want to drill the holes as quickly as possible and with the minimum possible "production" costs. In addition, specific project needs may impose significant restrictions or performance requirements. For example, the drilling of holes in urban environments is a very sensitive issue. A U.S. Army Corps of Engineers Regulation (1997) governs drilling of embankment dams and is valid for urban drilling operations also. This extremely significant document first notes that "in the past" compressed air and various drilling fluids have been used as circulating media while drilling through earth embankments and their foundations. Despite general success, there have been isolated problems resulting from pneumatic or hydraulic fracturing, and/or erosion of the fill materials during drilling. The Regulation therefore mandates the following:

1. Strong technical experience qualifications are required for all personnel involved in the design or construction of such drilling works.

[1] President, Geosystems, L.P., P.O. Box 237, Venetia, PA 15367, U.S.A., Phone: (724) 942-0570, Fax: (724) 942-1911, dabruce@geosystemsbruce.com.
[2] Zone Manager of Construction, Boart Longyear Construction Division, 626 Burns Ave., P.O. Box 15010, Cincinnati, OH 45215, U.S.A.; Phone/Fax: 513 233 7693; Email: jdavis@boartlongyear.com.

2. "Drilling in embankments or their foundations using compressed air (including air with foam) or any other gas or water as the circulating medium is prohibited."

The Regulation does permit auger drilling (without flush), cable tool (churn), or rotary drilling with "an engineered drilling fluid (or mud)." A separate appendix details acceptable practices for rotary drilling. However, for logistical, technical and/or economic reasons, this permissible array of methods may not, itself, be sufficient and in recent projects involving the drilling of tens of thousands of meters of grout holes through existing embankment dams, the rotary-sonic method has proved particularly attractive. For this reason it is discussed in a certain amount of detail below since it is directly applicable to micropile, anchor and nail drilling in many cases.

AN OVERVIEW OF DRILLING SYSTEMS, METHODS AND APPLICABILITY

Common Features

Effective drilling systems for overburden and fill must be capable of permitting continuous, acceptably straight penetration in materials which may vary from very soft to extremely hard and from homogeneous to heterogeneous. They must be capable of providing a constant diameter, stable (or temporarily stabilized) path full depth, from which the drilling debris has been wholly removed, and which is consistent with the needs of the specific operation they serve. Effective drilling systems will employ appropriate combinations of thrust, torque, rotary speed, percussive effort, and flush parameters to economically reach target depth within acceptable deviation limits. They must optimize the effectiveness of the flushing medium used. They must ideally be dictated by the ground conditions, cost notwithstanding, although historical bias and regional experience are often powerful factors. Application should determine technique, and methods should be left to the discretion of the contractor as far as possible. Methods must also satisfy project environmental restraints including noise, vibrations, and flush control and disposal. The hole must be used for its intended purpose as soon as possible after drilling to minimize any time-dependent deterioration of its walls and any opportunity for contamination. Either phenomenon may cause reinforcement installation and/or bond problems. Above all, the drilling process must not cause harm or distress to any structure being penetrated, or any adjacent structure. Within the typical range of borehole diameters used, the exact diameter selected owes most to practical issues such as the availability of equipment, dimensions of tooling, ease of flushing, packer sizes, hole stability, hole deviation, and so on.

In principle, the prime technical controls over the choice of drilling method should ideally be the ground conditions, and the hole depth and diameter. Other considerations such as hole linearity and drill access restraints may also have significant impact on choice (and cost) on any given project.

Classification of Methods

Drilling through fills or overburden can be more complex and difficult than rock drilling, and is often more controversial when consideration is given to levels of environmental acceptability. Reflecting the fundamental control exerted by the *stability* of the drilled hole (i.e., its ability to maintain shape and size without detriment to the surrounding ground after withdrawal of the drilling system), Figure 1 provides a basic selection guide to overburden drilling methodology. It must be noted that this guide relates only to routine production drilling for geotechnical construction purposes: core drilling in overburden is not viable in this context although it can be an integral part of many exploration and verification projects.

With respect to rock drilling, the following broad groups of drilling methods are observed:

- Rotary
  - High rotational speed (e.g., 600 to 1200 rpm), low thrust, low torque.
  - Low rotational speed (e.g., 50 to 600 rpm), high thrust, high torque
- Rotary Percusive
  - Top hammer.
  - Down-the-hole hammer (d.t.h.)
- Rotary Vibratory (Sonic)

Equally important in the selection of the appropriate drilling method may be one, or a combination of the following:

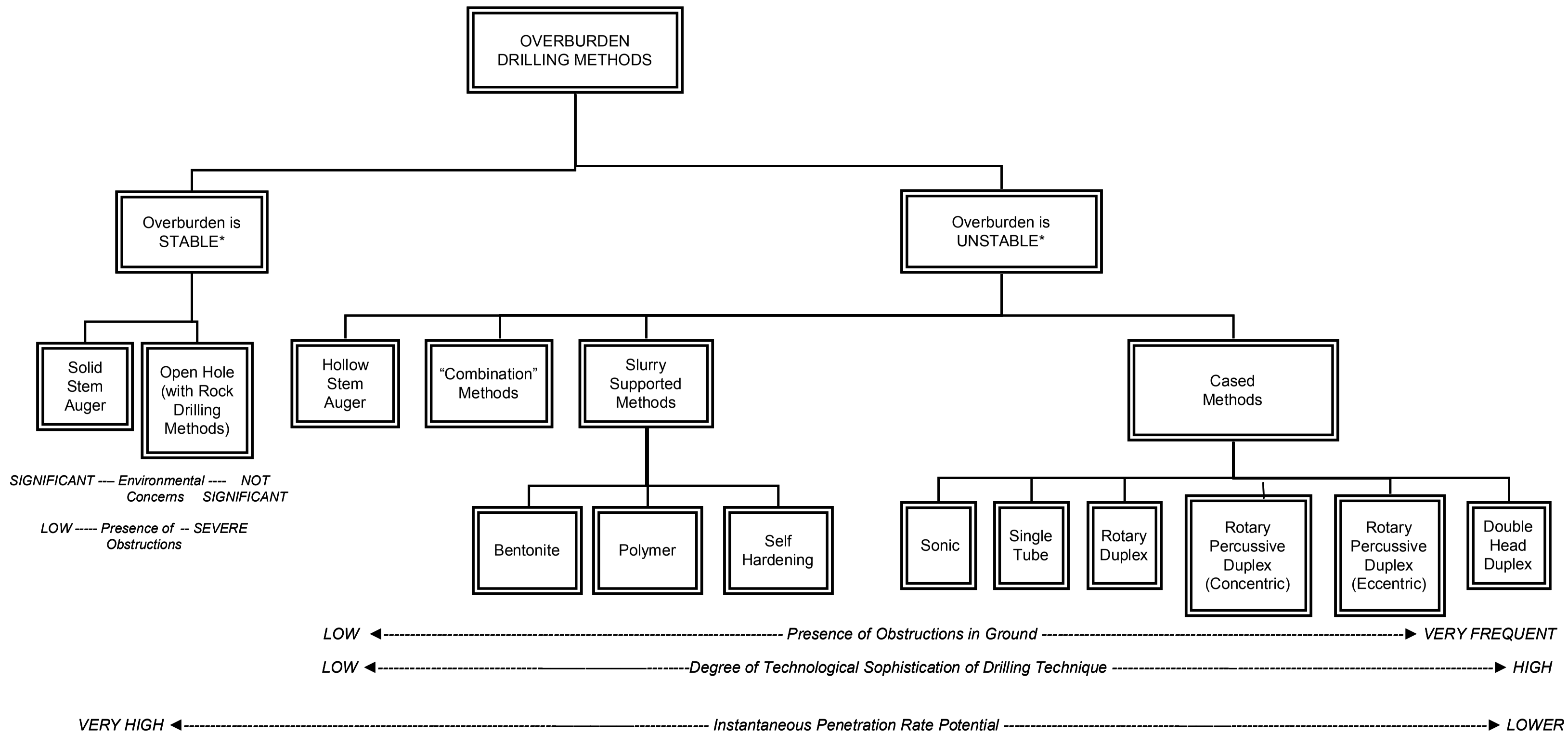
- Cost considerations.
- Drill rig access restraints.
- Hole depth, diameter, and inclination.
- Flush collection and disposal concerns; noise; vibrations.
- Possible impact of method on subsequent ability of hole to satisfy the project goals (e.g., bentonite slurry must not be used to stabilize holes which must later transfer peripheral bond, as in the case of rock anchors, although this may be perfectly acceptable for grout hole drilling).
- Regional preference, and contractor paradigms, experience, and resources.

Thorough reviews of drilling systems may be found in several sources (Bruce, 1984; and 2003; Houlsby, 1990; Weaver, 1991; Xanthakos et al., 1994; Kutzner, 1996; Australia, 1997; Rao Karanam and Misra, 1998, Weaver and Bruce, 2005).

Borehole Deviation

Every drill hole has a tendency to deviate to a certain degree from its intended path, even when the drill rig has been initially set up and oriented correctly. The amount of drill hole deviation depends on a number of factors, including:

- The nature and heterogeneity of the subsurface conditions.
- The stability and rigidity of the drilling platform and equipment.
- The particular drilling method, diameter and tooling.
- The inclination and depth of the hole.
- The expertise and technique of the driller.
- The extent to which stabilizing devices (e.g., guide casings, rod centralizers) are used.



*Stability refers to the overburden's ability to maintain the shape and size of the drilled hole without detriment to the surrounding ground after withdrawal of the drilling system.

Figure 1. Basic drill method selection guide for overburden (Bruce, 2003)

Deviation of drill holes is rarely measured. However, project specific requirements may demand that measurements are made on a certain number of initial holes, or on a certain percentage of all holes drilled. It is not uncommon that deep anchor holes in dams and long horizontal holes for compensation grouting programs are monitored (and controlled) for deviation in real time: measurements can now be made during the drilling of a hole, as opposed to only upon its completion. Various principles of measurement are employed, including optical, photographic, magnetic and gyroscopic, while there is always scope for project specific adaptations. Certain instruments have sensitivities of finer than 1 in 1000 although, traditionally, such a high degree of resolution has not been attainable, or necessary. Published data are scarce on actual deviations of holes measured in the field. Table 1 presents data from more recently published data on rock holes. Given that overburden drilling systems typically have a higher rigidity due to their drill string and casing arrangement, it can reasonably be assumed that for holes in overburden within 20º of vertical, deviations of less than 1 in 100 can be expected as a reasonable standard of quality.

Monitoring While Drilling (MWD)

The fundamental — and often overlooked — concept is that every hole that is drilled in the ground is a potentially valuable source of information on the properties and variability of the ground itself. In other words, every production hole has value in helping to understand the subsurface conditions, not only specially designated investigatory holes which are typically relatively few in number and widely spaced.

Routine MWD data can be complied in two ways — manually or electronically. For either source, the data must be studied in real time to be most useful.

For manual monitoring, the value of routine driller's logs can be greatly enhanced by periodic recording of several parameters, including:

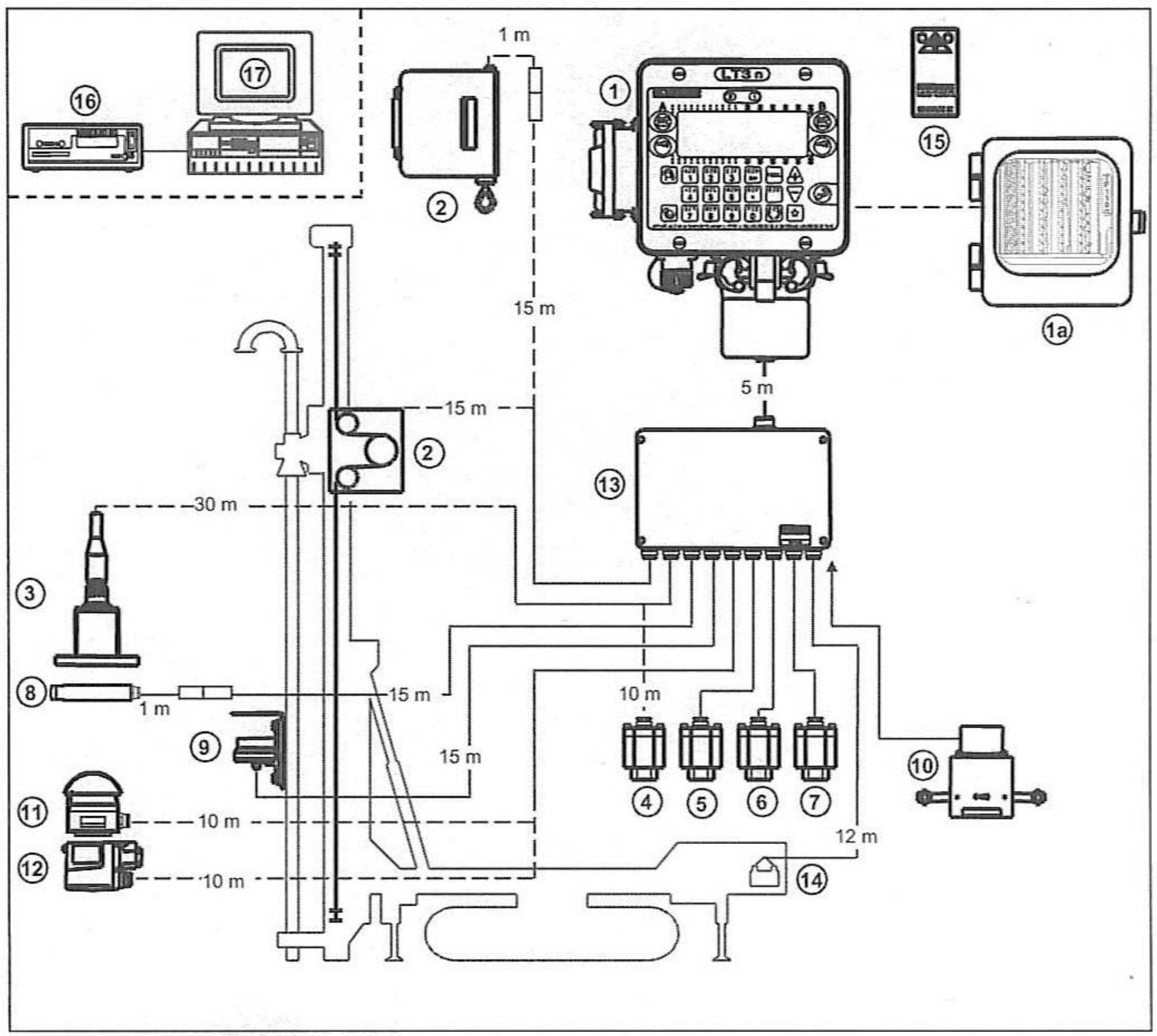
- penetration rate
- thrust and torque
- flush return characteristics and composition
- drill "action"
- interconnections, breakouts, etc.
- hole stability
- impacts on local piezometric conditions

Such data can easily be recorded by an experienced driller (or engineering assistant or technician) who has been previously briefed about the overall purpose of the project and the variability in the conditions to be anticipated. It is reasonable to expect that readings can be made routinely every 2 m or every 2 minutes of penetration, in addition to interim readings when "special events" are encountered. Guidance on the management of such data are provided by Cadden et al. (2005).

Electronic recording, display, and storage of drilling parameters has been common in Europe for over 20 years but has become popular in the U.S. only since the mid-1990's with the growing use of jet grouting. Any drilling rig can be equipped with an electronic "black box" which uses for its input data from several sensors (Figure 2). There have been several generations of such boxes, reflecting developments in computer technology.

Table 1. Summary of recorded drill hole deviations from more recently published data.

<table>
<tr><th>SOURCE</th><th>APPLICATION</th><th>METHOD</th><th colspan="2">RECORDED DEVIATION</th></tr>
<tr><td>Bruce (1989)</td><td>Dam anchors in rock and concrete</td><td>Down-the-hole hammer and rotary</td><td colspan="2">Target 1 in 60 to 1 in 240
Mainly 1 in 100 or better achieved</td></tr>
<tr><td>Bruce and Croxall (1989)</td><td>Deep grout holes in fill</td><td>Double head Duplex</td><td colspan="2">Achieved 1 in 50 to 1 in 1000 (average 1 in 80)</td></tr>
<tr><td>BS 8081 (1989)</td><td>Ground anchors</td><td>General</td><td colspan="2">1 in 30 “should be anticipated”</td></tr>
<tr><td>Houlsby (1990)</td><td>Grout holes in rock</td><td>Percussion</td><td colspan="2">Up to 1 in 10 at 60 m</td></tr>
<tr><td rowspan="2">Weaver (1991)</td><td rowspan="2">Grout holes in rock</td><td>Down-the-hole hammer</td><td colspan="2">1 in 100 increasing to 1 in 20 with increasing depth (70 m)</td></tr>
<tr><td>“Dry Drilled Percussion”</td><td colspan="2">1 in 6</td></tr>
<tr><td>Bruce et al. (1993)</td><td>Dam anchors in rock and concrete</td><td>Down-the-hole hammer</td><td colspan="2">Target 1 in 125: consistently achieved as little as 1 in 400</td></tr>
<tr><td>Xanthakos et al. (1994)</td><td>General in soil</td><td>Drive Drilling</td><td colspan="2">Up to 1 in 14</td></tr>
<tr><td rowspan="6">Kutzner (1996)</td><td rowspan="5">Grout holes in rock</td><td>Percussion</td><td>Up to 1 in 20</td><td rowspan="5">“Unavoidable”</td></tr>
<tr><td>Down-the-hole</td><td>Up to 1 in 50</td></tr>
<tr><td>Rotary Blind</td><td>Up to 1 in 33</td></tr>
<tr><td>Rotary Core</td><td>Up to 1 in 100</td></tr>
<tr><td>Wireline Core</td><td>Up to 1 in 200</td></tr>
<tr><td>Horizontal holes in soil</td><td>Percussive Duplex</td><td colspan="2">Less than 1 in 100</td></tr>
<tr><td>PTI (1996)</td><td>Tiebacks</td><td>General statement</td><td colspan="2">Up to 1 in 30 normally acceptable</td></tr>
<tr><td rowspan="3">FHWA (1999)</td><td rowspan="3">General</td><td>High Speed Rotary</td><td colspan="2">2 to 5 in 100</td></tr>
<tr><td>Top Drive Percussion</td><td colspan="2">< 5 to 20 in 100 depending on depth</td></tr>
<tr><td>Down-the-hole hammer</td><td colspan="2">Typically 1 to 2 in 100</td></tr>
</table>



Drilling parameter

	Measure
1	LT3 / EPF
1a	Printer (option)
2	Depth
3	Vibration
4	or Holding pressure
5	Grouting pressure
6	Weight on bit
7	Torque
8	Rotation speed
9	Inclinometer XY
10	Grout flow
11	Driller's button
12	or Pressostat
13	Junction box
14	Power supply
15	Digital memory card
16	Memory card reader
17	Processing software

Figure 2. Automated drilling parameter system (Courtesy of Davey Kent Inc.).

However, the constant issue is that electronic devices can rapidly compute the drilling "specific energy," in effect a quantitative measure of the "drillability" of the ground, and especially of its "exceptions and unexpecteds" (Weaver, 1991). Detailed analyses of specific energy readings from holes drilled in embankments will help identify specific features (e.g., sinkholes, or chimneys) and general trends (e.g., any systematic variation

in density for sections placed before, and after, long construction delays, such as occurred from 1941 to 1946 in many dams). Specific energy, e, is calculated as:

$$e = \frac{F}{A} + \frac{2\pi N T}{AR}$$

where

e =	specific energy (kJ/m3)
F =	thrust (kN)
A =	cross sectional area of hole (m^2)
N =	rotational speed (revolutions/second)
T =	torque (kN-m)
R =	penetration rate (m/sec.)

Benefits of MWD accrue to both Contractor and Owner and provide a freely available and often totally overlooked source of information upon which to correctly and responsibly base engineering decisions and to thereby manage technical and contractual risk.

Further Discussion of the Rotary Vibratory (Sonic Drilling) Method

On several recent major projects on existing Federal embankment dams, the method of choice for the embankment drilling has been the sonic drilling technique. It was first researched separately in the U.S. and the Soviet Union in the late 1940's and was developed commercially in the U.S. in the 1960's by the oil well drilling industry to speed investigation programs. Drilling rates 3 to 20 times greater than "conventional" rates were reported at the time. It is considered by one of its developers, Ray Roussy, "to be the only true innovation to come to the drilling industry since the Chinese invented cable tool drilling some 3000 years ago" (Roussy, 2002). In 1985, a current division of Boart-Longyear became the first U.S. firm to use the technique for environmental drilling and it is now becoming very popular in geotechnical construction projects where strong regulatory and environmental restrictions are in force.

It is a dual cased system that uses high frequency mechanical vibration to provide continuous core samples, or simply to advance casings for other purposes, such as grout holes themselves. The string is vibrated by a hydraulically powered drill head at continuously adjustable frequencies between 50 and 150 Hz, and is rotated slowly in harder formations (e.g., sandstone, limestone, shale, and slate) to evenly distribute energy and bit wear. The frequency is adjusted to achieve maximum penetration rate by coinciding with the natural resonate frequency of the drill string (Figure 3). Resonance provides extremely high energy to the bit, and in soil it also displaces the particles

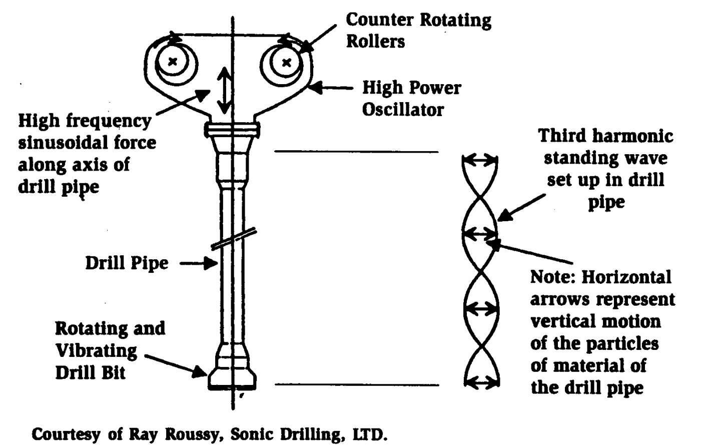


Figure 3. Principles of sonic drilling (Roussy, 2002).

laterally, greatly facilitating penetration rate. Penetration is optimized by varying frequency and thrust parameters.

The oscillator uses two eccentric counter-rotating balance weights, or rollers, that are timed to direct 100% of the vibration at 0º and 180º, while an air spring system in the drill head insulates the vibration from the drill rig itself. The outer casing can either be advanced at the same time as the core barrel and inner drill rods, or over the, or after the core barrel has moved ahead to collect the undisturbed core sample and been pulled out of the hole. Depending on the type of ground, degree of surface contamination, and the sampling objectives, the core barrel advancement can range from 0.3 to 9.0 m increments.

Regarding its advantages in difficult overburden conditions, sonic drilling

- can provide continuous, relatively undisturbed cores in soils (typically 100 to 200-mm-diameter) without using flushing media, at very high penetration rates (up to 18 m/min.) in many formations;
- can readily penetrate obstructions (natural and artificial), including boulders, wood, and concrete;
- has been used to depths of 600 m although most applications have been to less than 120 m, at up to 300 mm cased diameter;
- can easily convert to other types of rock or overburden drilling;
- requires no flush in overburden, and only minor amounts in rock, or to enhance penetration rates to greater depths;
- produces 70 to 80% less drill spoils.

Dustman et al. (1992) provided the data of Figure 4 as a comparison of drilling rates for various sample methods.

Sonic drilling can be used for split barrel sonic core sampling with acrylic, brass or stainless steel liners. It also permits multiple outer casing installations to seal off strata while advancing the borehole. SPT testing with an automatic hammer is feasible as is discrete water sampling with packer-pump systems.

Drilling Method	feet/day	Sample Method
Hollow-stem Auger	18	Split-spoon (5 ft.)
Cable Tool	20	Bailer
Air Rotary	95	Split-spoon (10 ft.)
Sonic	**160**	**Continuous Core**

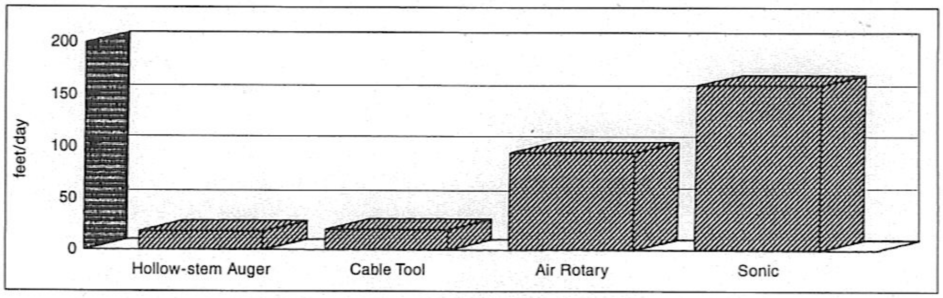


Figure 4. Comparison of drilling rates and sample methods (Dustman et al., 1992).

At the recent U.S. Army Corps of Engineers project at Clearwater Dam, MO, boreholes 40 m deep were drilled at a 15º angle through supporting gravel, cobbles, and boulders as well as through the clay core, and into rock. Previous conventional drilling attempts had taken up to 5 times longer to penetrate the embankment materials. Similarly, sonic was eventually selected to drill the 140 m deep angled holes at WAC Bennett Dam, BC in 1997. Multiple rigs operated continuously for weeks to obtain relatively undisturbed samples of very heterogeneous materials. No air, water or drilling muds were used in this very delicate, disturbed dam wherein conventional methods could not reach the required depths or provide samples of acceptable quality. Sonic drilling was also used during freeze hole drilling on a project at the Central Artery, Boston. Drilling was conducted under active railway lines, in materials including wooden piles and boulders.

Final Comments

As is the case for many other aspects of the specialty geotechnical construction industry, significant developments are being made by the drilling industry in terms of quantification and quality. Such advances are necessary to better meet the goals of environmental protection, optimum performance, reliable scheduling and controllable costs. Of particular interest to the small hole drilling community are the advantages offered by MWD, and by sonic drilling techniques cleverly promoted as “the wave of the future.” Despite these exceptional mechanical developments, however, it is prudent to recall that the drilling industry remains absolutely dependent upon the skill, judgment and integrity of the people who operate the equipment. It is therefore appropriate to end with the following quote from the Technical Training Committee of the Australian Drilling Industry (1997):

“Drillers are as diverse a group of people as the industry in which they work. Every drilling operation is different and requires a highly skilled person to ensure that the drilling process is successful.”

Australian Drilling Industry Technical Training Committee Ltd. (1997)

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