DRILLING IN THE URBAN ENVIRONMENT

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Abstract: The safe penetration of overburden is a particular challenge to engineers involved in remedial, investigatory or instrumentation projects in urban areas. The paper reviews current practice in drilling systems and methods, and provides guidance on classification, hole deviation, flush characteristics, and Monitoring While Drilling (MWD) in particular. Information is also provided regarding the sonic drilling method which is rapidly becoming the overburden drilling technology of choice in North America in difficult environments.

I INTRODUCTION

Urban construction and instrumentation often requires 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 construction activities such as grouting, anchoring, nailing and micropiling. Holes are typically 75 to 300 mm in diameter and are rarely more than 50 m deep. They may range in inclination from vertically upwards to vertically downwards. Whereas rock and concrete masses can be 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, from dry to saturated, and 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 through earth embankments is a very sensitive issue and indeed is the subject of a U.S. Army Corps of Engineers Regulation (1997). 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.
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 through existing embankment dams, the rotary-sonic method has proved particularly attractive, and for this reason is discussed in a certain amount of detail below.

Similar restraints apply in urban environments, where operations are frequently conducted under or adjacent to existing buildings and “loss of ground” is potentially highly dangerous. Factors which specifically impact urban drilling operations include the variability of the various layers of fill themselves the piezometric conditions and, frequently, a distinct lack of knowledge of the as-built conditions (including underground services, and foundation elements).

II AN OVERVIEW OF DRILLING SYSTEMS, METHODS AND APPLICABILITY

A. Common Features

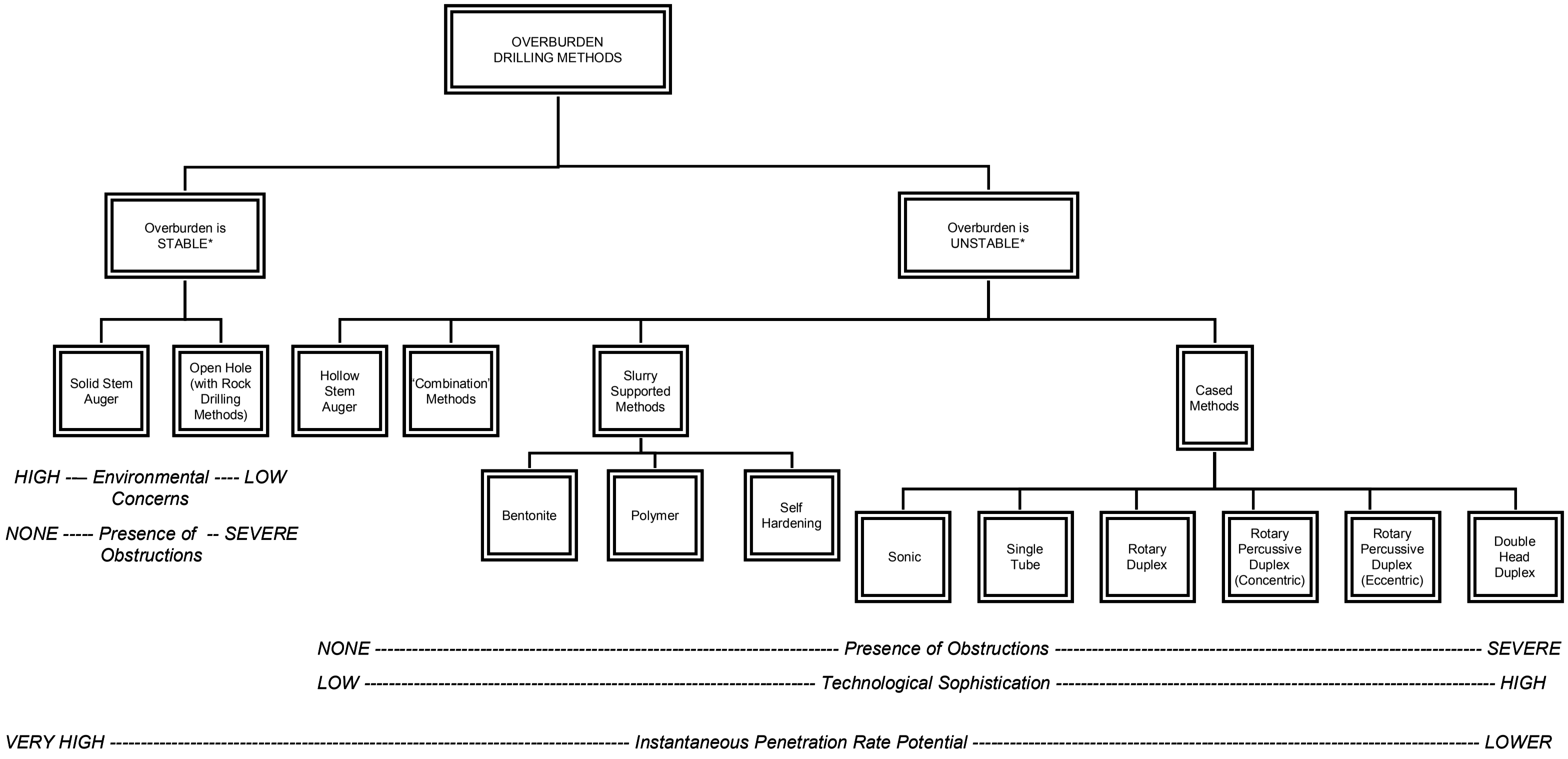
Effective drilling systems for overburden and fill must be capable of permitting continuous, acceptably straight penetration in materials which may vary from very soft to extremely hard and from homogeneous to heterogeneous. They must be capable of providing a constant diameter, stable (or temporarily stabilized) path full depth, from which the drilling debris has been wholly removed, and which is consistent with the needs of the specific geotechnical 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. 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.

B. 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 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.

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



*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)

- 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).

C. 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.

Deviation of relatively short drill holes in urban environments is rarely measured, in contrast to monitoring of long holes associated with compensation grouting or large rock anchor projects. 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. 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. Data are scarce on actual deviations of holes drilled in urban situations, although much more common for rock drilled holes (for anchors and grout curtains). 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 within 30% of vertical, deviations of less than 1 in 100 can be expected. For holes within 30% of horizontal, deviations of over 1 in 50 can be anticipated.

D. Drill Flush

A flushing medium is typically used during drilling operations to evacuate the drill cuttings and to cool the system components in contact with the ground. Fundamentally there are two basic considerations:

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

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

1. The flush must not be allowed to escape in an uncontrolled, uncontrollable fashion into the formation; and

2. The return flush must never be blocked or suppressed on its way back to the surface up the drill hole.

Either or both of these phenomena occurring will create conditions leading to washout, interconnections, heave or hydrofracture in the formation. It is exactly the fear of such eventualities which precipitated the U.S. Army Corps of Engineers' 1997 Regulation.

From a technical viewpoint, the flushing system must be carefully engineered to ensure that its uphole velocity (UHV) is greater than the "sinking velocity" of the drill cuttings. The UHV is calculated as follows:

$$\text{UHV (m/min.)} = \frac{1274 \times \text{Flush Pumping Rate (liters/min.)}}{D^2 - d^2 \text{ (m.m.)}}$$

where D = drill hole diameter (m.m.)
d = drill string diameter (m.m.)

Typical UHV's used in practice for various flushing media are:

- Air, or air and water "mist" : 1500 (to 2100 m/min. max)
- Water : 36 m/min. (to 120 m/min. max)
- Low to medium viscosity mud : 30 m/min.
- Very thick mud : 18 m/min.
- Foam : 12 m/min.

E. 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 readings at “special” intervals.

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 and 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. 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). Specific energy, e, is calculated as:

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

where

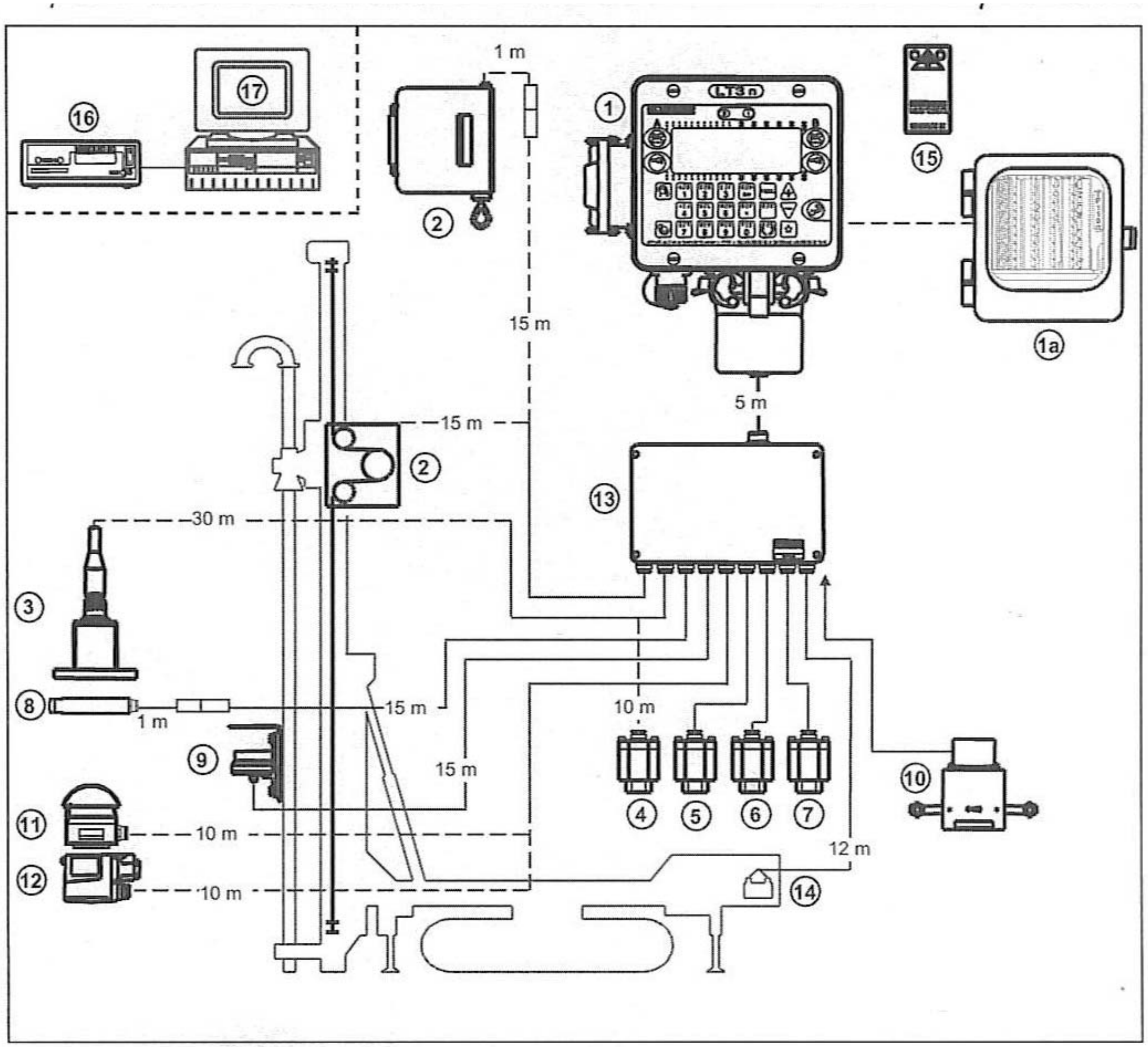
e = specific energy (kJ/m3)
F = thrust (kN)
A = cross sectional area of hole (m^2)
N = rotational speed (revolutions/second)
T = torque (kN-m)
R = penetration rate (m/sec.)

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

III FURTHER DISCUSSION OF THE ROTARY VIBRATORY (SONIC DRILLING) METHOD

On several recent major projects in difficult ground, 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 had been reported by that 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 eccentric counter-rotating rollers mounted in the hydraulically powered drill head and operating at continuously adjustable frequencies between 50 and 150 Hz. It is rotated slowly in harder formations (e.g., sandstone, limestone, shale, and slate) to evenly distribute energy and bit



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.).

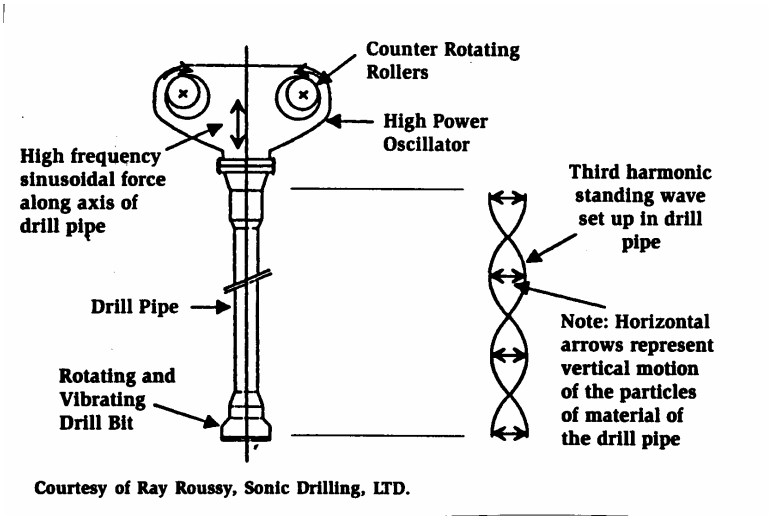


Figure 3. Principles of sonic drilling (Roussy, 2002).

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 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 0° and 180°, 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 urban drilling projects, 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 300 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;
- elimination of annulus assists in maintaining drill accuracy;
- is available in many base configurations, including the Minisonic drill rig (Photograph 1) for low head room, tight access conditions.

Photograph 1: Minisonic drill rig for low head room, tight access projects.

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

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**

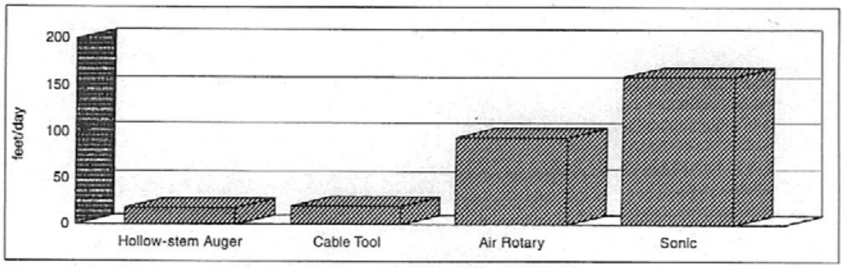
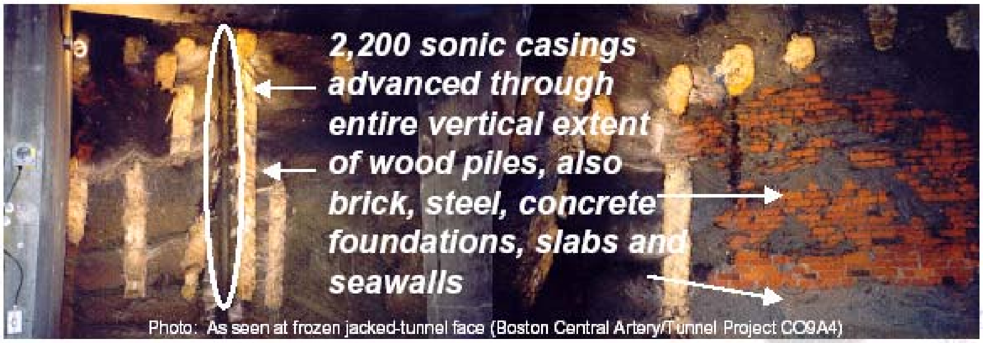


Figure 4: Comparison of drilling rates and sample methods (Dustman et al., 1992).

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.

With respect to some recent projects, the installation of freeze pipes at the Fort Point Channel project in Boston, over 2200 sonic casings were advanced through extremely heterogeneous ground conditions including wood piles, bricks, steel, concrete foundations, slabs and seawalls (Photograph 2).



Photograph 2: Fort Point Channel project in Boston.

At the recent U.S. Army Corps of Engineers project at Clearwater Dam, MO, boreholes 135 feet 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 435-feet-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.

IV FINAL COMMENTS

As is the case for many other aspects of the specialty geotechnical construction techniques being used for urban construction, significant developments are being made by the drilling industry. Such advances are necessary to meet the goals of structural safety, high performance, superior quality, reliable scheduling and controllable costs. Of particular interest 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."
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> *Australian Drilling Industry*
> *Technical Training Committee Ltd. (1997)*

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