A COMPARISON OF WATER JET, ABRASIVE JET AND ROTARY DIAMOND DRILLING IN HARD ROCK

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Introduction

Construction activities which require the placement of utilities in hard rock would benefit from a lightweight system which is capable of accurately drilling a short constant radius arc as illustrated in Figure 1. Existing mechanical drilling systems are capable of drilling shallow directional holes but the equipment is heavy, drilling rates are low and costs are high. A comparison of approaches for rapidly drilling a small-diameter (25-50-mm), near-surface, hole through a short-radius (30-m) arc in a variety of hard rock types is provided here. Four approaches were considered:

1. Rotary diamond drilling with a downhole motor
2. Ultra-high pressure (UHP) water jet drilling
3. Mechanically-assisted UHP water jet drilling
4. Abrasive jet drilling (abrasive water jet and abrasive slurry jet)

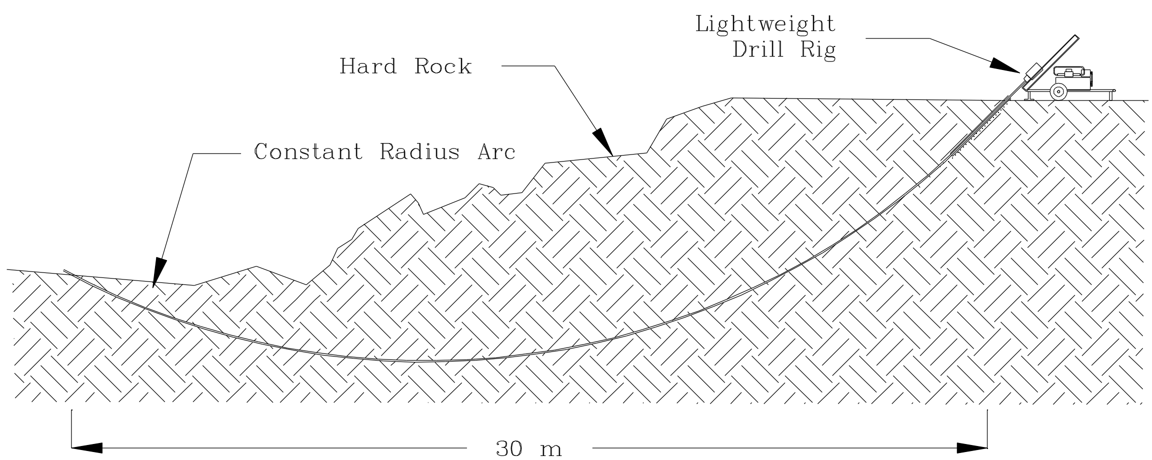

Figure 1. Short radius, near-surface directional drilling system.

Data relating mechanical and hydraulic drilling parameters with rate of penetration for each of these approaches was compiled from the literature and from drilling tests of all four techniques in black granite with a compressive strength of 280 MPa, using the drills shown in Figure 2 (Kollé et al. 1997). The drilling data is summarized in a common format to provide a direct comparison of drilling efficiency; jet pressure and hydraulic power; thrust and torque requirements and abrasive feed. In order to compare approaches for drilling, a specific energy parameter has been defined:

$$S_e = \frac{W}{Q_r}, \qquad (1)$$

where Q_r is the volumetric rate of rock removal and W is the hydraulic or mechanical cutting power applied. This basic parameter allows a calculation of the rock drilling rate for any approach based on the power available for drilling at the drill head.

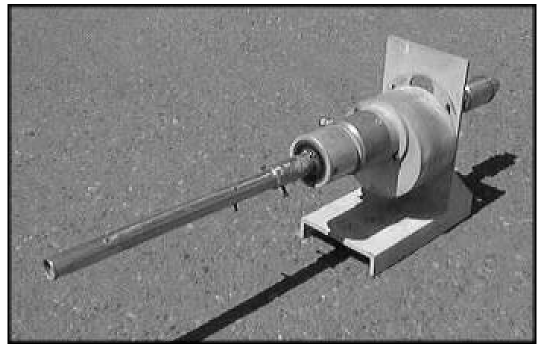

Figure 2. Drills (left to right): water jet, mechanically-assisted water jet, surface-set diamond, abrasive water jet (Kollé et al. 1997).

Rotary Drilling

A short-radius directional hole could be drilled in hard rock using a diamond bit mounted on a positive displacement downhole motor (PDM). A typical small motor has a diameter of 43 mm and a length of 2.1-m (84”) so the smallest hole diameter which could be drilled would be about 50-mm (2”). The motor could be built into a bent housing to provide directional control. At an operating pressure of 2.8 MPa and flow rate of 10^{-3} m^3/s (15 gpm) a 5:6 lobe PDM could deliver 80 N-m (60 lbf-ft) of torque at 200 rpm rotary speed with a mechanical power of 1.7 kW. Higher rotary speeds and lower torque could be provided by a 1:2 lobe PDM. An additional 10 kW hydraulic power would be required to provide turbulent chip cleaning and bit cooling.

A detailed comparison of diamond drilling with surface-set and impregnated diamond bits in a range of high strength rock types including granite, quartzite and taconite is provided by Clark (1987). The specific energy for drilling 150 to 400 MPa rock with a surface set diamond bit is between 1 and 2 J/mm^3, while the specific energy for drilling with impregnated diamond bits is around 10 J/mm^3. This is consistent with Jaeger and Cook (1976) who report the specific energy of diamond drilling in 200 MPa rock to be in the range of 1 to 10 J/mm^3. Based on these specific energy values, the rate of penetration of a 50-mm-diameter surface-set diamond bit with 1.7 kW mechanical power in hard rock would be 1.5 to 3 m/hr (5 to 10 ft/hr).

Kollé et al. (1997) discuss two drilling tests in black granite with a compressive strength of 280 MPa using the 38-mm (1.5”) diameter surface set diamond bit shown in Figure 2. At rotary speeds of 340-780 rpm and a thrust of 2200 N (500 lbf), the drilling rate was 1.8 - 2.9 m/hr (5.9 - 9.5 ft/hr).

Drilling rates with an impregnated diamond bit would be about 0.3 m/hr (1 ft/hr). Under normal operating conditions, abrasive wear limits the bit life of diamond bits to under 30-m in rock types such as granite which have a quartz content greater than about 20%. At the low thrust and rotary speeds a surface-set diamond bit might be capable of drilling 30 m.

The operation of diamond bits requires high thrust load to ensure that the cutters penetrate the rock. Clark (1987) relates diamond bit torque, thrust and penetration rate through an empirical friction coefficient. A bit torque of 82 N-m would require a thrust of 13 kN (3000 lbf). The thrust available is limited by buckling of the drill rod – fortunately drill rod in an inclined hole is stabilized by the hole as discussed by

Dawson and Paslay (1984). The critical buckling load for a drill rod having an OD of 38 mm an ID of 12 mm and laying in a 50-mm-diameter hole inclined at 45 degrees would be 13 kN (3000 lbf) .

Drilling with a small-diameter motor would be consistent with the short radius drilling requirement since the drill string would not rotate. The motor could incorporate a bend or stabilizers which would cause it to curve upwards while the azimuth remains constant. Over a distance of 30-m, a properly designed bent housing should provide azimuth and elevation accuracy of within 1 degree per 30 m (Dech et al. 1986, Yost et al. 1987). This would allow a prediction of the exit hole location to within a few meters as long as the drill exits at an angle of 30 degrees or more from the surface.

High Pressure Jet Drilling

High Pressure Water Jet Drill

Linear jet cutting experiments in rock have been carried out by a relatively large number of researchers. Table 1 lists the range of jet cutting and drilling specific energy for each reference as inferred from the reported operating parameters and data. Jet pressure, P_j, and unconfined compressive strength, s_c, are also listed where available. In general, high permeability rock types such as Berea sandstone, have a low threshold pressure and specific energy. Medium strength, low permeability limestones and sandstones have intermediate specific energy; and high-strength, low permeability rocks such as granite, quartzite and basalt have high threshold pressures and specific energy.

Table 1. High pressure water jet cutting and drilling.

Reference	Rock Types	P_j, MPa	s_c, MPa	S_e (J/mm^3)
Jaeger and Cook (1976)	Hard rock (200 MPa compressive strength)	-	-	10
Chadwick - (Maurer 1980)	Berea Sandstone, Salem Limestone, Tennessee Marble, Westerley Granite, Charcoal Granite, Sioux Quartzite, Dresser Basalt	345	-	3 - 10
Harris and Mellor - (Maurer 1980)	Barre granite	100 - 400	-	100 -500
Pols (1977)	Belgian Limestone, Gres bleu Sandstone, Solnhofen Limestone, Martelange Schist	90	80 - 210	100 - 170
Vijay et al. (1984)	Muskoka Pink Granite	69	-	10 - 50
Agus et al. - (Summers 1995)	granite	125-200	-	2.5 - 5
Cable (1993)	cherty and shaley limestone granite	70 - 100 70	170 210	10 - 30
Kollé et al. (1997)	black granite	350 - 240	280	70 - 100

Veenhuizen and O'Hanlon (1978) developed a non-rotating standoff control collar which allows jet drilling at a constant, low-level thrust. The most successful system used a carbide collar with a pair of jets, one vertical and one angled at 20 degrees from vertical as shown in Figure 3. This system drilled uniform gauge holes with a minimum diameter of 1-mm over the gauge. Veenhuizen and O'Hanlon found that the UHP water jet drilling rate increases as the square root of rotary speed with the best drilling results obtained at 1000 rpm. This drill was not used to drill hard rock at the time, however more recently the waterjet drill was used to drill black granite at a pressure of 240 MPa (Kollé et al. 1997). Results reported by Vijay et al. (1984) and Cable (1993) show that granite can be drilled at pressures as low as 69 MPa.

Because jet erosion requires no torque or thrust, high pressure water jet drilling provides a unique capability for drilling a constant radius directional hole without the need for steering corrections. As shown in Figure 3, the drill orientation could be controlled with a sleeve which orients a non-rotating bent housing. Pure water jet drilling is less sensitive to formation changes than mechanically-assisted drilling because cutting is controlled by the bit orientation.

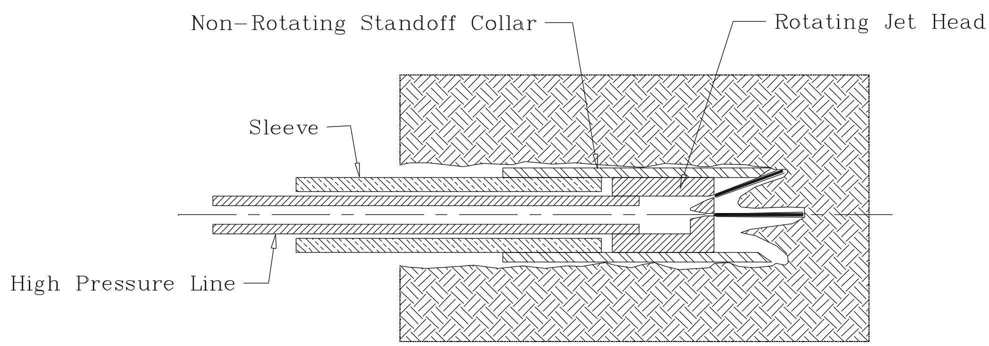

Figure 3. High pressure water jet drill.

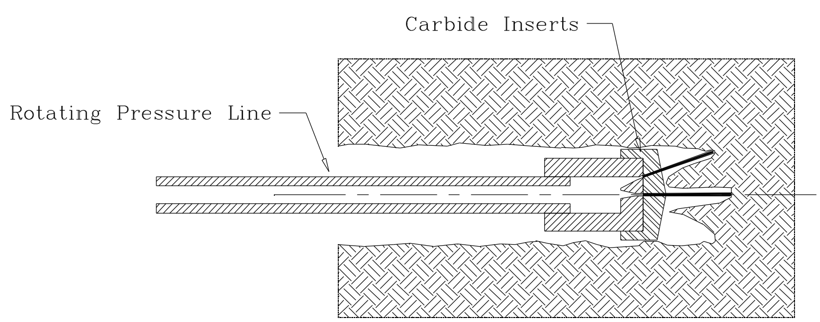

Figure 4. Mechanically-assisted jet drill.

Table 2. Mechanically-assisted jet drilling.

Reference	Rock Types	P_j, MPa	s_c, MPa	S_e, (J/mm^3)
O'Hanlon and Madonna (1982)	High Strength: Imberg Sandstone, andesite, Vermont Granite	240	-	4 -7
	High strength/impermeable: gneiss, schist, peridotite, quartzite, taconite, basalt, colorado sandstone, Taiwan Siltsone,	240	-	10 - 25
	Extremely high strength: flint	240	-	80
Flow (1981)	black granite	350	280	10
Kollé et al. (1997)	black granite	240-350	280	40 - 80

Mechanically-Assisted Jet Drilling

O'Hanlon and Madonna (1982) describe the evolution of mechanically-assisted drilling heads illustrated in Figure 4. The mechanical inserts ensure that the drill will not advance ahead of the full gauge hole area. In addition, the inserts break the ridges of rock which are formed by the jets. Torque and thrust levels are low enough to allow manual feed of the drill. Table 2 lists drilling parameters in a variety of high strength rock types including black granite.

Abrasive Jet Drilling

Abrasive jet drilling involves a supply of abrasive which is pumped with the fluid (suspension jet or ASJ) or entrained at the nozzle (abrasive waterjet or AWJ). Entrained abrasive jets are widely used for manufacturing applications including production of cut stone. This approach has been evaluated for cutting of deep slots in rock and concrete. Hashish (1989) discusses a variety of concepts for AWJ rock drilling. The basic concept is illustrated in Figure 5. This approach requires a separate feed line through which abrasives are fed. High pressure jets are discharged through carbide mixing tubes where the abrasive is entrained to form a jet. The high pressure jet and mixing tubes rotate together.

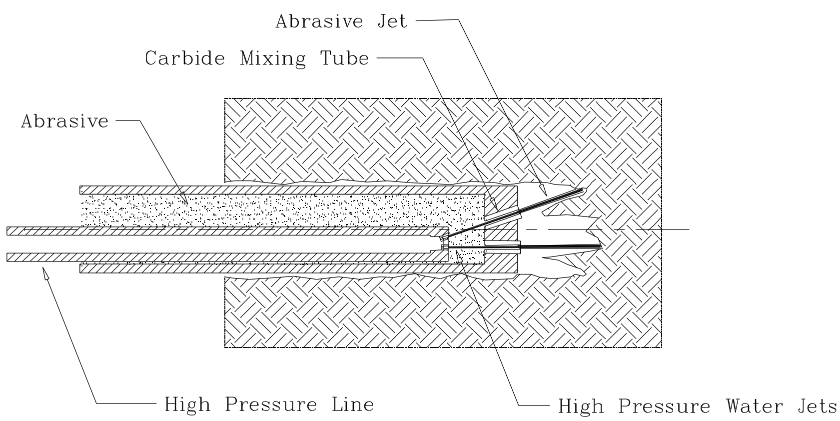

Figure 5. Abrasive water jet (AWJ) drill.

AWJ drilling has been used for deep kerfing of concrete and rock but has never been demonstrated for hole drilling in rock because of feed control limitations. Table 3 indicates the jet pressure abrasive usage and specific energy for slot cutting and surface erosion tests in sandstone, granite and concrete.

Table 3. Abrasive water jet (AWJ) cutting and erosion (no drilling results are available).

Source	Rock Types	P_j, MPa	m_a/m_r	S_e (J/mm^3)
Hashish (1989)	Wilkeson sandstone, Charcoal granite	345	6 - 20	30 - 100
Hashish et al. (1987)	concrete	240	-	100
Momber and Kovacevic (1997)	concrete (s_c = 4 - 40 MPa)	150 - 300	-	100 - 170
Kollé et al. (1997)	black granite (s_c = 280 MPa)	345	-	250

The AWJ drilling test described by Kollé et al. (1997) is consistent with previous results. Abrasive usage is given as the mass of abrasive used, m_a, divided by the mass of rock removed, m_r. As indicated, abrasive jet cutting requires an order of magnitude more abrasive than material removed. For example a 30-m-deep, 25-mm-diameter hole in granite would require about 1 ton of abrasive.

Direct injection abrasive jet (DIAJET or abrasive slurry jet, ASJ) cutting has been applied as an alternative to entrained abrasive jets (Summers 1995). In this process, abrasives are suspended in a polymer solution in a pressurized tank. The abrasive slurry tank is pressurized using a conventional high-pressure pump and the slurry is fed through an erosion resistant nozzle as illustrated in Figure 6. This process requires periodic mixing and filling of a large pressurized tank with abrasive and polymeric additives which suspend the abrasive. A 100 gallon tank, which weighing several hundred kg would only last for a few minutes of drilling. The available data on abrasive slurry drilling data is summarized in Table 4. ASJ systems have a specific energy which is comparable to that of high pressure AWJ systems but requires much higher water flow rates, and extremely high abrasive flow rates as indicated by the ratio of abrasive to rock mass removed..

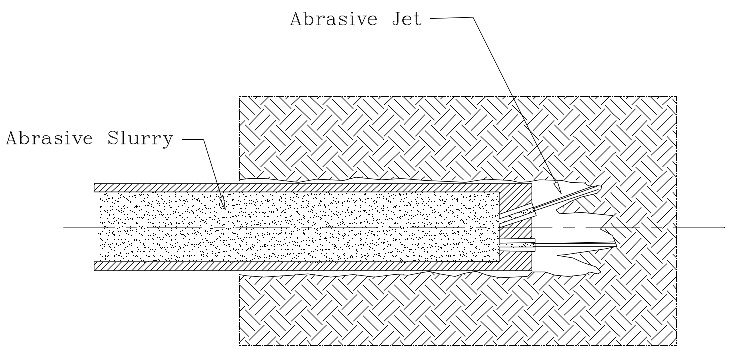

Figure 6. Abrasive slurry jet (ASJ) drill.

Table 4. Abrasive slurry jet (ASJ) drilling.

Source	Rock Types	P_j, MPa	m_a/m_r	S_e (J/mm^3)
Yazici (Summers 1995)	"rocks"	35	-	100 - 200
Summers (1995)	basalt	35	2500	70
Vestavik (Summers 1995)	sandstone and granite	30	1000	250 - 500

Drilling Technique Comparison

A comparison of various aspects of high pressure jet drilling techniques is provided in Table 5. The first three columns compare jet drilling systems operating with a hydraulic power of 38 kW (50 hhp) at the surface. The estimated drilling rates in were obtained using the specific energy data along with the bit hydraulic or mechanical power. The UHP water jet systems jet have little loss of pressure or power through a 30 m drill rod and the bit power is essentially equal to the power available at the surface. An abrasive slurry jet system would loose about half its power to pressure losses in the drill rod. (Abrasive water jet drilling is not listed since this approach has never been demonstrated). The characteristics of a small-diameter rotary diamond drilling system using a downhole motor are also provided. In this case the power available at the bit is limited by the mechanical power capacity of a PDM. The development status of each approach is indicated by meters of rock drilled, along with thrust and torque requirements and compatibility with a passive directional control system such as a bent subassembly.

UHP jet drilling flow rates are relatively small so hole cleaning is a concern. Okranji and Azar (1986) have shown that cleaning of horizontal holes requires turbulent flow. The critical flow rate for a 25-mm diameter hole with a 19-mm (3/4") is $9x10^{-5}$ m^3/s (1.4 gpm). A 38 kW, 240 MPa water jet drilling system would have a flow rate of 1.6x 10^{-6} m3/s (2.5 gpm) which is sufficient to ensure the turbulent transport of cuttings out of a hole inclined at less than 45 degrees from horizontal.

Table 5. Comparison of hard rock drilling techniques.

	UHP Water Jet	M-A Water Jet	Abrasive Slurry Jet	Motor Drilling Diamond Bit
Surface Pressure, MPa	240	240	35	15
Flow Rate, m^3/s	1.6 x 10^{-4}	1.6 x 10^{-4}	1.1 x 10^{-3}	1 x 10^{-3}
Bit Pressure, MPa	240	240	17	10
Bit Power, kW	38	38	19	1.7 mechanical 10 hydraulic
Hole Diameter, mm	25	25	25	50
Rotary Speed, rpm	100	100	100	200
Specific Energy, J/mm^3	5 - 100	3 - 100	70 - 500	1 - 10
Drilling rate, m/hr	3 - 55	3-80	0.2 - 2	0.3 - 3
Status, meters drilled	>300	> 1000 m	20	conventional
Abrasive use, kg/hr	-	-	500 - 4000	-
Thrust required, N (lbf)	110 (25)	400 (100)	300 (65)	13000 (3000)
Torque required, N-m (in-lbf)	0	10 (7)	0	80 (60)
Passive Directional Control	YES	NO	NO	YES

Rotary mechanical drilling using a downhole, positive-displacement motor would be capable of drilling a short radius, small diameter hole. Even though diamond drilling is more efficient than jet drilling, the mechanical power available at the bit is limited and a larger hole must be drilled to accommodate the motor so the drilling rate would be slower than any of the jet drilling approaches. The lowest rate given is for impregnated diamond bits in abrasive 400 MPa rock while the highest rate is for a surface set diamond bit in 200 MPa rock. The penetration rate is limited by the torque and rotary speed capacity of a small downhole motor. Abrasive suspension jet drilling is not considered a viable approach for this application because of the difficulty of handling and delivering massive amounts of abrasive and because of uncertainties in hole steering.

UHP jet drilling offers high rates of penetration because the power available at the bit is extremely high. Mechanically-assisted jet drilling provides slightly higher drilling rates but this approach generates torque loads which could cause the hole trajectory to spiral. The literature review and testing discussed here has shown that a UHP drill would be capable of rapidly drilling small-diameter holes in a wide range of erosion-resistant rock types. The system could be steered by providing a non-rotating bent housing which directs the drill. Finally, a UHP jet drilling system could be made very lightweight because the thrust and torque requirements are nominal.

Acknowledgments

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