RECENT ADVANCES IN OVERBURDEN AND DOWN-THE-HOLE DRILLING TECHNIQUES

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ABSTRACT

The safe and efficient drilling of overburden (fills and natural soils) and rock is integral to many specialty geotechnical construction techniques. The state of practice for overburden drilling techniques was most recently described by Bruce in 2012, and the history of Down-the-Hole (DTH) drilling for rock was provided by the authors in 2013 (Bruce et al., 2013). Thereafter, development and innovation have continued, principally to satisfy specialty contractors' goals for systems providing faster production, lower costs, more consistent and reliable performances, and easier operation and maintenance. This paper describes more recent developments in overburden drilling, and reviews innovations in DTH methods operated by air, and by water.

1. BACKGROUND

In specialty geotechnical construction techniques such as grouting, ground anchors, micropiles and ground freezing, overburden is regarded as those materials overlying top of geological rock. Hence, overburden can comprise fill materials (for example the materials constituting an embankment dam or levee), or it can be solely natural, unlithified deposits such as alluvium, colluvium or glacial outwash and till deposits. Often, as in the case of a reclaimed urban site, or for an embankment dam, both fills and natural soils will, together, constitute the overburden that must be penetrated to reach the bedrock which is to be the ultimate host of the process.

Because overburden is so variable in terms of variations in grain size, density, stiffness or degree of saturation, there are many different types of overburden drilling systems, as recently described by Bruce (2012). In certain applications, such as the drilling of embankment dams, there are governing Federal regulations (e.g., USACE 1997) which have driven the popularity of a certain overburden drilling system, such as rotosonic (Bruce and Davis, 2005). This relative newcomer to a field which was opened almost 50 years ago has been well described by various authors, such as Stare et al. (2012), and is now not just the chosen method, but the specified method for drilling through existing embankment dams to place standpipes for rock grouting, and for installing instrumentation.

With regards to rock drilling, the generic drilling methods are somewhat fewer – rotary drilling, or rotary percussive drilling, either by top hammer, or by DTH hammer. As described by Bruce et al. (2013), air-flushed drilling with top hammers began in Swedish mines in 1873, while DTH drilling, again with air flush (and activation) became operational first in 1950. Early industry debates about the relative merits of rotary vs.

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rotary percussive drilling for grout holes should really have been about the benefits of water flush over air flush since, in our opinion, air flush will clog fissures in competent rock masses, and will create extreme levels of ground disturbance in the variable conditions present in karstic carbonate terrains. However, for fast, reliable and straight drilling in rock where grouting is <u>not</u> the purpose of the drill hole, then air flushed DTH is still a very popular and sensible choice, and it is not the case that development and innovation in air DTH technology has stalled – quite the contrary.
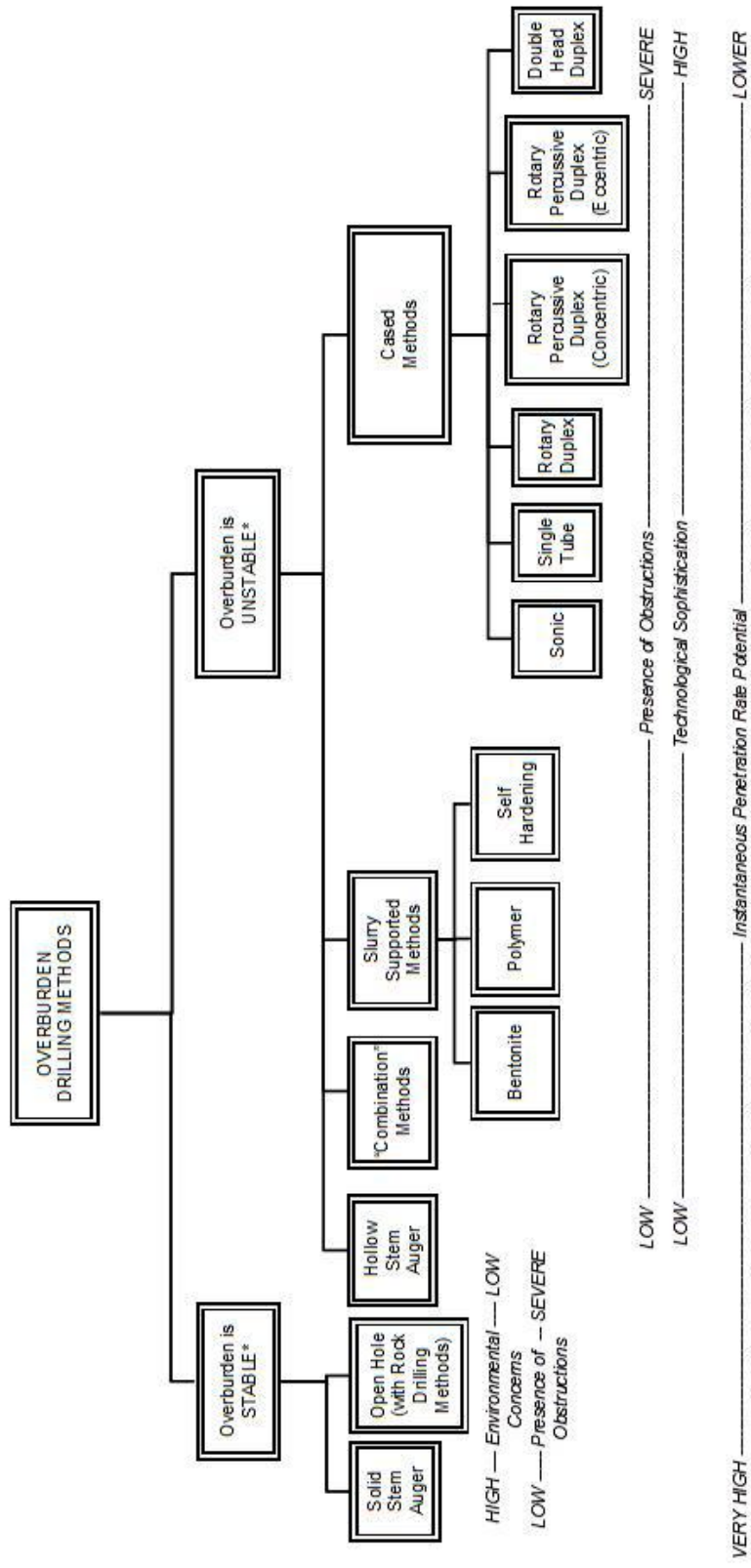
In this paper, recent developments in overburden drilling and in DTH drilling are presented, in order to update the state of practice review of 2012.

2. OVERBURDEN DRILLING

The overburden drilling systems in use in North America as of 2012 (and, coincidentally, 2003), are as summarized in <u>Figure 1</u>, and are as described by Stare et al. (2012). Most recently, research has focused on producing for specialty geotechnical construction contractors overburden drilling systems which are robust, reliable, user friendly, and compatible with standard sizes of commercially available drill casing (e.g., 5½ inches, 7 inches, and 9⅝ inches). Two typical examples are the SuperJaws® system provided by Numa, and the Elemex system of Atlas Copco.

SuperJaws® features "wings" that extend out beyond the end of the casing while in the drilling position. It is the direct descendent of the venerable Acker Anchor Underreaming System. When drilling is completed, "the bit is simply lifted off bottom, causing the wings to retract back into the guide body. This allows all tooling to be extracted while leaving the casing in place. There is no forward or reverse rotation required, nor any expensive rings left in the hole" (Numa Website, 2012). It is promoted in two versions. One uses an inexpensive drive shoe, welded to the front of the casing. As the bit advances through the formation, the casing is advanced at the same rate due to the drive shoulder on the guide body engaging the drive shoe welded to the casing. The second version — "SuperJaws® ND" — uses thick wall welded casing or thick wall threaded casing. The guide body has no drive shoulder and the casing is advanced via a casing hammer, duplex diverter, or dual rotary system. This version is often used in micropile and tieback work where the casing is to be recovered, or in deep overburden areas where high amounts of friction can develop around the casing. Both systems are used for drilling holes 5½ to 42 inches in diameter, and are provided in 2-, 3- and 4-wing configurations, depending on diameter.

Atlas Copco claims their Elemex system was designed to meet the environmental challenges of using compressed air in urban locations, as well as optimizing drill bit performance. It minimizes air escape to the surrounding ground as the high pressure air (used in the hammer) never touches the ground directly, but is redirected. The air is blown from the bit face against an extended ring bit (mounted on the casing), causing the redirection, but still maintaining the cleaning action. The ring bit encloses the drilling area and keeps the air in the flushing grooves. This ring bit also prolongs the life of the pilot bit. This is a simple and reliable system to operate (hence the name) and is claimed to drill faster and straighter holes than when "drilling with an old type of underreaming system" (Atlas Copco Website, 2012).

OVERBURDEN DRILLING METHODS

Overburden is STABLE*
- Solid Stem Auger
- Open Hole (with Rock Drilling Methods)
- Hollow Stem Auger

Overburden is UNSTABLE*
- "Combination" Methods
- Slurry Supported Methods
  - Bentonite
  - Polymer
  - Self Hardening
- Cased Methods
  - Sonic
  - Single Tube
  - Rotary Duplex
  - Rotary Percussive Duplex (Concentric)
  - Rotary Percussive Duplex (Eccentric)
  - Double Head Duplex

HIGH —— Environmental —— LOW
        Concerns
LOW —— Presence of —— SEVERE
        Obstructions

LOW ———————————————————— Presence of Obstructions ———————————————————— SEVERE
LOW ———————————————————— Technological Sophistication ———————————————————— HIGH
VERY HIGH ———————————————————— Instantaneous Penetration Rate Potential ———————————————————— LOWER

*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, 2012).

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A new type of casing underreaming and advancing system has recently been developed by Center Rock Inc. This features a patented method of extending and retracting cutting wings on the central pilot bit in a very simple and reliable fashion. Unlike other underreamed systems, the wings, when extended, are locked out mechanically, and so do not rely on downward pressure on the bit. They therefore prevent the outer casing from accidentally slipping off if a very soft or voided horizon is suddenly encountered. The system, named Roto Loc, leaves no sacrificial component in the ground, and fits casings of standard sizes 5½ to 24-inch diameter.

Roto Loc consists of three major parts, as shown in <u>Figure 2</u>. A SHANK adapts the system to a DTH hammer. The shank also includes a threaded section which screws into and out of the pilot. In addition, the shank also includes a conical end which engages the wings to force them outward when the shank is screwed clockwise into the pilot. A set of WINGS are contained within the pilot. The wings cut the kerf from the borehole needed to make clearance for the advancing casing. The wings are then allowed to retract when the shank is unscrewed and the assembly is pulled back through the casing. The PILOT holds all the components together with a retaining wire (not shown) which prevents the shank from fully unscrewing. The pilot contains a female thread which the shank engages. It also contains pockets which house and guide the wings. The front face of the pilot contains the cutting structure which advances the hole. Since the pilot leads the cutting structure of the wings it also provides radial stability and so the ability to drill straighter through pinnacled karstic terrains. This reduces bending stresses on the casing which, in extreme cases, may cause it to rupture, so leading to loss of casing at depth.
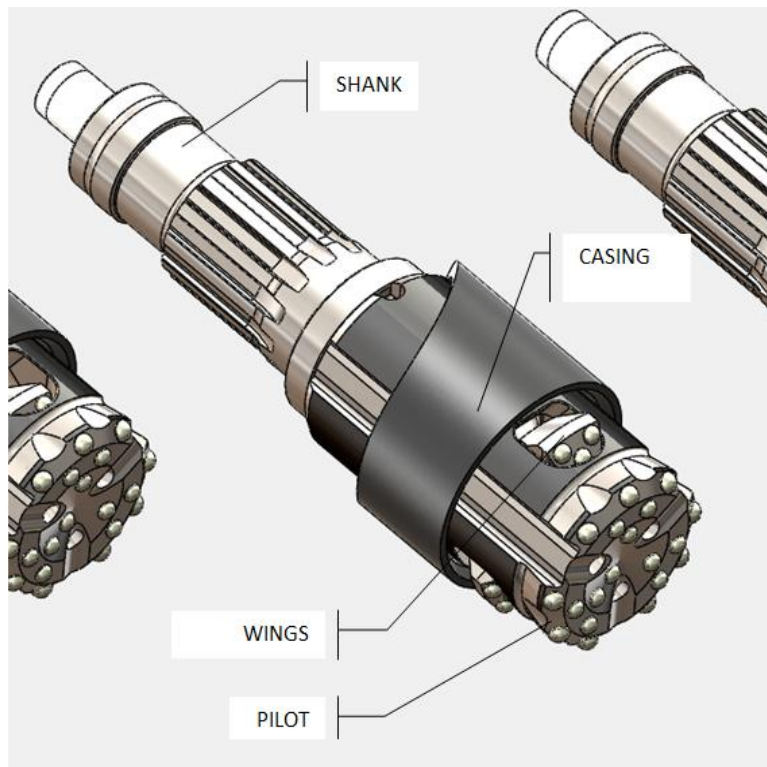

Figure 2. Roto Loc components (7" (178 mm) casing system)
with the wings extended below the casing.

An exploded view of the Roto Loc system and parts is shown in Figure 3. In this view the retaining wire is clearly visible.

Figure 3. Exploded view of Roto Loc.

Practical consideration for setup and operation include the following:
1. It is suggested that operating air pressures do not exceed 250 psi. With consideration for the compressor to be used, adjustments to jet subs or internal chokes should be made.
2. Due to the fact that a short period of reverse rotation and rattling (short burst of percussion without rotation) are required, the hammer joints (backhead and chuck) should be Baker-Locked and torqued to reduce the chances of accidental loosening.
3. Hammer, drill rod, and casing string are lifted onto drill and torqued. The flushing bell is added.
4. Advance Roto Loc through casing until wings are exposed.
5. Flush system with blowing air to ensure any debris that may be in the Roto Loc are blown free.
6. While blowing and rotating, advance assembly into soil and begin drilling. It is common to inject substantial volumes of water if drilling through clays or sticky soils.
7. Depending on the distance between end of casing and the wings, it may be possible to add drill rods and casings without retracting the wings.
8. The process for extracting the Roto Loc from the casing is to stop rotating, rattle system to loosen the Roto Loc thread following by roughly ¾-1 full rotation in reverse with Roto Loc on the bottom of the hole. Then retract wings into the pilot and extract the hammer and Roto Loc through the casing.

Table 1 summarizes the various sizes of Roto Loc systems. Note that when an "S" follows the diameter, the system contains a casing drive ring attached to the pilot bit.

Table 1. Scope of Roto Loc Systems.

System	Diameter				Applicable Casing					
	Expanded	Expanded (mm)	Retracted	Retracted (mm)	Outside Dia	OD (mm)	Inside Dia	ID (mm)	Wall	W (mm)
RL-0513-B34	5.54	141	4.07	103	5.125	130.2	4.250	108.0	0.438	11.1
RL-0513-C40	5.54	141	4.07	103	5.125	130.2	4.250	108.0	0.438	11.1
RL-0550-B34	5.87	149	4.40	112	5.500	139.7	4.670	118.6	0.415	10.5
RL-0550-C40	5.87	149	4.40	112	5.500	139.7	4.670	118.6	0.415	10.5
RL-0600-C40	6.40	163	4.98	127	6.000	152.4	5.118	130.0	0.441	11.2
RL-0600-Q5	6.40	163	4.98	127	6.000	152.4	5.118	130.0	0.441	11.2
RL-0663-Q5	7.28	185	5.58	142	6.625	168.3	5.625	142.9	0.500	12.7
RL-0663S-Q6	7.28	185	5.58	142	6.625	168.3	6.050	153.7	0.288	7.3
RL-0663S-B35W	7.28	185	5.58	142	6.625	168.3	5.625	142.9	0.500	12.7
RL-0663S-Q5	7.28	185	5.58	142	6.625	168.3	5.625	142.9	0.500	12.7
RL-0700-Q6	7.75	197	5.90	150	7.000	177.8	6.000	152.4	0.500	12.7
RL-0700-B35W	7.75	197	5.90	150	7.000	177.8	6.000	152.4	0.500	12.7
RL-0763-Q6	8.35	212	6.50	165	7.625	193.7	6.625	168.3	0.500	12.7
RL-0763-B35W	8.35	212	6.50	165	7.625	193.7	6.625	168.3	0.500	12.7
RL-0863-Q6	9.33	237	7.54	192	8.625	219.1	7.625	193.7	0.500	12.7
RL-0963-Q8	10.38	264	8.39	213	9.625	244.5	8.565	217.6	0.530	13.5
RL-0963-B38W	10.38	264	8.39	213	9.625	244.5	8.565	217.6	0.530	13.5
RL-0963S-Q8	10.38	264	8.39	213	9.625	244.5	8.835	224.4	0.395	10.0
RL-0963S-Q8-HW	10.10	256	8.13	206	9.625	244.5	8.535	216.8	0.545	13.8
RL-1075-Q8	11.42	290	9.45	240	10.750	273.1	9.560	242.8	0.595	15.1
RL-1188-N10	12.40	315	10.43	265	11.875	301.6	10.715	272.2	0.580	14.7
RL-1275S-N10	13.41	341	10.90	277	12.750	323.9	11.750	298.5	0.500	12.7
RL-1338S-N10	14.00	356	11.47	291	13.380	339.9	12.350	313.7	0.515	13.1
RL-1600S-Q12	16.93	430	14.37	365	16.000	406.4	15.250	387.4	0.375	9.5
RL-1800S-Q20	18.82	478	16.10	409	18.000	457.2	17.000	431.8	0.500	12.7
RL-2000S-Q20	20.87	530	17.63	448	20.000	508.0	19.000	482.6	0.625	15.9
RL-2400S-Q20	24.88	632	21.89	556	24.000	609.6	23.000	584.2	0.500	12.7

3. DOWN-THE-HOLE (DTH) HAMMERS

3.1 Air-Powered DTH Hammers

Ongoing advancements to the Air-Powered DTH state of technology over the past decade can be divided into the following categories:
- Air cycle improvements which address the manner in which air is delivered to and exhausted from the working chambers of the DTH hammer.
- Air bypass systems which provide alternative means for consuming air.
- Piston and bit geometry improvements which have contributed to smoother running, higher frequency hammers, as well as reduced costs.
- Accessories are now offered to make DTH hammers perform better and work more reliably in a broad range of applications.

DTH hammers are very simple machines in operation. High pressure air comes in one end (connection) and low pressure air goes out the other (bit). The exhausting air cleans cuttings from the bit face and carries them up and out of the hole. The hammer consists of two working volumes that are alternately filled with and exhausted of compressed air. The challenge to creating an efficient design for conventional valved

hammers is to optimize timing points for the four valved ports along with appropriate volumes.

In contrast, Figure 4 shows a broken-away section of a typical, contemporary, valveless DTH hammer showing the two working air volumes that exert force on the piston. Figure 5 shows a detail of the drive and return working areas on a piston.
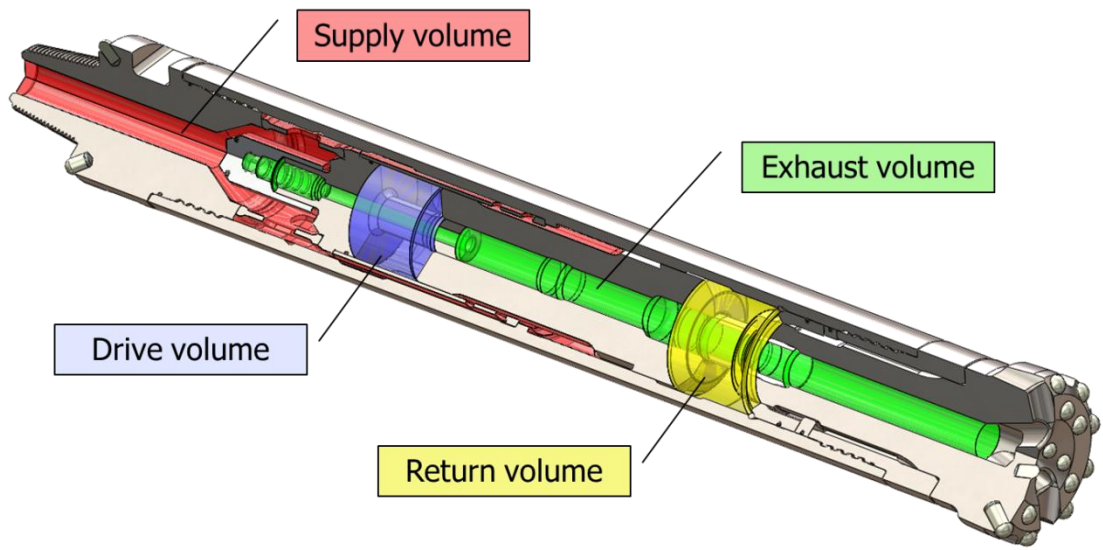
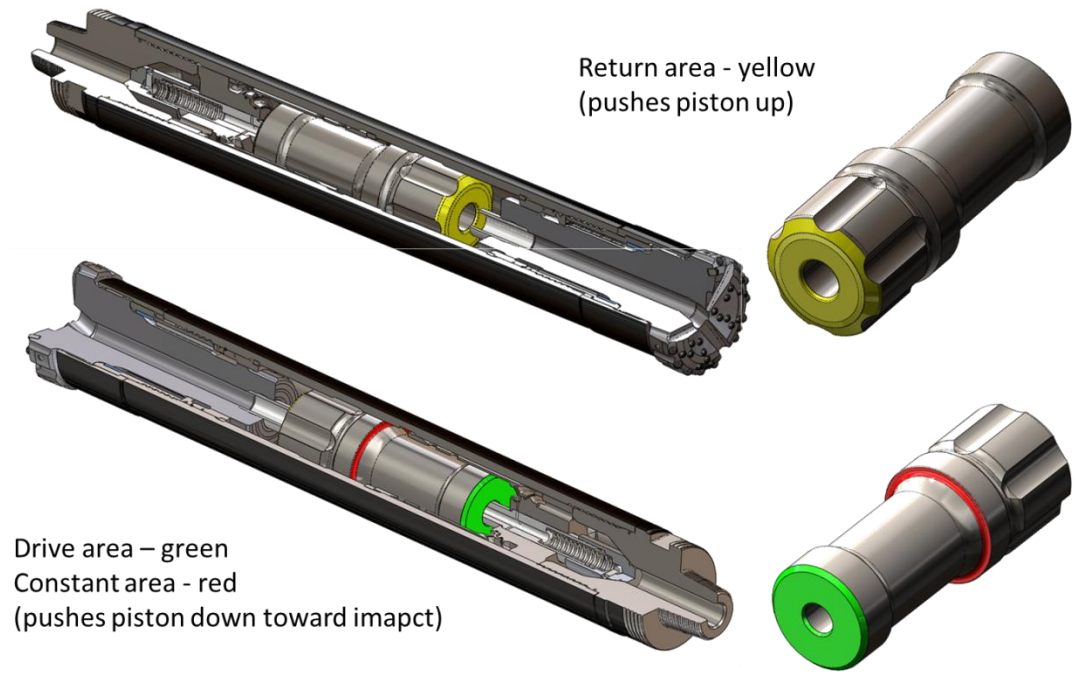Figure 4. Typical valveless DTH hammer.

Figure 5. Piston working areas.

A long standing limitation to optimizing porting was that most DTH hammers have what is referred to as fixed port air cycles. The term fixed port means the supply and exhaust ports open and close at the same location regardless of piston direction. In 1990 Ingersoll-Rand developed a new hammer cycle that was a hybrid between valved and valveless. In this new design, the major working chamber (the drive volume) was supplied through a poppet valve that would open near the top of the stroke and then close near the bottom at impact. This enabled high pressure air to accelerate the piston over a longer portion of the piston stroke and thus develop more power, and so at the time, this improved DTH hammer efficiency by about 15-20% in terms of power developed per flow rate. Ingersoll-Rand and later Atlas Copco enjoyed the benefits of this patented product for years until the patent expired. At that time, Center Rock further developed the technology using heat resistant steel components to improve reliability over the plastic parts previously used by the original manufacturers.

Figure 6 shows a cross section of a Center Rock RX70 hammer containing a variant of a hybrid valve (shown in red). Air supply is to the left of the valve and drive air is on the right. As the valve is lifted off the angled seat, supply air is able to rapidly fill the drive volume. It is common for these new steel valves and seals to outlast other parts within the hammer. Other manufacturers, such as Rockmore International, have made efficiency gains through improved air passages granting reduced losses and restrictions.
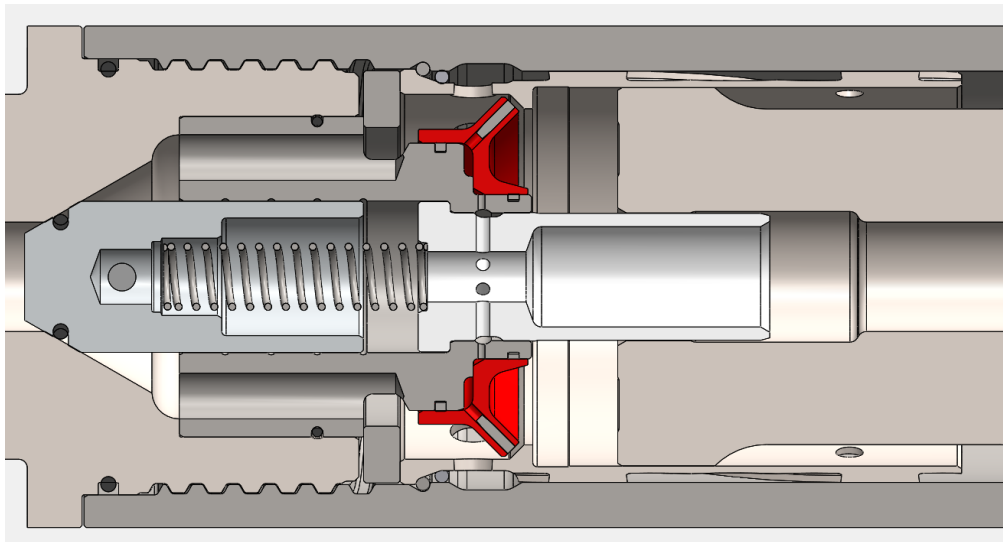

Figure 6. Steel hybrid valve and seals (RX70 Hammer).

For many applications that require high volumes of air, such as large diameter or deep holes, a means for bypassing air is required. This is simply because it would require too much pressure to push supplemental air through the hammer. Excess pressure would either overload the compressor or develop too much hammer power, or both. Either phenomenon will lead to excessive and accelerated wear, or sudden breakdown. Up until a few years ago, the only way to accomplish air bypass was to open an internal plug, called a choke, that would short circuit air from supply to exhaust. The problem with a choke system is that all the bypass air flowing through the hammer creates excessive backpressure on the piston which in turn generates a substantial loss

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in performance. This limitation has been addressed with the creation of a down-hole jetsub which bypasses air above the hammer rather than inside it.

Another element of hammer design that has seen substantial improvement relates to the matching of piston and bit geometry. Newton's cradle (Figure 7) provides a good analogy to the goal of matching piston and bit mass and geometry. Mission-Sandvik took a major step forward with their introduction of the "Mission" series hammers in the late '90's. This new series of hammer touted mirror technology in which the bit and piston were mirror images of each other. Center Rock took this concept a step further by more closely matching bit and piston mass and substantially lightening both. This became the core technology in a new hammer type (RX series), that features high frequency and smoother operation to reduce vibration-induced wear on the hammer and the drill head. High frequency is caused by the light piston and smooth operation from the bit recoil being absorbed by the piston rather than the housing, as is common in conventional hammers.

Other accessories provide additional flexibility for air adjustment such as including check valves with pressure relief systems for oil and gas operations as well as down-hole water separators called Hydrocylones for extracting power-robbing injected water from the compressed air.
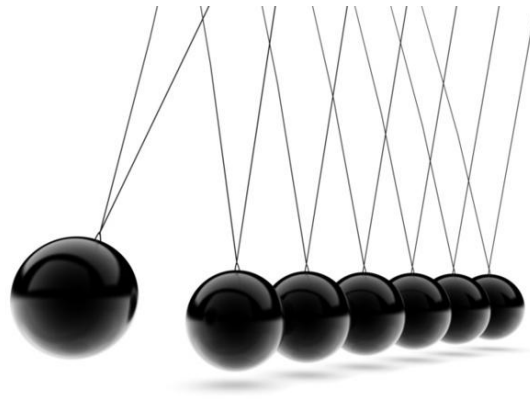

Figure 7. Newton's Cradle.

3.2 Water-Powered DTH Hammers (WDTH)

The concept of a water-powered Down-the-Hole hammer (WDTH) had been explored prior to G. Drill acquiring the original patent from Atlas Copco in 1988. LKAB, a huge underground mining company owned by the Swedish Government and providing about 90% of the European Union's iron ore, purchased G. Drill in 1991 and encouraged the commercial development of the WDTH for mining-related operations. The first full-scale WDTH production works were carried out for LKAB in 1995. Since then over 30 million lineal meters of drilling have been recorded in both underground and surface applications. The most commonly used WDTH's are produced by Wassara, also based in Sweden, although cheaper equivalents are manufactured in certain Asian countries without regard to patent right or protection.

Water, delivered at up to 180 bar, is used to activate the impact mechanism of the hammer at high frequency and with high efficiency. When the water leaves the hammer, it has a low pressure and low up-hole flush velocity (100-500 ft/min) which is still adequate to bring the cuttings to the surface and to clean the borehole. This "gentle" drilling mechanism simply reflects the fact that water is an incompressible medium, unlike compressed air, the volume of which expands as pressure reduces (such as occurs when air flush passes out of the hammer and begins to move up the drill hole annulus). The hydrostatic column created above the hammer helps to keep the hole stable and prevents collapse. In strata with high water tables it prevents ground water being sucked into the hole, as would be the case with air flush, giving rise to hole stability problems and potentially environmental implications.

Typical dimensions and operating parameters for WDTH hammers are shown in Table 2.

Table 2. Water-Powered Down-the-Hole hammer, bit dimensions and operating parameters.

HAMMER	Ø DRILL BIT	WATER CONSUMPTION	MAX OPERATING PRESSURE
W50 (2")	60mm, 64mm (2⅜", 2½")	80-130 l/min (20-35 USgpm)	170 bar (2500 psi)
W70 (3")	82mm, 89m (3¼", 3½")	130-260 l/min (35-70 USgpm)	180 bar (2600 psi)
W80 (3.5")	95mm (3¾")	130-260 l/min (35-70 USgpm)	180 bar (2600 psi)
W100 (4")	115mm, 120mm (4½", 4¾")	225-350 l/min (60-95 USgpm)	180 bar (2600 psi)
W120 (5")	130mm, 140mm (5⅛", 5½")	300-450 l/min (80-120 USgpm)	180 bar (2600 psi)
W150 (6")	165mm (6½")	350-500 l/min (95-130 USgpm)	150 bar (2200 psi)
W200 (8")	216, 254mm (8½", 10")	470-670 l/min (125-180 USgpm)	150 bar (2200 psi)

There are numerous other advantages to using WDTH. There is reduced component wear since the velocity of the flushing water is relatively low, resulting in low rates of wear on the surface of the hammer and drill rods. It is not unusual for the service life of the W100 hammer body to be up to 30,000 lft. even in very abrasive conditions, while the limitation on rod usage is typically thread wear at over 100,000 lft. Hammers are serviced every 5,000-10,000 lft. of drilling, depending on water quality.

Less harm is caused to the ground since the flushing water exits the hammer under low pressure and, given the fact that the rate of flow is moderate, the up-hole velocity is correspondingly low. Further, the hydrostatic pressure created by the flushing water helps stabilize the hole wall and therefore promotes straightness in soft formations or overburden by reducing "overbreak." Likewise, such low up-hole velocities permit the use of tight tolerance hammer and rod stabilizing devices further enhancing straightness, and deviations in the range of up to 1 degree can be anticipated, and values less than 0.2 degree can be achieved.

WDTH permits very fast and straight drilling for grout holes and has already been used throughout North America for over 15 years on major dam remediation projects. WDTH can also be used with the Roto Loc overburden drilling system to install casings from 4½ to 8½ inches in diameter.

A potential disadvantage of WDTH is that water requirements are not insubstantial, although this may not in reality be a problem when drilling adjacent to a reservoir. Further, the initial capital investment in the basic components (hammers,

rods, and pumps especially) will be higher than for air DTH, and this may deter contractors with meager resources. However, the main technological concern is that, if the hole becomes blocked, then the formation will "see" the full delivery pressure of the pump and so may hydrofracture. The authors would comment as follows.

Firstly, unlike air, water is an incompressible fluid and so, upon exiting the WDTH, by Boyle's Law, it will immediately suffer a pressure drop (P x V = K). Secondly, the authors have never seen a situation develop where either a) loss of flush return at the surface has not met with immediate response by the driller, and/or b) a total annulus blockage has actually occurred. The authors have often observed transient pressure "spikes" on nearby piezometers when drilling in karstic formations with the WDTH, but have never seen any long-lasting effect. No dam safety incidents have been recorded to the authors' knowledge, resulting from the use of WDTH technology.

4. FINAL REMARKS

It is clear that very significant and important developments continue to be made in both overburden drilling and down-the-hole drilling techniques. These are partly driven by contractors' needs (e.g., the development of Roto Loc for micropile drilling in karst), and partly by intense market competition among the hammer manufacturers (e.g., the hybrid valve innovation in the RX series hammers). In both cases, these developments have been greatly facilitated by highly sophisticated computer-aided design capabilities. The authors believe that there still remains wide scope for similar advances to be made by equipment manufacturers for the foreseeable future.

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