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Hydropower technology can assist in meeting the safety and health '2013 milestones' and save energy: a case for 'localized' hydropower systems in general and hydropowered stope drill rigs in particular

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Safety, health and energy are 'external driving factors' demanding change in the South African mining industry. Hydropower technology offers safe, clean and energy efficient alternatives to conventional compressed air. This paper looks at a new method of applying hydropower technology known as 'localized hydropower' suitable for both new mines and incremental implementation in existing mines. When localized hydropower is combined with on-level, clean-water recirculation dramatic energy and water savings can be achieved. In addition to this concept, the paper examines the particular challenge of stope rigs for hard-rock, narrow, tabular, dipping orebody mechanization. The paper also provides an overview of the current status and opportunities of hydropower technology in South Africa.

Introduction

Hydropower was originally conceived as a method of delivering cooling and harnessing the energy in the head of water entering in mines primarily to power rockdrills. Since its conception, hydropower has developed into a wide ranging technology capable of powering all drilling operations, ancillary equipment with the ability to mechanize both stoping and development. The last decade has seen the rise of mechanization through drill rigs, particularly for development, and the in the last few years the electricity supply constraint and price increases have seen an interest in localized hydropower system consisting of half-level, small-bore (100NB and less) reticulation fed by a pump. Localized hydropower systems appear to be the system of choice in small new mines with narrow, tabular, dipping orebodies especially at or in existing mines at depth or where compressed air pressures are inadequate.

Of all areas to mechanize, the narrow, dipping stope is the most difficult, especially at depth. For South African mining, this is the most significant yet-to-be-solved technical challenge[1].

This paper looks at trends in hydropower technology generally and in stope drill rigs in particular.

This paper is structured in the following way:

- 2013 Milestone attainability: safety, health and environmental benefits
- Safer: reduced exposure, safer location under support
- Energy efficient: localized hydropower with recirculation uses less energy and less water
- Flexible, manoeuvrable and easy to use: the 'holy grail' of drill rigs
- Lower cost: offers production improvements and cost savings by optimization of the drill-and-blast method
- Challenges: acceptance, training, reliability and maintenance
- Discussion, conclusions and recommendation.

2013 Milestone attainability: safety, health and environmental benefits

In 2003, the tripartite body representing the Government, labour and the mines agreed the following milestones[2]:

- Achieve safety performance levels equivalent to international best practices for underground metalliferous mines as per the 'milestone' trend line in Figure 1 as well as reduce the number of FOG related fatalities.
- The total noise emitted by a single source should not exceed a sound pressure level of 110 dBA in any location of the workplace.
- The noise exposure over an 8-hour period should not exceed 85 dBA.
- Using present diagnostic techniques no new cases of silicosis will occur among previously unexposed individuals. This milestone does not fall within the scope of this paper.

The use of hydropowered drill rigs will assist in attaining these milestones. By moving the operator back from the face under permanent support and offering a more powerful drill, the risk to the individual from FOGs is reduced and the total drilling 'man-hours' exposed time is reduced. This is discussed further below.

Hydropower machines are quieter, drill faster and, when mounted on a rig, will be further from the operator. Together, these factors reduce the 8-hour noise exposure level.

Hydropowered, rig-mounted drills also offer the benefits

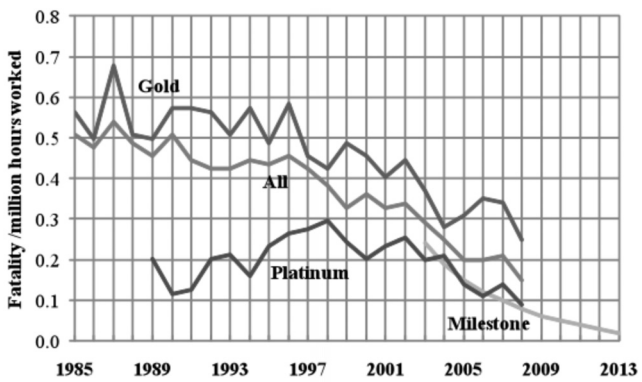

Figure 1. Fatality frequency rate (FFR) i.e. fatalities per million hours worked in SA mining since 1985 including the 2013 Milestones[3,4]

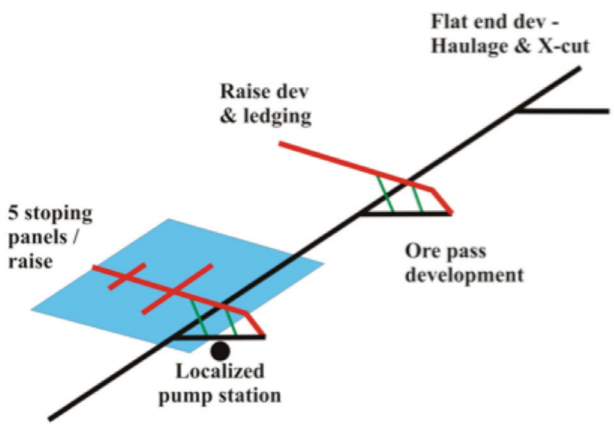

Figure 2. A typical 'half-level' mining layout connected by small-bore piping (100 NB or less) to a localized hydropower pump station

of positional cooling, elimination of hand-arm vibration injuries, reduced visibility due to fogging and no harmful oil mists in the atmosphere. These drills also effectively eliminate dust from drilling and therefore improve the local working environment and promote wellness.

Safer: reduced exposure, safer location under support

A study making use of Department of Minerals and Energy fatality data base over the last 10 years estimated that stope drill rigs have the potential to reduce the fatality frequency rate (FFR = fatalities per million hours worked) by an estimated 3% to 15% in the platinum sector and 7% to 22% in the gold sector[5]. These figures were determined by estimating the effect of relocating the operator in the safest position (up-dip and behind the rig away from face under permanent support behind the clamping post) on historical accident data. Clearly such improvements apply to all mechanization initiatives.

Energy efficient: localized hydropower with recirculation uses less energy and less water

Localized hydropower systems comprise a group of positive-displacement pumps located in a cross-cut that boost the pressure of the mine service water from typically 1 to 18 MPa. This water is the reticulated to the working areas in a small-bore (100 NB and less) localized pipe network as shown in Figure 2. The hydro-pumps are moveable and can be relocated periodically as mining progresses. Typically, the pumps would be less than 500 m from the furthest working area. Unlike centralized hydropower systems the capital costing is low and the system can be quickly installed and relocated later.

Localized hydropower systems can include all types of drill rigs (stope, roofbolt, raise, flat end development, incline-decline, long-hole) as well as hand-held drilling or any combination, e.g. hand-held stoping plus rig development drilling. A sample of development rigs is shown in Figure 3 and selection of the wide variety of ancillary equipment available is shown in Figure 4.

Localized hydropower systems can incorporate recirculation. This involves collecting the clean hydro-drill discharge water not used for flushing and returning this by gravity in a hose to a recirculation tank at the hydro-pump. Here it is pumped back into the mine service water pipeline and reused by the hydro-pump. This effectively reduces the volume of water to be lifted. It is not possible to recirculate 100% of the water on the level as this will cause a heat and salts build-up; however, up to about 70% of the water may be recirculated. Only having to pump the non-recirculated water out of the mine dramatically reduces dewatering pumping energy and water required.

Half-level mining systems powered by a local hydropump (i.e. 'localized hydropower') are very energy efficient as compared with alternative energy delivery mediums as shown in Figure 6[6,7]. Drilling energy comparisons that omit the dewatering energy are unrepresentative and incorrect.

While hydropower drills have a higher instantaneous water flow rate (1 ℓ/s), they have a dry shut-off and use water only while the drilling, unlike electric and most air drills which consume water as long as they are connected to the water supply. The kWh/m drilled in Figure 6 assumed a

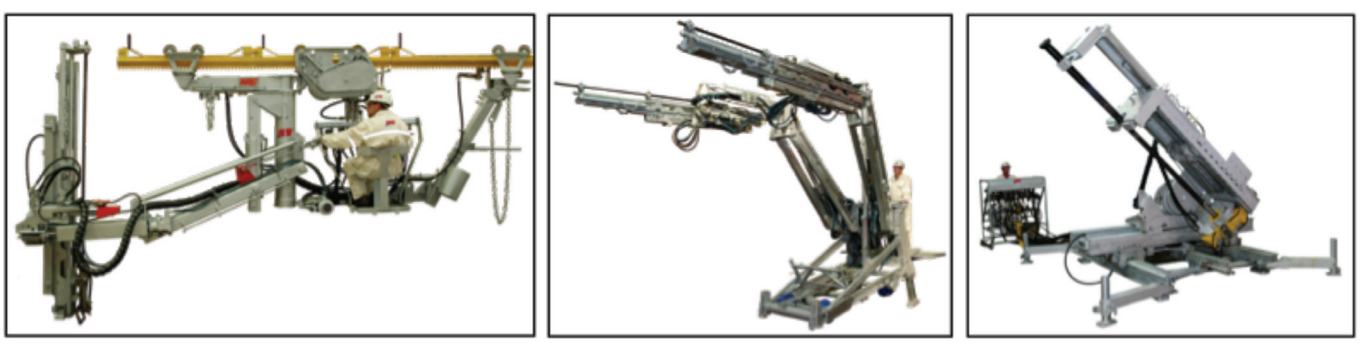

Figure 3. Raise and universal development drill rigs and long-hole drill rig

Figure 4. Ancillary equipment—roof-bolter, sweeping tool, pod setter and blast-hole cleaner

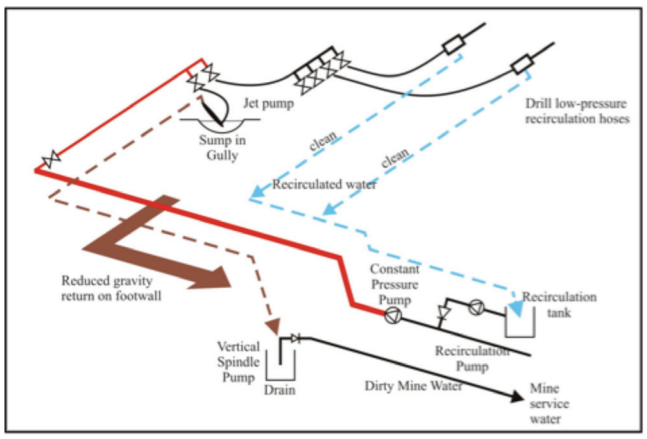

Figure 5. On-level recirculation of the clean water (not used for flushing) exhausted water from a hydro-drill

that the air drills consumed 0.12 and 0.18 ℓ/s (7 and 11 ℓpm) respectively for 6 hours of the drilling shift. Furthermore, because the electric and air drills are slower (due to the lower percussive output power), more drills are required and hence the total cooling/flushing water used over a shift is similar or more than that of a fewer number of hydropowered drills.

The increase in energy with increasing pumping depth is due the additional energy required to lift the water out of the mine.

Importantly, localized hydropower systems enable compressed air to be removed (except for refuge bays) thus making 'airless mining' possible.

Localized hydropower half-level mining systems also use much less water for drilling compared with electric or air drilling, especially if most of the water is recirculated as shown in Figure 7. The water consumption for electric and air drills is constant with and increasing density of holes because the water usage is linked to the time the drills are connected to the hose, not the number of holes drilled.

Recirculation, besides reducing the volume of water to be pumped (and the associated energy) also reduces the water entering the boxhole chutes and hence of 'mud rushes'. Properly designed boxhole chutes with slotted doors (Figure 5) and the use of hydropowered jet pumps to pick up water off the footwall and pump it into a drain pipe (Figure 6) further reduce this risk. These are proven means of managing water and have also been applied in conventional mines.

Key to the success of localized hydropower is the means to generate pressure that can deliver the variable flow demanded by the users. This is currently done using

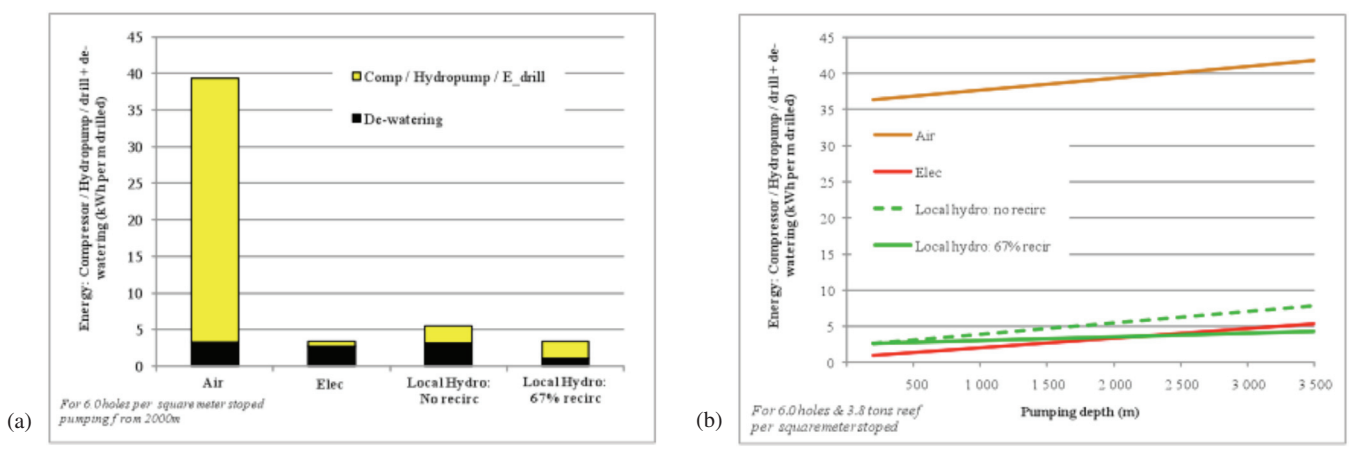

Figure 6. Energy required to drill one metre of blast hole including the motive energy (compressor or hydropump or electric drill) and the dewatering pump energy. (6a): Bar graph showing split between motive and dewatering energy, and (6b): variation of kWh/m drilled with pumping depth[5]

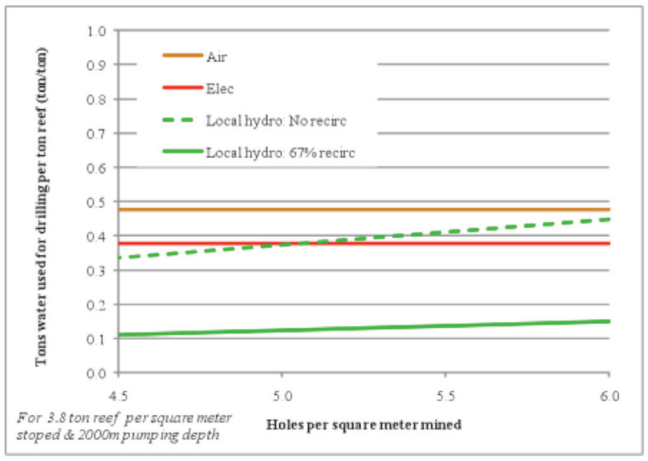

Figure 7. Drilling water consumption (tons water per ton reef) required versus the number of holes drilled per square metre mined[5]

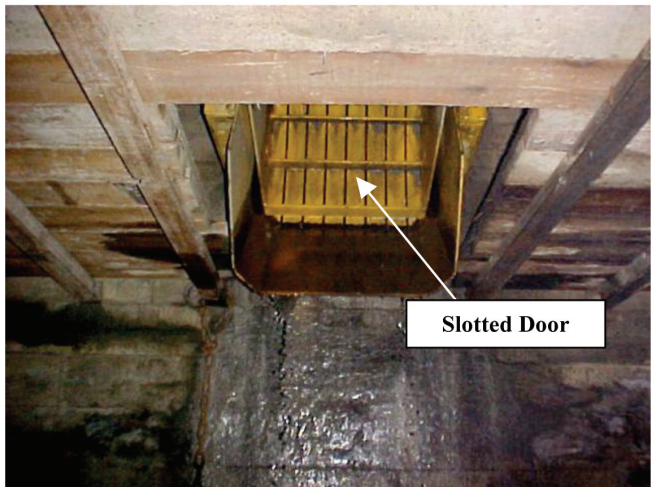

Figure 8. Boxhole chute with slotted door to allow water drainage and hence minimize the 'mud rush' risk

Figure 9. Jet pump in the gully to 'pick up' water and pump it into a pipe at the earliest possible opportunity to ensure the rock is kept 'dry' and to further minimize the 'mud rush' risk

Figure 10. Constant pressure pump

multiple, high-efficiency, positive-displacement pumps configured in a pump station with a suitable capacity control system. HPE is nearing the end of the development of a constant pressure pump shown in Figure 10 to do this.

While the focus of this paper is on rig drilling, the low energy and water needs apply equally well to hand-held hydro-stoping as is carried out at Gold's Modder East Gold Mine.

Flexible, manoeuvrable and easy to use: the 'holy grail' of drill rigs

The flexibility of raise, incline/decline, flat-end development and long-hole hydropowered rigs has been demonstrated[1,9,10,11]. The more difficult challenge of face, roofbolt and gully drilling in narrow, tabular, dipping stopes is the next stage.

At depth, the requirement for timber packs and props, temporary support props and hydraulic props and possibly even backfill reduce the space and make it difficult to move along the face 'through' the lines of support. Most mines have a allowable 'unsupported-span-after-the-blast' of less than the length of a drill steel plus drill necessitating that the drill boom manoeuvre around and between the support. Shallow platinum and chrome mines have a distinct advantage, especially when prop density is reduced by use of roofbolts.

The success of any rig in this environment depends how easily it can be moved from the protected parking place to the face, around and between the support, into the correct drilling position for every set of holes and then back to the parking place. In addition, the rig needs to be able to negotiate faults, follow the reef and deal with 'exceptions'. If these cannot be achieved easily by the operator, then success is unlikely.

Stope mechanization of hard-rock, narrow, dipping orebodies in South Africa has been approached in many ways with very limited success. Some of these (1, 2, 8, 9 and 10) offered the promise of continuous mining without re-entry, but most were designed around the drill-and-blast method.

- Mechanical rock-cutters clamped between the hanging and footwalls (COMRO experiments—bulky, difficult to move cutter and rock and hard to integrate with support. Superseded in favour of conveyor mounted hammers).
- Mechanical rock-breaking device (hammer) mounted on a face conveyor (COMRO experiments—expensive,

bulky, inflexible and complex. Superseded in favour of water-emulsion drilling).

- Blast-on reciprocating flight conveyors which also form a track for the conveyor (COMRO experiments—expensive, bulky, heavy, inflexible, complex and exposed to full force of the blast. Superseded in favour of water jet cleaning and water-emulsion drilling).
- Wheeled or 'tank tracked' multi-boom rigs that traverse the footwall (various including 'Stomech'[11]—difficult to get into face, hard to manoeuvre around support, slip on steep dips).
- Multi-boom rigs that move over a footwall metal or plastic rails that act as a datum (Sulzer[12], TDS/ Boar[13], and MM&E—these drilled well, but have not been widely adopted—rails required effort to install, limited flexibility, hard to manoeuvre around support and took time to set-up and pack-away).
- Single boom stope jig that moves along a light rail supported off temporary support props (Novatek[14]—limited success, but not widely used mainly because of effort and discipline required to set up props and rails).
- Single boom stope jig suspended below a light tubular monorail supported off roofbolts (DDT—moderate success, but not widely implemented).
- Rock splitting using so-called non-explosive 'propellants' (Boart/Brandrill—required additional and very accurate drilling and dust and fumes, while significantly less than conventional explosives, were still an issue).
- Diamond wire rock slotting (slabs difficult to move once slotted).
- Mechanical rock-breaking device (oscillating disc cutter) on a 'walking frame' followed by a conveyor (Sandvik—big, inflexible, expensive and complex).
- Low-profile versions of electro-hydraulic face or roofbolt drill rigs or long-hole stoping (Sandvik, XLP, ULP etc.—Some successes where orebody is suitable—heavy, bulky, limited to shallow dips, expensive, needed to drill several panels per shift to justify capital cost, hard to move over gullies to adjacent panel, limited flexibility, requires special mining layouts, expensive logistics and considerable management and maintenance .

In addition to these attempts, HPE built an H-frame 3 boom rig, a single-boom, tethered 'Taxi' rig on a flexible frame with skids, a jig and the tethered, single-boom S.T.R.A.P. rig. HPE and is currently testing a further two stope rigs which it believes these will become the basis of a family of widely-used, flexible, manoeuvrable, easy-to-use, compact, simple, reliable, cost-effective stope drill rig small enough to fit in narrow stopes, yet sufficiently manoeuvrable to handle the geological discontinuities and to negotiate support props while not slipping on the steep dips. These are the S.A.F.E. stope drill rig and the 'Walker' stope drill rig shown in Figures 11 and 12.

The HPE S.A.F.E. stope drill rig is about 0.8 m wide × 1.5 m long and consists of a robust H-fame chassis supporting a single boom on an arm hinged off the clamping post. It has a permanent 4-wheel drive and a wire rope capstan-and-reel synchronized winch/safety tether for use on steep dips. It has patented manipulations that allow accurate drilling (the 'A' in S.A.F.E.) and allow the boom to swing around props. It can be configured to either a left-hand face or a right-hand face and needs no tools other than a stapleloc hammer to remove and refit modules. It separates into a number of modules each of which can fit on a mono-rope winch system. The basic driven chassis can be used to support a roofbolt drill boom, traverse gullies with a simple light-weight bridge, and with a post attachment drill the gully. It could also be used as an in-stope transporter. The controls may be mounted on the machine or remotely with umbilical hoses. The test version is designed to drill stopes between 1.0 and 1.8 m high on dips up to 34 degrees using a 1.8 m drill steel.

The HPE 'Walker' stope drill rig is about 0.7 m wide × 1.2 m long and consists of a robust telescope fame chassis supporting a single boom on an arm hinged off the chassis. It moves by alternately clamping the left or right clamping post and extending or retracting the telescopic member connecting the left and right ends of the chassis. It has skids rather than wheels which can traverse broken rock or an uneven footwall. It pioneered the patented the boom manipulation that removes operate discretion and thus facilitates accurate drilling. The controls are remote with umbilical hoses. The test version is designed to drill stopes between 0.9 and 1.5 m high on a 25 degree dip using a 1.5 m drill steel.

Both the HPE rigs are inexpensive (compared with imported trackless drill rigs) and have a single boom to aid manoeuvrability and lightness. Both are water powered and can be adapted for different drill steel lengths, stope heights, etc. Both have to be parked in a safe place during the blast and driven into the face for filling. Both have removable booms. Both will need to be supported by a suitable logistics and preferably with an OEM maintenance

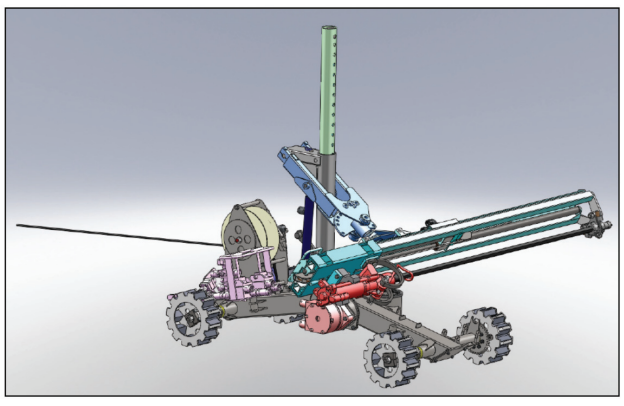

Figure 11. HPE S.A.F.E. driven (4 × 4 + winch assist) stope drill rig

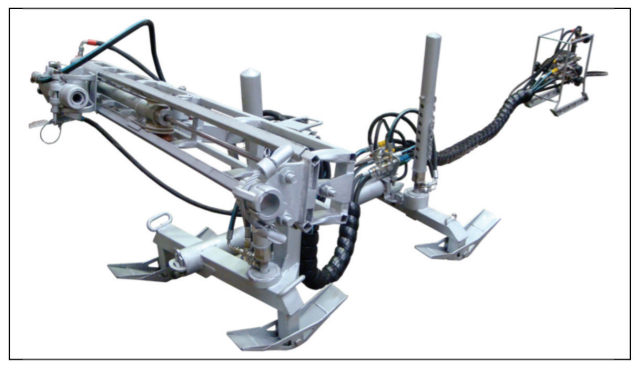

Figure 12. HPE 'Walker' stope drill rig

contract. In both cases the operator is located behind the drill rig and permanent support.

Initial results are promising, but it is still early days in terms of the trial programme.

Lower cost: offers production improvements and cost savings by optimization of the drill-and-blast method

The drill and blast method is an energy efficient way of fragmenting rock into so that it can be handled and processed. The method is well established in South Africa, but cannot optimally be implemented with hand-held drilling. This is because the drill operator cannot see through the rock and has not datum to position the drill between holes an results in significant variation in hole-angles, end-of-hole spacing and hole depths. To overcome these variations in blast-design parameters holes are often overcharged, resulting in poor advances, sockets, poor fragmentation, free-gold loss, over-break, dilution, uneven hanging- and footwalls and reduced hangingwall integrity necessitating additional support. By contrast, accurate drilling, however, offers safer hanging- and sidewalls, increased advances, better grades, increased productivity and generally easier mining.

The benefits of localized hydropower and the use of drill rigs can be separated into 'hard-to-measure or intangible' and 'measurable and quantifiable' as shown in Table I.

The capital cost of localized hydropumps and reticulation per drill is less than that for compressed air systems. A 2008 estimate of a large centralized compressor station worked out at R178 000 per air drill (based on R7.5/US$). This is compressor cost per drill is less if mobile screw-compressors are used, but these have higher energy and maintenance costs[6].

Given that fewer hydro drills are required to do the same job as air drills this cost difference is further expanded. In a number of new localized hydropower start-up mines, it has been decided to drill half the panels on day shift and half on night shift thus further reducing the capital cost of the hydropower option. The cost of the high-pressure localized reticulation system is less than the larger and longer air pipelines from the surface compressor installation. Furthermore, the hydropower pipes can be relocated and reused.

Energy costs, as shown in Table II, are lower while maintenance costs of the drill are higher than air drills, but less than electric drills. A detailed examination of these costs can be done using the HPE 'Half-level Model', but this is outside the scope of this paper[6,7].

The calculation shows that the capital cost of a pair of stope rigs can be recovered in between 3 and 14 blasts. This is modest and should be attainable due to accurate drilling and fewer lost blasts, in much less than a year and many times over after that.

Similar cost comparisons with hand-held drilling versus hydropower raise and flat-end development rigs normally show that an increase in advance of about 40% more the hand-held average achieves break-even in the overall cost per metre developed. In these development break-even calculations there is no revenue aspect. Including the revenue contribution reduces the additional advance for break-even to just a few per cent more the hand-held average. Low-cost stope rigs offer huge savings when significant improvements in advance can be achieved.

Similarly, the benefit of an improvement in head grade due reduced dilution is calculated in Table III. Again the capital cost can be recovered in less than two years on this basis alone. This, however, falls into the 'hard-to-measure' category.

Safety, noise induced hearing loss (NIHL), etc. while important are normally not included in the financial pay-back calculation, but do have financial implications.

This simple approach illustrates that the relatively low capital cost can be recovered quickly with modest levels of management, logistics and maintenance and equipment utilization compared with more expensive and complex machines.

Labour benefits have been excluded in these calculations

Table I
Benefits and/or measures of localized hydropower and the use of drill rigs

Hard-to-measure or intangible	Measurable and quantifiable
Safety improvements	Capital cost and payback period
Grade improvement (reduced dilution)	Operational performance improvements (R/ton; Centares/person)
NIHL compensation reductions	Maintenance costs (R/ton; R/m drilled)
Blast damage reduction (Better stope shape; easier support)	Advance per month increase
Better fragmentation (less fines losses & easier rock handling)	Lost blast reduction
Better and easier mining	Energy savings
Life-of-Mine (LoM) extension	Water reduction

Table II
Number of additional blasts required to recover capital cost

Scenario		Conservative		Optimistic
Head grade	g/ton	4	5	6
Tons per blast	ton	80	100	120
Precious metal extractable per blast	kg	0.32	0.50	0.72
Price of precious metal	R/kg	280 000	320 000	360 000
Revenue per blast	Rand	89 600	160 000	259 200
Marginal production cost / revenue	%	60%	50%	40%
Contribution (revenue - prod'n cost) per blast	Rand	35 840	80 000	155 520
No. of blasts to payback two rigs @ R250 000 each	**blasts**	**14**	**6**	**3**

as this may not be possible in existing operations. In a start-up operations, however, there is a significant additional benefit.

Challenges: acceptance, training, reliability and maintenance

Whereas there are many sound technical and financial reasons for localized hydropower in general and stope mechanization in particular to succeed, it is people who drive and accept or reject new technology and change. The ability to manage change is a key factor in the survival and evolution of any organization. Reinventing the workplace and management systems to support hydro-stoping or mechanization is critical.

Acceptance is necessary by management who may perceive that the benefits of faster drilling faster are not passed on as improved production. Conversely, workers may see the change as a threat to their job. The positive side is that lower mining costs extends the life-of-mine and thereby creates more jobs and safety improvements make it easier for mining companies to attract investors.

There is no short cut in introducing new technology other than good planning, effective training and follow-up with suitable measures. 'New technology bonuses' and proper selection can ensure the right persons are selected and a successful 'pilot project' in an 'easy-to-succeed' area can generate confidence.

There is a now considerable experience of both centralized and micro-hydropower in South Africa, but the technology transfer process must be well managed if the same old mistakes are to be avoided. Many mining groups have training centres that introduce users to hydropower technology and there are a growing number of personnel who have had experience with hydro-stoping and development rigs. Training modules exist, as do introductory materials for managers, supervisors and operators.

From an engineering design and maintenance point of view, the harsh environment (fumes, dust, corrosion, dirt, blast fragments, and confined space) present challenges, but these can be overcome with a suitably simple robust design and a practical approach to maintenance with in-stope exchangeable modules. The transport of the modules by mono-rope winch and the use of quick-release connections makes the rigs easier to maintain than large, bolted-together machines.

No mechanization can succeed without out the correct logistics and maintenance support (spares, stores, maintenance personnel, measurements, supervision and management) which is generally not as significant a factor in hand-held stoping, but can, and must be put in place.

Discussion

While there is never a single 'one-size-fits-all' solution, hydropower technology has come a long way in the last decade and shows every sign that bigger things are on the horizon especially given the 'external driving factors' from the safety imperative and the electricity supply shortfall and cost increases.

Localized hydropower is compatible with 'airless' mining and half-level mining approaches. It is retrofitable in existing conventional or hybrid mines and can be trialled or implemented incrementally or validated using a 'pilot-project' approach. It is also suitable in remote or under-serviced areas (e.g. shaft pillar extraction or remnant mining) and can be scaled up or down and is semi-mobile and reusable. It only requires electrical power, mine service water, dirty water drainage and the normal ventilation requirements.

Unlike compressed air technology, which is in the 'twilight stage' of its life cycle, hydropower is in the growth phase having emerged from infancy. It offers many growth paths and options. For example, stope drill rigs could be fitted with off-the-shelf remote control, lights and data loggers powered by an on-board, low-voltage, turbine alternator. It also offers alternatives to electric and oil-hydraulic drills thus avoiding the hazards electricity in the face, oil spillage/contamination and is supported by a growing number of suppliers and range of products. It has also been very successfully used out side South Africa, e.g. the Swedish developed Wassara in-the-hole drill and the new Pete Stow closed-loop water-hydraulic drill being manufactured in Swaziland by a UK company.

Hydropower technology is not limited to 10–18 MPa drilling systems. The understanding of high-pressure water hydraulics has enabled many valve and energy saving projects (e.g. 3 chamber pump systems) and efficient de-watering pump control valves. Many saving opportunities exist to synergistically combine load-shift, consumption reduction (e.g. water conservation valves) with energy recovery. Low-pressure hydropower technology can also be used to power traditional air powered boxhole chutes thus enabling compressed air to be shut off or reduced in air mine between drilling shifts. The definitive difference between the SA and overseas water-hydraulic industries is that SA hydropower industry has a adopted a 'dirt-tolerant' approach because it uses mine service water as the hydraulic medium.

Table III
Payback period to recover capital cost based on improvement in grade due to reduced dilution resulting from more accurate drilling

Scenario		Conservative		Optimistic
Head grade	g/ton	4	5	6
Tons per blast	ton	80	100	120
Precious metal extractable per blast	kg	0.32	0.50	0.72
Price of precious metal	R/kg	280 000	320 000	360 000
Revenue per blast	Rand	89 600	160 000	259 200
Improvement in grade	%	2.5%	5.0%	7.5%
Extra revenue	Rand	2 240	6 400	10 368
Payback on two rigs @ R250 000 each	blasts	223	78	48
Blasts per month	blasts	10	14	18
Payback period on two rigs	**months**	**22**	**6**	**3**

Having said all this, why have all attempts at mechanizing stope drilling in hard-rock, narrow, tabular, dipping orebodies met with so little success thus far? If it has not worked in the past, why should it work now? It is the author's premise that although need has always been there: (1) the 'external driving factors' for change have never been in strong enough to force change, (2) the economics have been marginal, (3) the right rig with the correct features has yet to become available and, (4) conventional compressed air mining has been viable and preferred by both labour and management.

Conclusions

- Rigs can assist the mining industry attaining the 2013 Milestones.
- A compelling case for localized hydropower in general and stope drill rigs in particular has been presented.
- The energy and water pumping requirements of localized hydro-drilling with on-level, clean-water recirculation are lower than either conventional compressed air or electric drilling and the relative differences improve with increasing depth.
- No definitive predictions on the future of stope drill rigs can be made except to say that many have been tried with very limited success, but need is there and the forces for change are increasing. However, two promising rigs are being tested and their progress should be followed with interest.

Recommendation

Go hydro.

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