Rapid mine development – Current trends

Suorineni, F. T.
MIRARCO-Mining Innovation / Geomechanics Research Centre, Laurentian University,
Sudbury P3E 2C6, Ontario, Canada
Email: fsuorineni@mirarco.org

Abstract

Vertical and lateral mine developments have conventionally been performed by drill-and-blast. In this paper mine development advance rates are tracked through the 1800s to date. The records indicate, that while advance rates initially increased with the development of new technologies in drilling, explosives and blasting accessories and technology, current advance rates attainable by this excavation method have flattened off, and to some extent declined. In recent years the world economy has been in a major crisis. This crisis has affected the mining industry in such a way that mining companies have become more forward thinking than ever before. Each mining project will have to result in quick returns in net present value (NPV). Strategies to achieve this objective include adopting low cost mining methods where they will normally not be used, technologies for fast mine development, and mine automation. The paper examines the limits of the drill-and-blast excavation method, and the alternatives of non-explosive excavation methods for quick access to orebodies, and concludes that the successful adoption of both low cost mining methods, and mine automation in today's world economy hinges on quick access to orebodies.

1. Introduction

Suorineni et al. (2008) gives a historical review of advances in tunneling technology, and the influence on tunneling advance rates. The focus of this work was on drill-and-blast practice in lateral developments. One of the significant conclusions in that paper was that while mines are in dare need for rapid drifting advance rates, what is achieved to date is far below what is required. Suorineni and Kaiser (2006) presented the geomechanical challenges facing rapid drift development efforts.

Experience in the Canadian mining industry shows there is urgent need for more rapid mine development advance rates. In 2000, The MIRARCO / Geomechanics Research Centre at

Laurentian University, was invited by the Canadian Mining Industry Research Organization (CAMIRO) to undertake a study to develop a rational for optimizing ground support needed for safe drift support design for underground hard rock conditions during drift advance. The primary objective of that study was to promote safe rapid drift development by minimizing time required to install adequate support during or after a drift development cycle in order to improve advance rates. The study was triggered by the observation that available data from the Canadian metalliferrous underground mines show that advance rates in single development headings are of the order of 0.5 m/manshift, which translates into 120 m/month. A survey by Laurentian University Mining Automation Laboratory (LUMAL, 1997) (Fig. 1) showed that the greatest amount of development cycle time (36–46%) is spent on support installation. This observation is supported by evidence presented by Willis and Rupprecht (2002) from the South African underground mines. Hence, it was hypothesized that by optimizing support installation time, drift advance rates could be significantly improved. Details of the CAMIRO study can be found in Kaiser et al. (2003).

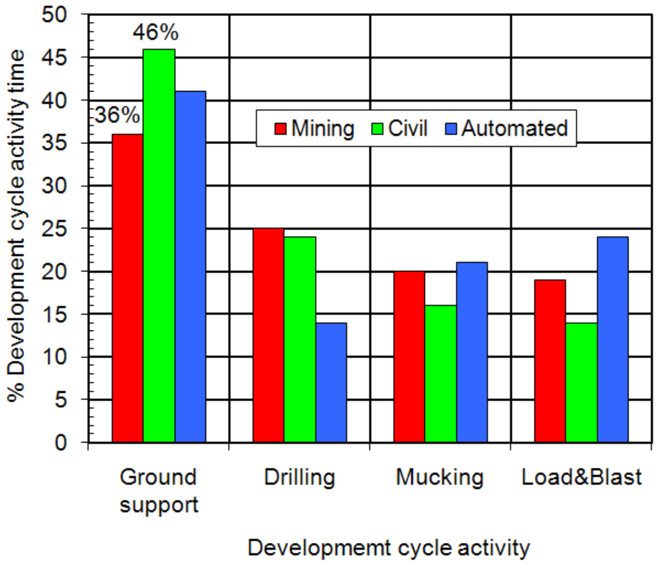


Fig. 1. Comparison of development cycle activity times in drill and blast drifting and tunneling in mining and civil tunneling.

Mass mining of large low grade orebodies at depth is the future direction of most mining companies. For this purpose, block caving is the optimal mining method. Caving mining methods require large networks of pre-developed drifts. Rapid drift and shaft developments are critical for these mining methods. Quick access to orebodies with these mining methods improves the net present value (NPV). This is more so because cave mining is a high capital cost mining method. Immediate revenue to offset this initial cost is critical for the success of the method.

2. Drill-and-blast excavation

The development of an excavation by drill-and-blast is a cyclic operation sequentially consisting of: (i) Drilling a round, (ii) Loading and blasting the round, (iii) Scaling and mucking the broken rock, and (iv) supporting the round. Ventilation and water services must be supplied to the face and interferes with the face activities. The cyclic nature of drill-and-blast implies that to optimize the process each activity time must be optimized to obtain the overall increase in advance rate.

Drifting in metalliferous mines dates back to 3500 B.C. in Caucasia, near the black sea. Initial methods of drifting in rock consisted of the use of fire at rock faces, dousing the hot rock with water and removing the fractured rock away with picks and wedges (Wahlstrom, 1973). By the 6th century BC, hand-worked tunnel advance rates in hard rocks had reached 9m/year (Beall, 1973).

The shift from the use of fire and water to the use of explosives starting with black powder to nitroglycerine through to dynamite and slurry explosives coupled with innovations in drilling from chiseling to automated hydraulic drills systematically improved development advance rates (Fig. 2). The figure shows the tunnelling and shaft sinking advance rates from 1850 to 2007. It is shown in this figure that the advance rates are correlated with the progressive advances in drilling and blasting technologies**.**

While Fig. 2 shows a steady increase in advance rates up to about 1890, between 1890 and 1960 tunnelling and shaft sinking advance rates remained stagnant. There is a gradual increase in advance rates from 1960 which could be attributed to the introduction of slurry and emulsion explosives coupled with the use of hydraulic drilling.

The technological developments in drilling and blasting should have resulted in an accompanying significant increase in advance rates to about 2.5m to 5m/day (National Academy of Sciences, 1994).

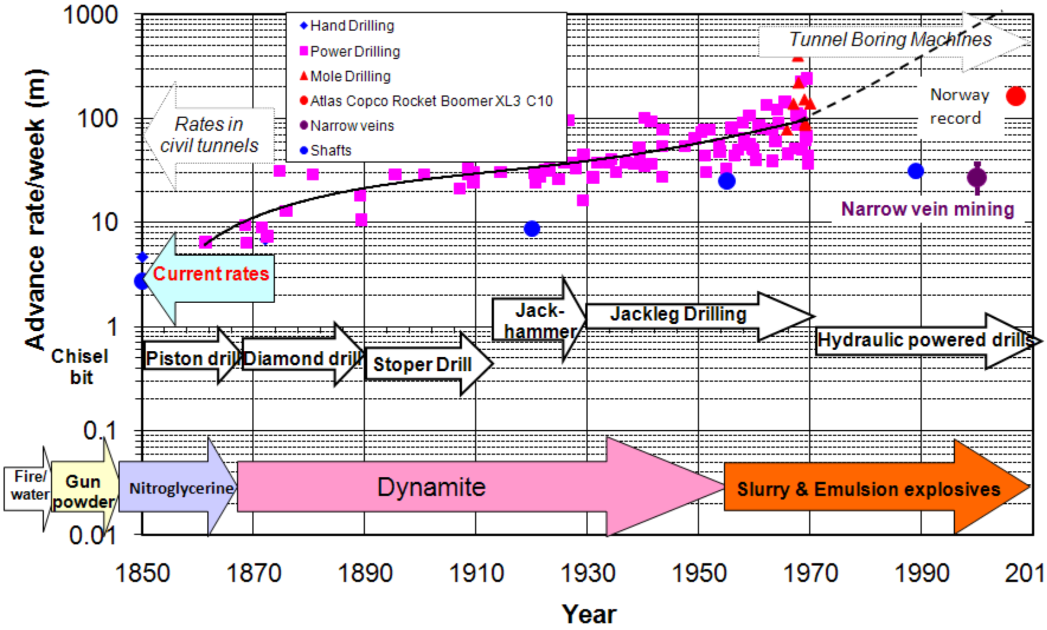


Fig. 2. Progress in advance rates in drill-and-blast tunneling with advances in drilling and explosive technologies: broken line is an extrapolation.

Surprisingly, data from the mining industry today indicates a leveling-off of advance rates since the 1890s. Current data shows that while advance rates have remained stagnant or even dropped in mining (Fig. 3), higher advance rates in the order of 120m/week are achieved in civil engineering rock tunneling.

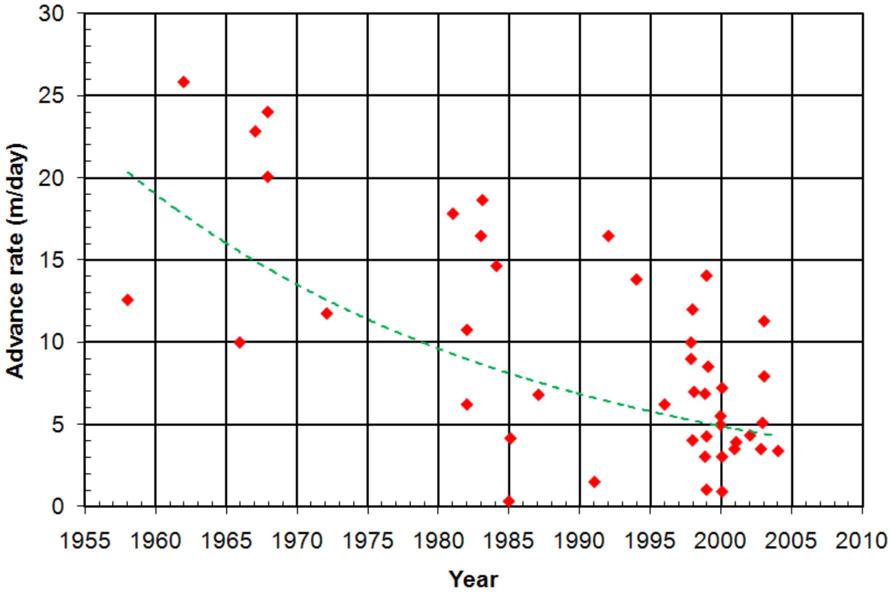


Fig. 3. Decline in drift development advance rates from 1955 to 2005.

A case history from Norway shown in Fig. 2 (big filled circle) achieved an advance rate of 165 m/week in a 38 m^2 cross-section tunnel excavated by drill-and-blast. At this site, two shift crews worked 24hrs/day and installed a total of 199 3 m-length rockbolts along the 33 drift rounds blasted for a tunnel length of 165 m. Demetri (2007) reports that an Atlas Copco Rocket Boomer XL3 C30 was used for drilling and Orica's bulk emulsion Titan 7000 slurry explosive was used as the blasting agent. Chadwick (2009) also reports advance rates by drill-and-blasts of 6 to 12 m/day in a hard rock mine (VSK Mining) in Slovakia. Empirical drill and blast models developed in the Norwegian University of Science and Technology (NTNU) show that advance rates of 81 m/week in 7.7 m-span (60 m^2 cross-sectional areas) tunnels are achievable with current technologies (Zare and Bruland, 2007). Fig. 2 and the Norwegian case history suggest that advance rates of about 60 m to 120m per week for 6-m or less tunnel diameters should be achievable today in mining, but this is currently difficult to achieve.

2.1 Challenges in drill-and-blast advance rate improvement

The geomechanical challenges in drift and tunnel support during construction include (i) Poor rockmass quality and high stress, (ii) Design of ground condition-based support systems as opposed to standard support (iii) Management of "unexpected" ground conditions (iv) Development of alternative support systems, and (v) Management of construction induced rockmass damage. These challenges are briefly discussed below.

Ground condition related constraints to advance rates can come about in three ways, namely: (i) Rockmass quality is so poor support is immediately required, (ii) Stress to strength ratio is so high that strong support is required immediately (Destressing may be required to reduce dynamic failure potential), and (iii) Ground condition is such that support can be staged but not pre-planned and rigid ventilation ducts are used.

For poor rockmass qualities with low stand-up times and for high stress to strength ratios rapid advance is not practical as excessive time will be required to stabilize the ground. For rockmasses with stand-up time less than development cycle time, immediate support within the development cycle is needed, and thus directly increase round time and the schedule. High stress to rock strength ratios, also require immediate use of strong support. Support demand increases with increasing stress to strength ratio as more broken rock has to be supported. In extreme cases (e.g. squeezing grounds) it is necessary to pre-install support ahead of the excavation face. Such a strategy implies excavating through support, and supporting within the pre-support, which may require special equipment different from what is being used.

Poor drilling and blasting practices reduce advance rates. Construction related rock wall damage reduces the rockmass quality and increases support demand. This factor is often ignored or underrated in current methods for support selection. Cotesta et al. (1999) showed that blasting-induced overbreak dominates overbreak caused by poor drilling. Poor blasting can result

in as much as 40% or more overbreak (Fig. 4). Hoek and Brown (1980) state that blasting for underground construction purposes is a cutting tool, not a bombing operation, and this must be born in mind when designing blasting operations, particularly, for fast advance.

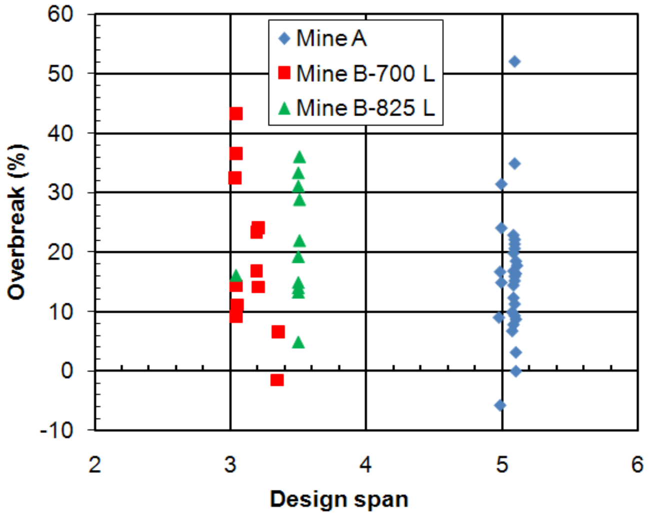


Fig. 4. Blast-induced overbreak in drift development.

Blasting operations must be designed such that rock bridges are preserved, as these are sources for a rockmass self-support capacity. Kaiser et al. (2002) showed that a 0.01m by 0.01m rock bridge in 1 m^2 area (i.e. 1% rock bridge area) is equivalent to one cablebolt support capacity. Preserving rock bridges means preserving the rockmass self-support capacity, and hence, less support and increased advance rates.

2.2 Non-supported related challenges

A number of non-support related factors have significant impact on the rate of drift advance and includes: (i) Equipment constraints: equipment size, types, number, availability, and excavation method - Equipment constraints on drift advance are well discussed by Willis and Rupprecht (2002) and are not discussed in this paper. (ii) Human factors: travel times, skills, contractual flexibility, lack of ownership, resistance to change, (iii) Regulations: federal, provisional and mine specific mining regulations, (iv) Mine planning, scheduling, influence of existing infrastructure: development layout (number of faces), (v) Ventilation infrastructure, and (vi) Limited/restricted face area. Human factors and mining regulations affect development advance rates. Long travel times, lack of skill and resistance to change affect productivity. Some mines base bonus systems on quantity of support installed rather than quality of construction. This encourages workers to spend more time on support rather than focusing on quality of construction.

Mining regulations indirectly restrict the use reduced or no support options. The "Mines Act" in the "Workplace Safety and Health Act" under Subsection 121(4) – Rockbolts, states as follows: "Where, in the opinion of the employer and the workers, the installation of rockbolts is required for ground control in order to advance, the rockbolts shall be installed to (a) within 1.5 m of the face, and (b) when a handheld machine is used, after each hole is drilled". In practice, this clause encourages workers to protest against ground control engineers to go under unsupported ground, even when technically support is not required.

The type of ventilation duct used during advance affects the possibility of support staging. There are two types of ventilation ducts, the flexible and rigid types. Second pass support (out-of development cycle support) is not possible, when rigid ventilation ducts are used near the face, as the rigid duct inhibits access to the rock face. Hence, advance planning is needed, if support staging is anticipated.

Today, higher advance rates in civil engineering tunnelling are attributed to the availability of technology for multi-tasking. Multi-tasking in civil engineering tunnelling is possible because of the large tunnel face areas (in the order of 100 m^2) compatible with equipment sizes. Barton (2000) shows TBM tunnelling advance rates increase, with tunnel diameter. This is only logical because the large diameters allow multitasking of activities such as mucking, support and advance.

In mining engineering tunnel face areas are limited (in the order 50 m^2 at best) and therefore are incompatible with current equipment sizes used in multi-tasking. Hence, increasing tunnel diameters, without multitasking will reduce advance rates. This partly accounts for the stagnation of advance rates in mining since the 1900s as shown in (Figs. 2 and 3). Drift sizes have increased to accommodate large equipment without accompanying multitasking strategies. Fig. 5 shows decreasing advance rates with increasing tunnel size. These constraints can only be overcome by sound construction management practices.

2.3 Achieving rapid advance in drill-and-blast drift/tunnel excavation

Achieving rapid excavation advance rates with the drill-and-blast excavation method means: (i) Improved rockmass characterization, (ii) Diligent construction practice, (iii) Adoption of ground condition-based support systems, (iv) Diligent planning, (v) Multi-tasking, and (vi) Adopting human factor and quality-based bonus systems. The rockmass classification systems all underrate the effect of rockbridges by not adequately accounting for discontinuous joints. This results in underestimation of rockmass self-support capacities, and results in immediate over supporting, and hence inhibiting rapid advance. Suorineni et al. (2008) provides a rockmass rating system that preserves rockmass self-support capacity.

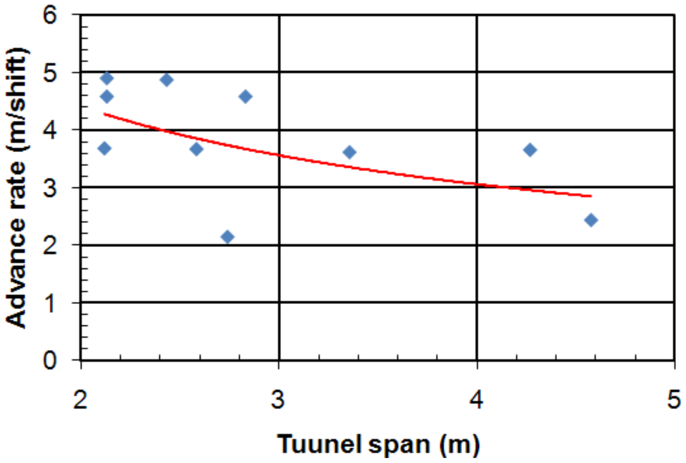


Fig. 5. Decreasing drift advance rates with increasing drift size.

For rapid drift development, the construction method should result in minimum rockmass damage. Thus, for drill-and-blast method of excavation, controlled (perimeter) blasting is pre-requisite. Cotesta et al. (1999) present a detail procedure for managing blast induced damage in excavation walls. The importance and benefits for good blasting practice cannot be better stated than the following statement by Hustrulid (2010): "Effective drifting practices are a very important part of modern caving systems. Today, available drilling and blasting technology has developed to the point that there is no reason why the rockmass cannot be 'cut as with a knife', if so desired. One of the missing items in the overall process is a simple, but technically sound, method for assigning the damage radius produced by a particular explosive-hole-rock combination. Through the application of careful perimeter blasting practices, the damage to the remaining rock will be minimal, the shape of the opening will be similar to the as-designed and the succeeding operations such as scaling and rock reinforcement will be easier and more effective (and less costly – author's addition)). This translates into improved safety and better economy, both of which are essential to modern mining."

In conventional support design methods, the support is selected for both short- and long-term survival on the belief that it is more economic to install a more elaborate support system than required for the short-term. This implies that a support capable of controlling the ground over the lifetime of a drift is often used. In mining, this means that support systems are often selected to survive the effect of nearby mining that often result in adverse stress changes.

The use of long term support at excavation faces during development is counter-productive in some ground conditions. Sections of excavations near the face are temporary during development (and are temporary excavations), and only sufficient support for worker safety within the time window of face activity is required. Thus, the conventional practice to use strong or standard support independent of ground condition during excavation development is not optimal practice, and ground condition-based near excavation face support should be adopted.

The following are ground condition-based support classes: (i) No Systematic Support (NSS): In this case geomechanics considerations show that the rockmass self-support capacity is sufficient for safe face activities and no additional support is required. This class precludes any regulatory or company policies (ii) Light Support (LS): For this support class, Geomechanics considerations show that the rockmass needs some help for safe face activities. Help may be in the form of spot bolting or application of thin spray-on liners (TSL) and (iii) Strong Support (SS): Ground conditions show that rockmass needs a lot of help and immediately for safe face activities. Help is in the form of structural reinforcement (pattern rockbolting and mesh – standard support). Table 1 is a summary of the support class details with examples. Fig. 6 is a ground condition-based support matrix for rapid drifting applications near face. Fig. 7 is an example of a no support class (NSS) drift from Vale Thompson Mine in Manitoba (A) and Holy Pond Mine in Timmins (Ontario) (B).

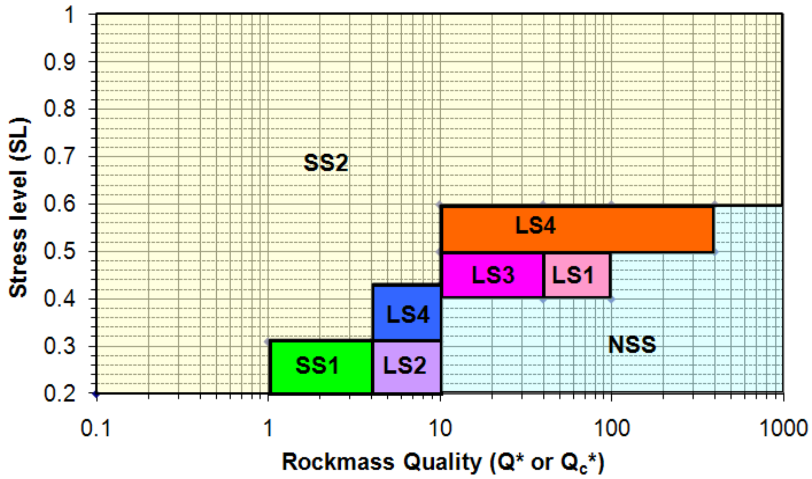


Fig. 6. Ground condition-based support matrix during drift development.

Table 1. Ground condition-based support systems

Support class		Support system category	Support system capacity	Examples
NSS		NSS	Rockmass only	Rockmass
Light Support (LS)	Ultra light	LS1	Low capacity – tendons	Ultra wide pattern tendons
		LS2	Low capacity - boltless	Thin spray-on liner (TSL) or fiber reinforced shotcrete (thickness<50mm and cures within 5 hours
	Light	LS3	Moderate capacity – Tendons only	Regular tendon pattern – No areal support
		LS4	Moderate capacity – sparsely bolted with SoL	TSL with ultra wide bolting
Strong Support (SS)		SS1	Moderate to high capacity	Tendons with screen or TSL
		SS2	High capacity	Tendons with screen or TSL

In appropriate quality rockmasses, support can be staged or subdivided to improve advance rates. Support staging is applied where either a single component of a planned multi-component support can be delayed, or when only a fraction of the total long term support is sufficient to ensure safety at the working face.

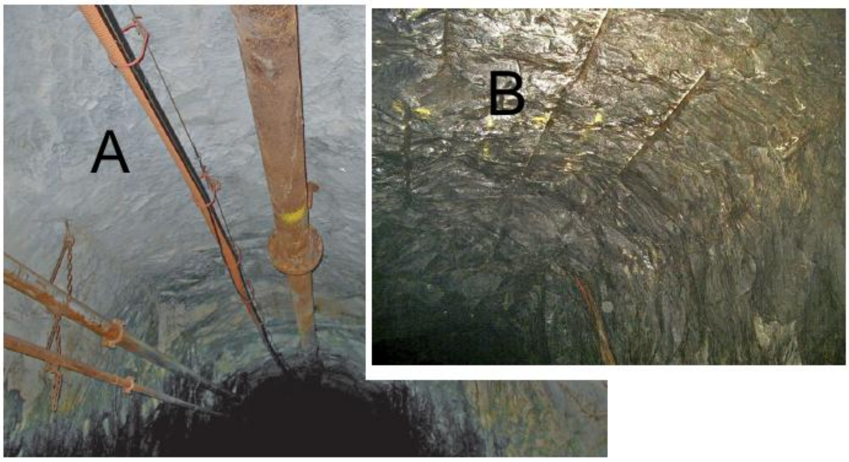
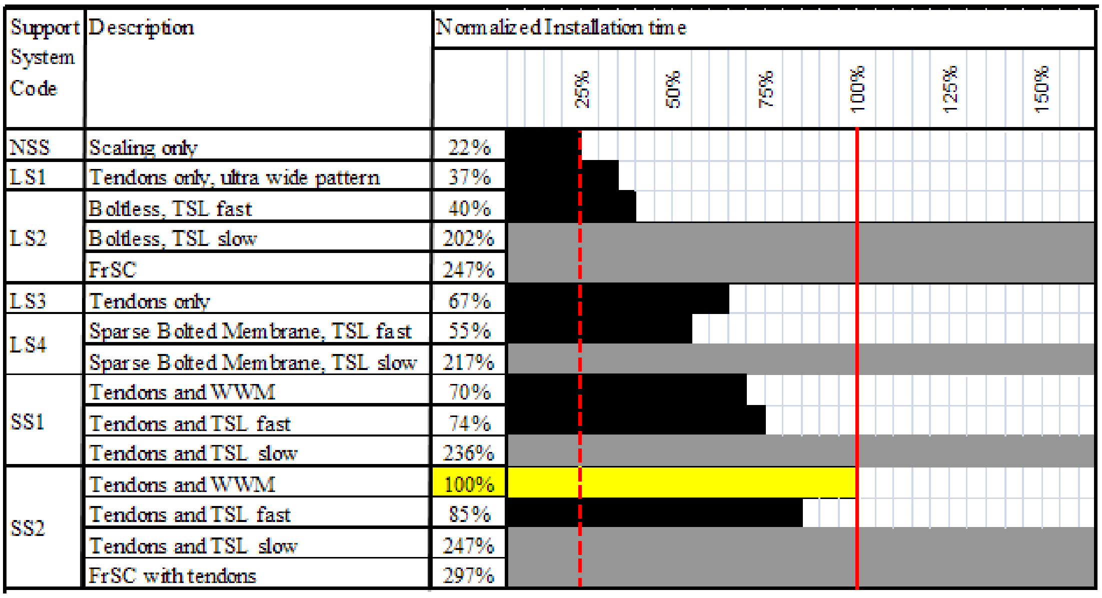


Fig. 7. Examples of ground conditioned-based support: No Systematic Support (NSS) class from Valley Thompson Mine (A) (Manitoba) and Holy Pond Goldcorp Mine (Ontario) (B).

The ability to reduce support installation time is a critical factor in achieving high advance rates. The use of thin spray-on liners is only acceptable for safe rapid drifting if adequate strength characteristics are achieved within a reasonable time period (curing time should be not more than four hours). Fig. 8 shows gains in support installation time for various support options with pattern bolting and mesh (standard support in most mines) used as baseline. The figure shows ultra wide spaced bolting and fast curing thin spray on liners have good potentials in rapid drift development.

Because eliminating uncertainties in ground characterization through detailed exploration is rather difficult if not impossible, strategies must be developed to manage the accompanying risks when they occur to reduce downtime. This implies planning for the unexpected. Planning for the unexpected ground conditions implies selecting a support system that can be easily and quickly adapted to changes in ground conditions when they occur.



Support System Code	Description	Normalized Installation time
NSS	Scaling only	22%
LS1	Tendons only, ultra wide pattern	37%
LS2	Boltless, TSL fast	40%
	Boltless, TSL slow	202%
	FrSC	247%
LS3	Tendons only	67%
LS4	Sparse Bolted Membrane, TSL fast	55%
	Sparse Bolted Membrane, TSL slow	217%
SS1	Tendons and WWM	70%
	Tendons and TSL fast	74%
	Tendons and TSL slow	236%
SS2	Tendons and WWM	100%
	Tendons and TSL fast	85%
	Tendons and TSL slow	247%
	FrSC with tendons	297%

Fig. 8. Gains in development cycle rates relative to standard supports.

Some mining companies base development bonus systems on quantity of support installed by crew. This practice results in over support, and the use of support systems that are easy to install rather than their ability to perform. Bonus systems for development crews should be based on quality of work to discourage over support and use of wrong support systems.

Since 2000, the mining industry in Canada has been aggressively finding ways of increasing advance rates with the aim of achieving 15 m/day. At current advance rates and schedules, this rate can only be achieved if each mining shift completes one round. This is certainly a monumental challenge. In recent times, attention is turning away from drill-and-blast as the main excavation method in mining. Alternative excavation technologies have been in various stages of development and are discussed in the next section.

3. Alternative technologies for rapid excavation in mining

As shown in Figs. 2 and 3, and discussed in Section 2, in the authors opinion the drill-and-blst excavation method has been stretched to its limits such that a technological leap is now required, if significant changes in excavation advance rates are to be achieved in mining to meet today's challenges in mining in the new world economy. In recent years several competing technologies are being developed to improve or replace the conventional drill-and-blast method. These include: (i) Cardox technology, (ii) Nonex technology (iii) Penetrating

Cone Fracturing (PCF) technology (iv) Controlled foam injection technology (CFI) (v) Plasma blasting (vi) Water injection technology, and (vii) Mechanical excavation technology.

Several authors (Olson, 1974; Olsson and Atchison, 1997; Singh, 1998; Caldwell, 2005; Young and Graham, 1999) have described in detail some aspects of these technologies, and only a brief description of them is given in the following sections, with a focus and more details on mechanical excavation because of increased interest in this excavation method in mining in the past two years to develop this technology as a replacement for the drill-and-blast technology in hard rock underground mine developments.

3.1 Cardox technology

The Cardox system is classified as a high pressure gas generator rather than as an explosive and consists of a high-strength, reusable steel tube filled with liquid carbon dioxide, a chemical energiser, and a rupture disc (Fig.9). A detailed description of the Cardox rock breaking technology is given by Caldwell (2005). When the Cardox tube is ignited, the carbon dioxide is almost instantaneously converted from a liquid to a gas at pressures up to 300 MPa, expanding into the rock microsfractures to fracture it.

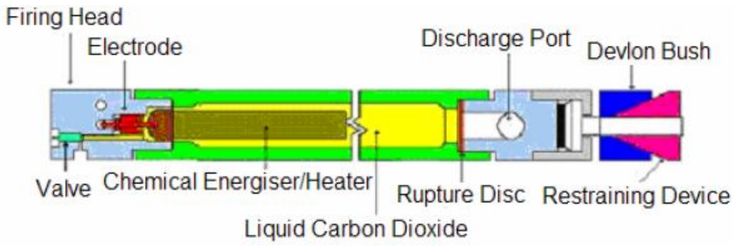


Fig. 9. The Cardox system (from Caldwell, 2005).

3.2 Nonex technology

The Nonex system consists of a cartridge which contains a propellant, which when ignited produces high volumes of harmless gases such as nitrogen and carbon dioxide, providing a pressure increase when the cartridge is sealed in a drillhole. Nonex is particularly suited in situations where the rock is not required to be fractured, but rather, split as it does not cause the rock to shatter. Nonex is classified as a 1.4S pyrotechnic rather than as an explosive.

3.3 Penetration cone fracturing (PCF)

The Penetration Cone Fracturing (PCF) technology consists of a hollow plastic tube, open at one end that is then filled with a powdered smokeless propellant, and then closed with a small cap. The other end is then machined into a wedge to lock into the stemming, and to seal the hole when inserted for ignition. There is an entry port in the cap for insertion of an electric match, which is the means of detonation. On detonation the heat ignites the propellant. The application of rapid pressure generates a tensile stress field in the rock to be broken. The classification for PCF is 1.4S pyrotechnic. As a safety precaution, the electric match used for detonation is inserted right before firing.

The name 'Penetrating Cone Fracture', or PCF, refers to the residual cone left in the rockmass after the removal of the rock by the initial propagation of the fracture. Singh (1998) gives a detail description of the PCF technology in rock excavation, and summarizes its benefits as follows: (i) The technique is considered one of the most energy efficient methods known for rock fracturing; (ii) It has the potential of being developed into a quick, efficient and inherently safe excavation technique; (iii) Its simplicity of operation and low cost make it a good candidate for automation; and (iv) It has the potential to be easily integrated into a continuously operating excavation system.

The product has been found to be particularly useful in the deep, South African mines as its low toxicity reduces re-entry time in these hard to ventilate mines, thus improving productivity by up to 40 % (Minesite News, 2000).

3.4 Controlled foam injection (CFI)

In the Controlled Foam Injection (CFI) method, viscous foam is injected into the bottom of a pre-drilled hole in the rock to be broken by means of a barrel incorporating an inexpensive and highly effective hole-bottom sealing method. Pressures needed to break rock with the CFI method are significantly less than are required in methods based upon the use of small explosive or propellant charges.

The general features of a device to use Controlled Foam Injection (CFI) for either rock excavation, or secondary breakage, are illustrated in Fig. 10. A foam injection tube or barrel is inserted into a pre-drilled hole. The successful sealing of this tube into the hole, as indicated in Fig. 10 is needed for the proper operation of the CFI process. A simple and inexpensive means, to obtain the requisite seal has been developed and successfully tested. Consistent rock and concrete breakages have been obtained with relatively crude foams, indicating that the successful commercial development of the process will not depend upon unduly sophisticated means for generating unique or complicated foams. Further details of the CFI excavation method can be found in Young and Graham (1999).

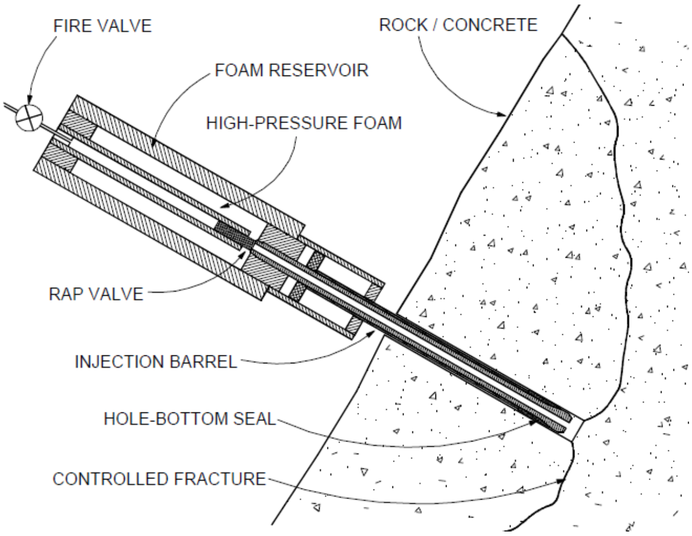


Fig. 10. Basic hardware and geometry for Controlled Foam Injection (CFI) fracture of rock (Young and Graham, 1999).

3.5 Plasma blasting

The plasma blasting method in described in detail by Singh (1998) and is only briefly summarized here. The plasma blasting concept developed by Noranda Minerals Inc. (Nantel and Kitzinger 1992; Horton, 1993) is similar in some respects to other experimental work that uses electrical energy to break rock. Such work included early studies by the USBM which demonstrated the ability of electric discharges in a confined underwater environment to generate stresses and fracture rock (Kutter, 1969).

The Noranda plasma blasting concept uses a rapid discharge of electrical energy into an electrolyte in a pre-drilled hole (Nantel and Kitzinger, 1990 and 1992; Whiteway 1991). By converting the electrolyte into high-pressure plasma, which expands very rapidly, the Noranda concept creates a shock wave. The stress field created by the expanding shock wave produces rock breakage effects very much like those produced by chemical explosives, but without the adverse effects such as fumes and excessive rock throw. The electrical energy is transmitted through an electrode that fits tightly into the hole, holding the electrolyte. The method is reported to fracture rocks with uniaxial compressive strengths up to 350 MPa.

3.6 Water injection

Hydraulic means of breaking rock have been used for decades. Initial applications involved the fragmentation of consolidated minerals or rock by a high-pressure steady or pulse jet of water. Several attempts have been made to fragment rock by injecting water into drilled holes.

Stadler (1967) attempted to break rock by blasting a charge while maintaining water pressure in the borehole. In another approach to breaking rock, a piston was driven into the water-filled drill hole to impact the fluid by means of a gun, at speeds ranging up to several hundred meters per second (Denisart, 1976). Lavon (1978) fractured the rock by forcing a fluid in the form of a longish coherent mass column into a pre-drilled hole.

Although effective in splitting unconfined boulders, hydraulic fracturing is not an effective means of excavating rock from confined conditions. Simply pressurizing a borehole results in a single fracture parallel to the borehole axis, that is not sufficient for the excavation of a face. Water jet technology has however been successfully used in scaling of excavations following drill and blast (Dunn et al., 2006).

3.7 Mechanized excavation

The first tunnel boring machine (TBM) was invented by Colonel Beaumont in 1881-82 and used to drive several kilometers of tunnel through the Channel chalk, same strata containing the Channel tunnel today. Sugden (2005) notes that the development of the TBM was rapid and motivated by the following benefits: (i) The possibility of rapid completion of tunnels, usually on the critical path, with the resultant early utilization of the heavy capital investment in the project; (ii) Increased safety of personnel working in the tunnel during boring operations; (iii) Reduction in vibration and noise in urban job sites allowing 24 hours working schedules; (iv) Reduction in damage to the surrounding rock and reducing the need for wall support structures; and (v) Virtual elimination of overbreak and excess rock removal outside the desired envelope and reduces construction cost.

In mining engineering mechanized excavation has additional benefits to the ones listed above. Because mechanization excavations result in smooth excavation wall profiles, ventilation efficiency is improved.

Peterson (1996) notes that compared to drill-and-blast tunneling, full-face tunnel boring machines (TBMs) produce the fastest tunnelling advance rates and that 50 m/day advance rates are achievable. Peck et al (1969) concluded that for identical rock conditions and support systems TBM excavation method costs sixteen to twenty percent less than the drill-and-blast method. Fig. 11 shows that for rates of advance less than 23 m/day TBMs are more expensive compared to drill-and-blast. The figure also shows that the higher the rate of advance, the lower the cost independent of excavation method.

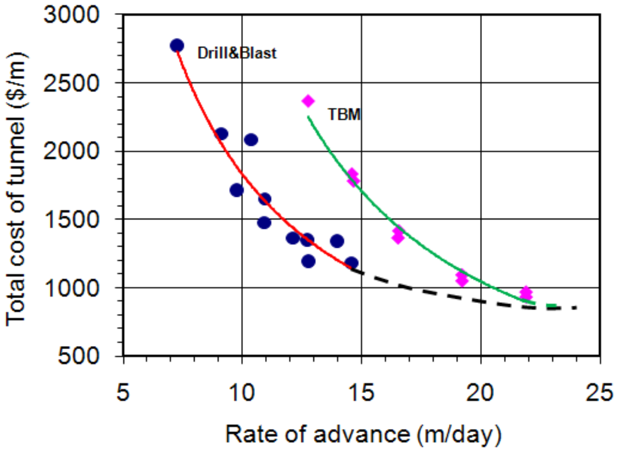


Fig. 11. Comparison between TBM and drill-and-blast cost based on advance rate.

Despite the numerous advantages of mechanized excavation over drill-and-blast, the former is only popular in civil engineering tunneling construction and in mining in soft rocks. The use of shearers and roadheaders in the coal mining industry is well researched, established and common. The roadheader was developed for soft rocks where drag bits are effect as cutting tools. The efficiency of drag bits as cutting tools in soft rocks is small and light weight machines suitable for flexible excavation shapes, as these machines can be mounted on crawlers. They need little thrust forces for the cutting action (Fig. 12).

Robbins (1987) states that the great breakthrough in hard rock tunneling occurred in 1958 when drag bits were discarded and replaced for the first time with disc cutters in a Toronto sewer project. Disc cutters excavate the rock by rolling over the rock face and penetrating the rock in a perpendicular direction by crushing it. This mode of cutting, while efficient for hard rocks, requires a massive thrust from the machine. This thrust implies heavier and less mobile machines. Thus the successful roadheader for soft rocks cannot be used with disc cutters.

Fig. 12. The roadheader machine (from Sugden, 2005).

To provide the level of cutter forces required by disc cutters heavier and less mobile machines are required. The huge sizes of TBMs for hard rock civil engineering tunneling are the result (Fig. 13). These machines are successful in civil engineering tunnel construction because the tunnels are often straight, relatively long and with no tight curves.

Fig. 13. Typical Gripper TBM for hard rock tunneling.

Today TBMs are bigger with more thrust power and stronger cutters, capable of excavating rocks with uniaxial compressive strengths greater than 300 MPa. Disc cutters have increased in size from 280 mm in diameter to the current diameter that is in excess of 480 mm. Thus TBMS have since bored through harder rocks more reliably and at improved advance rates but at initially higher cost compared to drill-and-blast. Its acceptance was also hindered by severe strainbursts in the hard rock tunnel faces, and advance rates were not superior to what drill-and-blast produced. The association of strainbursts with mechanical excavation is still an issue in hard rock civil engineering tunneling. Stacey and Jongh (1977) reported strainbursts around a deep-bored tunnel in a hard rock gold mine in South Africa, and attributed them to the excavation method.

3.7.1 Experiences with mechanized excavation in hard rock mines vertical developments

Sugden (2005) observed that one of the outstanding applications of the disc cutter technology is the raise drill for boring vertical and subvertical shafts in civil construction and ventilation raises and orepasses in underground mining.

Shaft boring machine technology evolved from the roadheader technology for soft ground tunneling. The roadheader boom with a cutter drum is equipped with drag bits for soft ground. For vertical shafts the boom is attached to a frame that can be equipped with gripper pads to stabilize and support the machine (Fig. 14), which is operated from the surface

(Frenzel and Randaxhe, 2009). The roadheader is briefly discussed in the next section. For dry conditions in relatively hard rocks (70 – 120 MPa) a pilot hole is used to remove the spoil. Raise boring is now a common practice for ventilation shaft and orepass developments in hard rocks.

Fig. 14. Adaption of the roadheader for shaft boring (from Frenzel et al., 2010).

3.7.2 Experiences with mechanized excavation in lateral development: TBM application in hard rock mining

In 1983 Robbins Company funded a study to develop a machine that works on the disc cutter principle for the hard rock mining industry (Robbins, 2001). The Mobile Miner, designed by Sugden was the result of the study. The Mobile Miner uses disc cutters mounted only on the periphery of a cutting wheel. The wheel is swept across the excavation face turning to advance the excavation.

The Mobile Miner produces excavations with flat roofs and floors, allows easy access to the face, is less bulky and heavy, and cost far less than a Tunnel Boring Machine (TBM), making it more suitable for underground. It was intended to be a versatile machine for mine drift development, cut and fill mining, and for production in tabular orebodies (Robbins, 2001). The disadvantage of the Mobile Miner is that its cut geometry is not as flexible as the roadheader.

In mining drifts of non-circular cross-sections are preferred for a reason, and this is contrary to the circular sections commonly encountered in civil tunneling that makes it convenient to excavate with TBMs. Rectangular, horseshoe or trapezoidal excavation shapes are preferred because transportation and muck haulage systems, whether on rail or rubber-tired, are best adapted to a flat floor. Sometimes the mine drift sections are modified to suit the geology (e.g. in bedded strata flat roofs may be preferred). These preferred excavation shapes in mining imply that, machines designed for mine tunneling should be capable of excavating these shapes, and pose an additional challenge in hard rock excavation.

Various versions of the Mobile Miner (MM) were employed at three sites: 2 mines and 1 civil tunnel construction sites - Mount Isa Mine, North Broken Hill Mine, and a Japanese civil construction firm.

The MM completed two tunnels at Mount Isa Mine in quartzite and was shutdown. In Broken Hill Mine the machine was used to excavate rock twice the strength of that for which it was design and with abrasive minerals. The performance of the machine was not considered impressive to inspire further application. The Japan's version was successfully used to excavate a two lane traffic tunnel in granite. Atlas Copco acquired the Robbins Company in 1993, and had shelved the Mobile Miner development. Robbins (2001) noted that the machines built to date for the hard rock mining industry have not achieved a performance and operating cost levels that would cause a mining company to develop a mine dependent on mechanized excavations. Thus while TBM application is the first choice today in the civil engineering tunnel construction, very few successful applications of TBM technology in hard rock mine development exist.

Bullock (1994) reports two case histories of full face tunneling in hard rock mines. At the Stillwater Mining Co., Chevron Resources Co. had to develop 30,500 m of footwall drifts in crystalline rock with uniaxial compressive strength between 87 to 165 MPa. The drifts paralleled the ore body at a distance of about 30 m. The TBM yielded a one-third direct cost reduction compared to drill-and-blast, and only 10% to 12% of the normal roof bolting was required. The greatest benefit was reduced development time. This mine application of a TBM was considered a success. The problem encountered during the TBM operation was that at times the ore body curved in less than the 244-m turning radius of the TBM, causing problems in the diamond drilling program that was used to delineate the orebody from the development drift.

At the Magma Copper Co., to increase production, the San Manuel Mine acquired
a 4.5-m-diameter Atlas Copco/Robbins TBM. Two key factors in choosing the TBM over drill-and-blast were reduced time for 10,353 m of development work for caving. The TBM development openings are in a series of continuous loops. These become the grizzly and haulage levels for block caving. The relatively short curves, some at 107 m radius, required a new TBM design. The ground conditions varied from severely faulted areas, having a standup time estimated at only 30 minutes, to stable quartz-monzonite with a uniaxial compressive strength of 150 to 180 MPa that had stand-times ranging from months to years. Part of the development was a 5.5% decline, pushing the limit for rail haulage. Even with a cost of about $6.75 million for the TBM and trailing gear, the projected cost/m was equivalent to that of drill and blast. The machine drove the 5.5% decline and cut a 152.4-m curve. However, problems developed in cutting curves and in muck pickup. During July and August 1994, the TBM underwent modifications that improved it for this application and allowed Magma to achieve its goals.

Garrett (2002) and Downing et al. (2007) observe that TBM tunnelling in mining is still not popular because of operational and logistics issues. Garrett (2002) observed that TBMs are not the best option when the excavation geometry is complex or where each excavation (drift) is relatively short (such as crosscuts), necessitating the constant re-mobilization of the machine for starting new drifts. Further, TBMs have limited steering capabilities for their lengths, precluding them from making sharp radius turns. These constraints on the suitability of TBMs are typical characteristics of underground mining excavations, and hence the drill-and -blast method of excavating drifts remains the main excavation method in underground mining to date.

4 Current trends in mining and mine development

4.1 Current trends in mining methods

Hustrulid (2000) discussed mining method selection for large scale underground mining at the mass mining conference in Australia where he presented trends for future mining. The conference which focused on mass mining was telling by itself. Future underground mining will largely be high tonnage mining at costs comparative to surface mining in order to be competitive in today's world economy. This trend is promoted by stricter environmental laws forcing mines to go underground coupled with depleting high grade ores and near surface orebodies, declining metal prices and the benefit of improved technology for low grade ore processing.

Fig. 15 shows the conventional mining methods including the relative mining cost for each. The high tonnage mining methods are the caving methods with the lowest mine operating cost. Chitombo (2010) observed that the strong attraction of large mining companies to cave mining methods in recent years is driven by the typical low cost and high productivity of these methods. In particular, block and sublevel caving are the only underground mining methods that can approach the high productivity and low mining costs of open pit mining.

The caving methods are capital intensive (Fig. 16) low production cost mining methods. These methods require several kilometers of initial development before start of production as shown in Fig. 17. Therefore, the success of these methods depends greatly on quick access to the orebody for early revenue generation, and acceptable net present value (NPV).

Quick access to orebodies by conventional drill-and-blast cannot be guaranteed or achieved, as discussed in Section 2 of this paper. This technology appears to have reached its limits in terms of optimized process for speed. Butcher and Smith (2010) lists non-geotechnical factors governing caving methods which includes (i) commodity price, (ii) exchange rates, (iii) exploration development timing, and end of mine life dilution. All these factors imply that for success block caving rapid access to the orebody is a key factor.

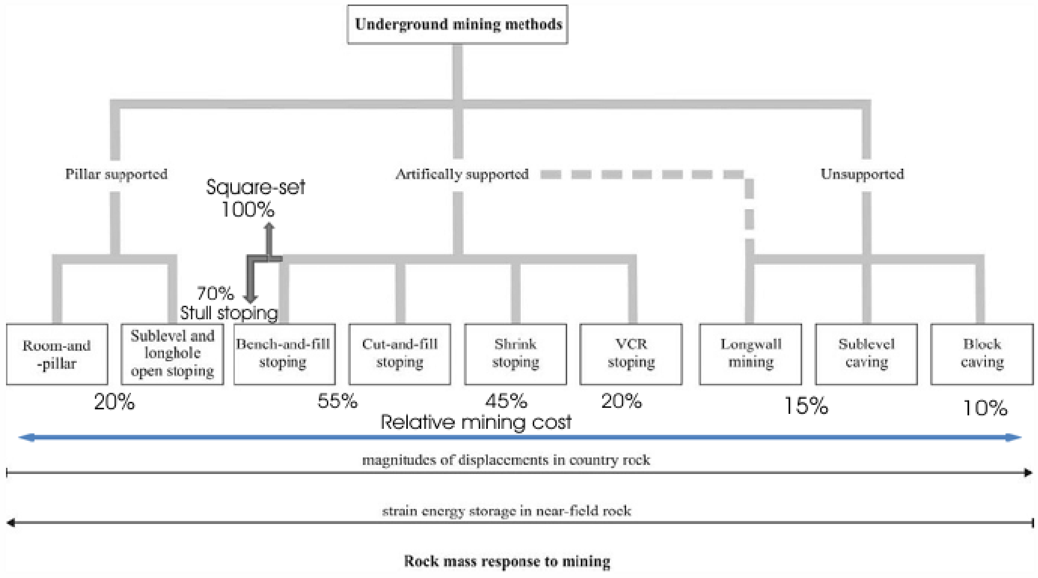


Fig. 15. Mining methods with associated relative mine operating costs (modified from Brady and Brown, 2004).

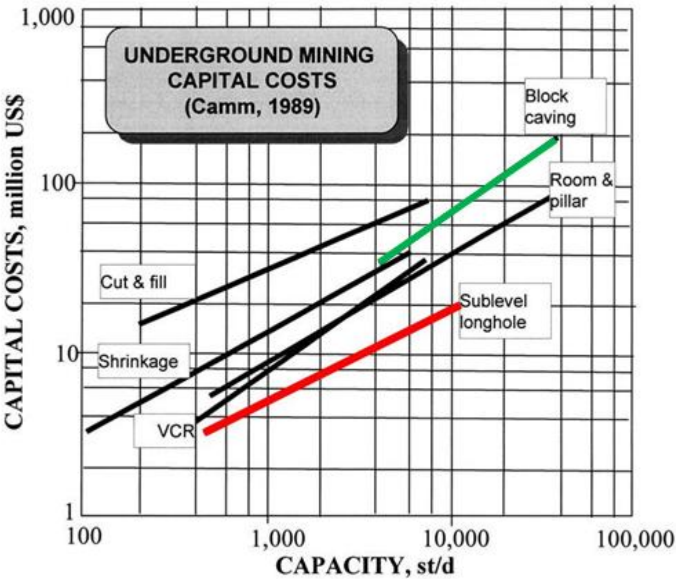


Fig. 16. Underground mining methods capital cost (after Camm, 1989).

Hence, major mining companies like Riot Tinto are looking for technological break throughs in mechanized excavation in hard rock as published in the recent press release () and at various conferences this year:

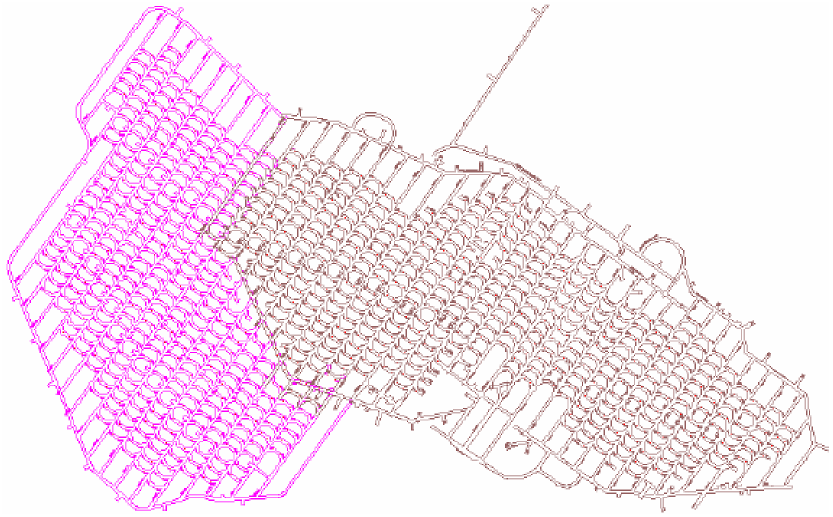


Fig. 17. Mining footprint for block cave mining (from Botha et al., 2008)

4.2 Current trends in hard rock mine development

Of all the potential hard rock non-explosive rock excavation methods discussed in Section 3, it will be argued that the option of mechanical rock excavation has the greatest potential since its technology has the most real world hard rock mine development experience, compared to any of the other methods. The recent press release by Rio Tinto (Anon, 23 February 2010) to adapt this technology for its Mine of the Future™ is a confirmation of the high potential for this technology to be successfully used in hard rock underground mine development. Rio Tinto's strategy for success in this high stakes venture is to form alliance with experienced TBM and VMS companies, namely: Atlas Copco, Herrenknecht AG and Aker Wirth. The profiles of the three companies as outlined in the press release are as follows:

Atlas Copco is an industrial group with world-leading positions in compressors, construction and mining equipment, power tools and assembly systems. The Group delivers sustainable solutions for increased customer productivity through innovative products and services. Founded 1873, the company is based in Stockholm, Sweden, and has a global reach spanning more than 170 countries. In 2009, Atlas Copco had about 30,000 employees and revenues of BSEK 64 (BEUR 6.0).

Herrenknecht AG located in Germany is a worldwide technology and market leader in mechanized tunneling. Herrenknecht is delivering cutting-edge tunnel boring machines for all ground conditions and with all diameters – ranging from 0.10 to 19 meters. In all parts of the world, around 1,000 Herrenknecht tunnel boring machines are at work. On demand we are creating project-specific equipment and service packages for our customers. The company also provides state-of-the-art deep drilling rigs to bore to a depth of 6,000 meters.

Aker Wirth is one of the leading equipment suppliers, serving the energy sector for oil and gas drilling products as well as mining and civil construction products for the industry. For more than 110 years, Aker Wirth has been supporting the establishment of a modern and efficient development of natural resources and infrastructure, promoting growth and improving the standard of living around the world. Aker Wirth is a fully controlled subsidiary of Aker Solutions AS, a global provider of engineering and construction services, technology products and integrated solutions. The roles of these companies in Rio Tinto's Mine of the Future^{TM} are discussed in the appropriate sections below.

4.2.1 Mechanized shaft sinking in hard rock

Herrenknecht AG in Germany is pioneering the vertical shaft machine (VSM) technology for shallow shafts that will expand the capability of the vertical shaft machine (VSM) to excavate blind shafts to depths greater than 100 m in rocks with strengths greater than 120 MPa (Frenzel and Randaxhe, 2009). In dry conditions the muck is removed by a pneumatic system in combination with hoisting of skips. A vacuum sucking system in combination with exchangeable skips is under development for sinking blind shafts.

A detail description of the design and performance of various models of the VSM is given in Suhm (2006). Since 2003, Herrenknecht AG has been developing and manufacturing mechanical solutions for shaft construction, aiming at increased flexibility in regard to both, shaft depth and diameter as well as geology and hydrology. Several types of shaft with differing designs are available for shaft construction in different countries with different requirements and under different conditions - from sandy geology to hard rock, and with and without groundwater. Shaft depths of sometimes more than 100 m and diameters of up to 9 m are constructed. Thus, Herrnknecht AG already has technical solutions to adapt the "VSM" shaft sinking equipment to underground mining purposes in hard rock.

For deep hard rock shafts, a new shaft boring system (SBS) has been developed by Herrenknecht AG in collaboration with Rio Tinto (Frenzel et al., 2010), and summarized in the following. The development of the SBS is based on proven technologies. The SBS integrates excavation, mucking, primary rock support, installation of the final lining, and shaft infrastructure. This new system dramatically improves the health and safety of shaft construction.

The semi full-face sequential excavation process is based on the use of a rotating cutting wheel excavating the full shaft diameter in a two stage process for one complete stroke. An overview of the SBS is shown in Fig.18. The SBS machine can be separated into five main functional areas as shown in the figure: (1) Excavation chamber with cutting wheel having a diameter equal to the excavation diameter of the shaft (10–12 m)and equipped with 480 mm disc cutters, cutting wheel drive assembly, mechanical machine support structure, shotcrete and probe drilling equipment (2) Adjustable front support with slew bearing/drive assembly cutting wheel support and dust shield (3) Regular rock support area for rockbolts (4) Mainframe with gripper carrier, gripper system and thrust cylinders and (5) Rear alignment system (secondary gripper) and muck handling system.

A full mining cycle will consists of the following steps, once the SBS is reset:

(i) Trench excavation (plunging),
(ii) Bench excavation (slewing),
(iii) Extend SBS support legs,
(iv) Retract and reset main gripper system,
(v) Adjust SBS vertical alignment with rear gripper system, and
(vi) Activate main gripper system.

Further details of this innovative shaft boring systems can be found in Frenzel et al. (2010).

4.3 Mechanized hard rock mine development

Rio Tinto has selected Altlas Copco and acker Wirth to develop two different two rapid development tunneling equipment for deep hard rock underground mining. This is in preparation for the two new Rio Tinto mines that are to be exploited using block cave mining. The two mines are Resolution Copper in Arizona and Oyu Tolgoi in Mongolia.

Atlas Copco will develop a new tunneling machine called the Modular Mining Machine (MMM) that utilizes the learnings of the Atlas Copco Robbins Mobile Miner discussed in a previous section.

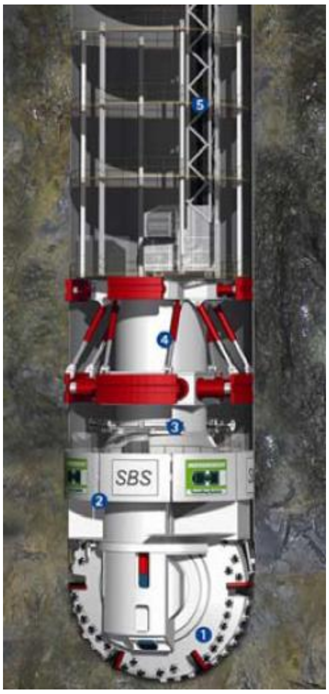


Fig. 18. Shaft boring system (SBS) for sinking shafts in hard rocks, up to 2000 m-depth (from Frenzel et al., 2010).

The Modular Mobile Miner is anticipated to be able to achieve more than twice the performance of normal tunneling methods in the expected ground conditions. Aker Wirth's winning model concept combines the flexibility of a roadheader operation with the robustness of a tunnel boring machine. This concept utilises the learnings of the previous version that was developed and tested in the early 1990s. Using the undercutting technology at the core of the concept, Aker Wirth's Mobile Tunnel Miner (MTM) (Fig.19) will be capable of meeting the challenges set out by Rio Tinto to improve the safety and speed of tunnel construction in underground mining.

5. Potential hurdles in mechanization

5.1 Design issues

Because of the scale and associated cost with huge machines like TBMs, and likely SBSs, the only time to know if it works or fails is when it is on the actual job! This means ensuring that no stone is left unturned in the design process both mechanically, and geomechanically.

Design issues on new machines for the hard rock mining industry are well summarized by Robbins (2001) based on his experience with the design and performance of several mechanical excavation machines for the hard rock mining industry. Robbins (2001) noted that the cost and time required to develop such machines is often much greater than expected by the developers. He states that approximately fifty million dollars was invested by the Robbins Company and their industry partners over a period of 16 years mostly in the operating, testing, and improvement of the machines in the field.

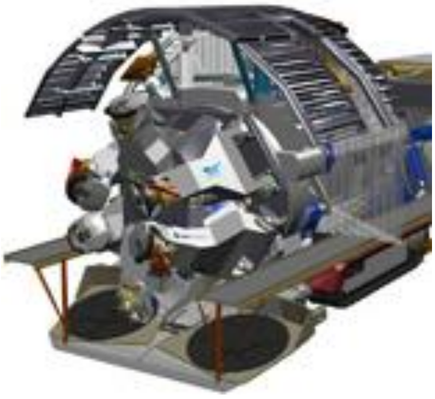


Fig. 19. Aker Wirth model Mobile Tunnel Miner (MTM) (Aker Wirth, 2010)

He suggested that to minimize this cost and time, the development concepts of these machines be thoroughly tested on paper, especially their projected performance. These observations probably serve as guidelines for today's mining equipment developers, more so when such equipment are developed full scale directly and sent into operation. Any flaws can lead to huge lost in development and liabily costs.

5.2 Ground characterization issues

The greatest known enemy of mechanized excavation is "unexpected" ground conditions. The greatest advantage of mechanized excavation that makes it attractive in the construction and mining industries is its rapid advance rates. This attraction is immediately lost when a TBM or SBS gets stack in unexpected ground conditions, and cannot be quickly liberated. In such cases, these technologies become nightmares and liabilities, and excavation advance rates can be negative. In extreme cases projects have been abandoned. In these situations the drill-and-blast method are more favourable.

The United States National Committee on Tunnelling Technology (Anon, 1984) studied ten tunnel and shaft project case histories in detail from site investigation to completion of construction to assess the effect of “unexpected” ground conditions on downtime and construction cost overruns. The results (Fig. 20) show that “unexpected” ground conditions are responsible for most construction delays because the contractor is not prepared for it and hence slow advance rates and construction cost overruns.

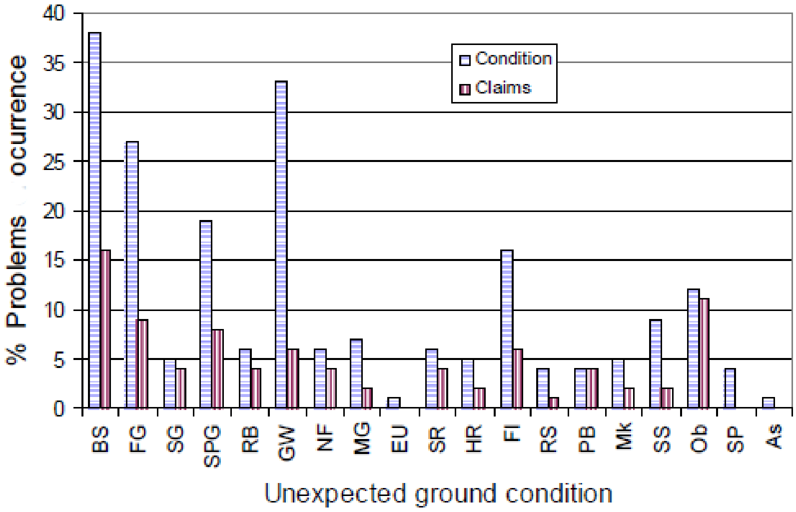


Fig. 20. Frequence unexpected ground condition occurrence and contractor claims: BS=Bocky/slabby,FG=Flowing ground, SG=Squeezing grond, SPG=Spalling ground, RB=Rockburst, GW=Groundwater inflow,NF=Noxious fluids, MG=Methane gas, EU=Existing utilitlies, SR=Soft rock, HR=Hardrock, FI=Face instability, RS=Roof slabbing, PB=Pressure binding, MK=Mucking (oversize), SS=Surface subsidence, Ob=Obstructions (boulders, pipes, etc) SP=Streering problems and As=Air slaking.

The figure shows that 61% of the time the unexpected subsurface condition is rockmass quality related, followed by groundwater and stress related problems. Rockmass quality and stress form 74% of the unexpected problems. Unexpected ground conditions and material property variability can completely stall tunneling advance independent of excavation method. The study also revealed that misinterpretation of geotechincal site investigation results is equally dangerous.

In another study on geotechnical site investigations (Anon, 1984) 84 tunnels and 3 shaft case histories were surveyed to determine the effect of "unexpected" ground conditions on contractor claims (Fig. 21). Most contractor claims originate from "unexpected" ground conditions.

It is difficult if not impossible to eliminate unexpected ground conditions from construction risks. In civil engineering only 0.01 to 20% (median of 0.7%) of the construction cost is often allotted to ground characterization (Clayton, 2002). This number is inadequate to provide adequate subsurface ground conditions to avoid unexpected ground conditions. Barton (2000) note that unexpected ground conditions are responsible for the slowest advance rates in TBM tunnelling.

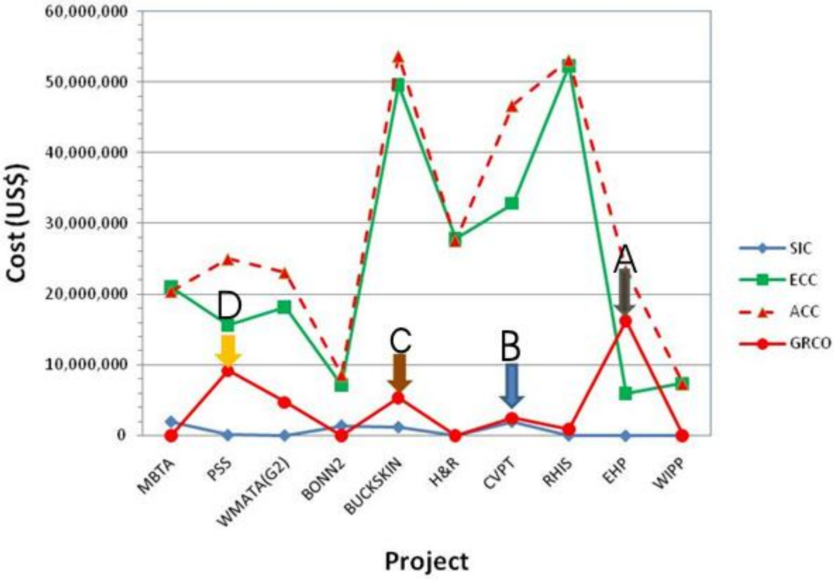


Fig. 21. Consequences of "unexpected" ground conditions on construction costs: SIC=Site investigation cost, ECC=Estimated Construction Cost, ACC=Actual Construction Cost, GRCO=Ground Related Construction Cost Overrun. A=D&B based on wrong interpretation of geotechnical report, B=Soft rock, faulty zones and blocky ground, C=TBM tunnel in running ground and D=TBM tunnel collapsed trapping 17 men for 22 hours.

Various technologies currently exist or are being developed to overcome the "unexpected" ground dilemma. These technologies are based on geophysical tools and drilling. The geophysical tools are less expensive compared to probe drilling. Some geophysical methods with high potential are discussed by Kaus (2008) and Pelizza and Peila, (2005). Kaus (2008) describes a real time ground condition prediction drill boring using a Bore-Tunnelling Electrical Ahead Monitoring (BEAM) method.

6. Conclusions

This paper has identified that cave mining methods are the future mining methods to enable underground mining companies to be competitive with surface mining companies, and to meet the challenges of today's world economy. The success of the cave mining methods depends greatly on rapid access to the orebodies for quick revenue generation and acceptable net present values.

The conventional mine construction method using drill-and-blast has reached its limits and cannot provide the advance rates needed for rapid access to orebodies and early production from block cave mines that require several kilometers of development.

Alternative methods of mine development have been developed and tested over the years. Of all the methods, mechanical excavation is the most tested and tried with several benefits for underground mining. This technology is the best alternative to the conventional drill-and-blast method to achieve today's perceived mine development advance rates. There are however, huge risks in adopting this technology for hard rock underground mining. Experienced mine excavation machine development companies such as Atlas Copco and Aker Wirth stand to minimize those risks based on their history.

This however, is not achievable without large investments from big industry partners, and Rio Tinto is taking this leap with the manufacturing industry.

References

Aker Wirth, (2010), Aker Wirth selected to develop new machine for rapid underground mine development, Press Release, 10 March 2010, 1 p.

Anon, (2010), Rio Tinto expands Mine of the Future™ program and selects partners for rapid construction of deep underground mines, Press release, 23 February 2010, 3 p.

Atlas Copco, (2010), Atlas Copco and Rio Tinto to explore advanced tunneling equipment for deep underground mines, Press Release from the Atlas Copco Group, 24 February 2010, 2 p.

Barton, N. (2000), TBM Tunnelling in Jointed and Faulted Rock, Balkema, Rottadam, 172 p.

Barton, N.R., Lien, R. and Lunde, J. (1974), "Engineering classification of rock masses for the design of tunnel support", Rock Mech., Vol. 6, pp. 189-239.

Beall, J.V. (1973), Mining place and contribution: In: Cummins, Givens (Eds.), SME Mining Engineering Handbook, vols. 1: 1-2 to 1-13. AIME, NY.

Bieniawski, Z.T. (1973), "Engineering classification of jointed rockmasses", Trans. S. Afr. Inst. Civ. Engnrs, Vol. 15, pp. 355-344.

Botha, J., Watson, S., Arkadius, T., Samosir, E. (2008), "Simulation applications at PT Freeport Indonesia's DOZ / ESZ Block cave mine", Proceedings 5th International Conference and Exhibition on Mass Mining: MassMin 2008, H. Schunnesson and E. Nordlund (eds), Luleå, Sweden, 9–11 June, 2008, pp. 237-246.

Brady, B.H.G., Brown, E.T., (2004), Rock Mechanics for Underground Mining, Third edition, Springer, 626 p.

Bruce Downing, B., Carter, T., Beddoes, R., Moss, A., Dowden, P. (2007), "Use of tunnel boring machines at depth: Extending the limits", RETC Proceedings, 10-13 June, 2007, pp. 1131-1142.

Bullock, R.L. (1994), "Underground hard rock mechanical mining", Mining Engineer, November 1994, pp. 1263-1268.

Butcher, R. and Smith, G. (2010), "Strategic considerations in block caving, Proceedings of the Second International Symposium on Block and Sublevel Caving", Potvin, Y. (ed), Australian Centre for Geomechanics, Perth, Australia. In News Letter, ACG, Vol. 34, May 2010, pp. 3-7.

Camm, T. W. (1989), "Mine and Mill Models for the Juneau Mining District", BuMines Rep., Mar. 1989, 41 pp.

Chadwick, J. (2009), "Cost effective tunnel development in Slovakia", T&UC, June 2009, pp. 35-36.

Chitombo, G.P. (2010), "Cave mining — 16 years after Laubscher's 1994 paper 'Cave mining – state of the art', Caving 2010, Potvin (ed), Perth, pp. 45-61

Clayton, C. (2002), "Managing geotechnical risk", IGT Seminar, Zurich, 2002.

Cotesta, L., Lidkea, W. and Martin, D. (1999), "Quality control in drift development", Proceedings of the 101st CIM-AGM, Calgary, 2-5 May, 1999, CD- ROM, 11 p.

Demetri, G. (2007), "Norwegians set new drill-and-blast record", Tunnelling and Trenchless Construction, Vol. 33, 4.

Denisart, J. P. (1976), Method of braking a hard compact material", U.S. Patent No. 3, 988,037, Oct. 26.

Downing, B., Carter, C., Beddoes, R., Moss, A. and Dowden, P. (2007), "Use of tunnel boring machines at depth: extending the limits", In: Proceedings, Rapid Excavation and Tunnelling Conference, Traylor, M. and Townsend, J. (eds), Toronto, Canada, SME, 10-13 June, 2007, pp. 1131–1142.

Dunn P.G., Whitmore, J., Szwedzicki, T., Robb,A., McHugh, C., Maciejewski, L. and Blythe, M.G. (2006), "Hydroscaling for rapid drift development", Second international Symposium, Rapid Mine Development, 7-8 June, 2006, RWTH Aachen, Germany, pp. 41-54.

Frenzel, C. and Randaxhe, R. (2009), "Development of block caving mines with mechanized excavation", Mining Reporter, Vol. 3, pp. 23-27.

Frenzel, C., Delabbio, F. and Burger, W. (2010), "Shaft boring systems for mechanical excavation of deep shafts", Proceedings of the Second International Symposium on Block and Sublevel Caving, Y. Potvin (ed), Australian Centre for Geomechanics, Perth, Australia. In News Letter, Australia Centre for Geomechanics, Vol. 34, May 2010, pp. 2-4.

Garrett, R. (2002), "Montreal breaks new ground with roadheader", World Tunnelling, pp. 306–312.

Golder Associates, (1976), An appraisal of the state of the art for application to transit systems, Tunnelling Technology, Ministry of Transportation and Communications, Research and Development Division: 1976, 166 p.

Hoek E. and Brown, E.T. (1980), Underground excavations in Rock, Instn Min. Metall., London, 527 p.

Horten, N. (1993), "Plasma blasting", World Mining Equipment, Vol. 17, pp. 20-26.

Hustrulid . W. (2000), "Method selection for large –scale underground mining", MassMin 2000, Brisbane, (eds), 29th October – November 2000, pp. 29-56.

Kaiser, P.K., Cotesta, L., Vasak, P., Anderson, B., Cai, M. and Dasys, A. (2002), Drifts@Risk User Documentation, Mirarco IDG Group, December 2002.

Kaiser, P.K., Suorineni, F.T., Henning, J., Diederichs, M., Cai, M., Tannant, D.D. and Hajiabdolmajid, V. (2003), Guidelines on Support Selection for Safe Rapid Drift Development, Report Submitted to Canadian Mining Industry Research Organization (CAMIRO), 237 p.

Kaus, A. (2008), Geo exploration Technology Manual, 18 p.

Kutter, H. K. (1969), The electrohydraulic effect: Potential application in rock fragmentation, U.S. Bureau of Mines RI 3717, 35 p.

Lavon, E. V. (1978), Method and device for breaking a hard compact material, U.S. Patent No. 4,123,108, Oct. 31, 1978.

LUMAL, (1997), Laurentian University Mine Automation Laboratory.

Minesite.com incorporating, (2000), MINEWS, 2000, http://www.minesite.com/archives/news_archive.

Nantel, J. H. and Kitzinger, F. (1990), "Plasma blasting technique", Proc. 3rd International Symposium on Rock Fragmentation by Blasting, Brisbane, Australia, 18-19 June, 1990, pp. 79-82.

Nantel, J. H. and Kitzinger, F. (1992), "Environmental impact of electric blasting", Presented at the Randol Gold Forum, Vancouver, B.C., Canada, March 25-27, 1992.

National Academy of Sciences, (1994), Management and Disposition of Excess Weapons Plutonium, National Academy Press, Washington, DC, p. 150.

Olson, J.J. (1974), "Rapid excavation research – Elements of a new excavation technology", In Proceedings RETC, SME, Chapt. 100, pp. 1503-1535.

Olson, J.J. and Atchison, T.C. (1997), "Research and development – Key advances for rapid excavation in hard rock", In Proceedings RETC, SME, Chapt. 78, Vol. 2, pp. 1393-1441.

Pelizza S. and Peila, D. (2005), "TBM tunneling in rock: ground probing and treatments", World long Tunnels, 2005, 36 p.

Peterson, F. (1996), "Long-term safeguards for plutonium in geologic repositories", Sci. Global Security,Vol. 6 , pp. 1–29.

Robbins, R. (1987), "Machine tunneling in the 21st century", Tunnelling and underground space Technology, Vol. 2, pp. 147-151.

Robbins, R.J. (2001), "Mechanical mining in hard rock: A glimpse into the future", SME Annual Meeting, 26-28 February, 2001, 7 p.

Stacey, T.R. and Jongh, (1977), "Stress fracturing around a deep-bored tunnel", Journal of the South African Institute of Mining and Metallurgy, pp. 124-133.

Stadler, H. (1967), Borehole blasting device, U.S. Patent No. 3,307,445, Mar. 7, 1967.

Sugden, D.B. (2005), "Innovation through design" Michell medal Oration, Australian J. Mechanical Eng., Vol. 2, pp. 1-9.

Suhm, W., (2010), "Area of application of mechanized tunnelling in the mining industry", Second International Symposium, Rapid Mine Development, 7-8 June, 2006, RWTH Aachen, Germany, pp. 523-533.

Suorineni, F.T. , Kaiser, P.K. and Henning, J.G. (2008), "Safe rapid drifting – Support selection", Tunnelling and Underground Space Technology, Vol. 23, pp. 682–699.

Suorineni, F.T., Kaiser, P.K., (2006), "Rapid drifting – geomechanical challenges and practical constraints"' In: Proceedings of the 2nd International Symposium: Rapid Mine Development, RTWH Aachen, Germany, pp. 159-176.

United States National Committee on Tunnelling Technology, Sub Committee on Geotechnical site Investigations, (1984), Geotechnical site investigations for underground projects, National Academy Press, Washington, D.C., Vol. 1., 182 p.

Wahlstrom, E.E. (1973), Tunneling in Rock, Elsevier, 250 p.

Whiteway, P. (1991), "Made-in-Canada mining technology", Canadian Mining Journal, Apr. 1991, 19-25.

Willis, R.P.H., and Rupprecht S (2002), "The challenges of rapid access development in South African deep level mines", In Proc. NARMS-TAC, Hammah, R., Bawden, W., Curran, J. and Telesnicki, M,University of Toronto, Toronto, ON., 7-10 July, 2002, p. 119-128.

Young, C. and Graham, C., (1999), "Controlled foam injection - Progress towards automated hard rock Excavation", 5th Int. Symp. Mine Mechanics & Automation, Ontario, Canada, June, 1999, 15 p.

Zare, S., Bruland, A. (2007), "Progress of drill and blast tunnelling efficiency with relation to excavation time and costs", In: Proceedings of the 33rd ITAAITES World Tunnel Congress, Prague, Czech Republic, pp. 805–809