Technical considerations for TBM tunneling for mining projects

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Abstract

Tunnel boring machines (TBMs) have been used for the construction of various tunnels for mining projects for the purpose of access, conveyance of ore and waste, drainage, exploration, water supply and water diversion. Several mining projects have seen the successful and economic beneficial use of TBMs, and there is an increasing awareness of the benefits of TBMs for mining projects. Key technical considerations for the use of TBMs for the construction of tunnels for mining projects include geological issues (rock type, rock alteration, rock strength, rock abrasivity, durability, ground water inflows), depth of cover and the potential for overstressing/rockbursts, site access and terrain, portal locations, TBM constraints, minimum tunnel size, tunnel support requirements, contractor and labor experience, and project schedule demands. TBMs offer key project schedule benefits with high rates of progress, which is a unique economic advantage recognized for mining projects where timing is of the essence in order to advance mining development and achieve early startup for operations. A thorough evaluation of the anticipated ground conditions should be performed as part of the decision to adopt a TBM for a mining project. Minimum specifications for TBMs are necessary in order to prevent the incorrect type of TBM from being used. Appropriate geotechnical investigations are necessary in order to provide key information on the anticipated subsurface conditions for careful planning and design of the proposed tunnel alignment. The overall site and geological conditions associated with some projects may suggest that it is not appropriate to use TBMs for some mining projects due to a perceived higher risk.

Key words: TBM, Tunnel boring machines, Tunneling in mining

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Introduction

Technical considerations for the use of tunnel boring machines (TBMs) for the construction of tunnels in mining projects are distinct from those for typical civil engineering applications. One of the key technical considerations is that subsurface geological conditions in and around most mining projects comprise highly altered bedrock that represents weak conditions that can pose special challenges for the use of TBMs.

TBMs have been used for various purposes as part of new and expanding mining projects since the 1950s, including new access, conveyance of ore and waste, drainage, exploration and water diversion. The use of TBMs for mining projects has not been without its fair share of challenges. Any simplified perception that TBMs cannot be used for mining projects is false, as it is subject to geological risk.

This paper outlines the key technical issues that need to be considered for the use of TBMs for mining projects, the advantages and disadvantages of the use of TBMs, some minimum requirements for their use and some unique approaches for geotechnical investigations required for the their use.

Historical use of TBMs for mining

There have been several successful and economically beneficial applications of TBMs for the construction of tunnels for mining projects. Table 1 presents a list of projects where TBMs have been used for the construction of tunnels for access, conveyance, drainage, exploration and water diversion purposes for new and existing mines.

The early use of TBMs at mines was for exploration tunnels and mine development, or access tunnels where there was a need for fast excavation to complete exploration and new access as part of mine expansions. The greatest use of TBMs for mining has been for mine access at the Stillwater Mine in the USA, where a third campaign of TBM excavation is currently underway. Figure 1 presents the high-powered open type TBM with a slightly larger diameter than previously used. Other key uses of TBMs at mines have been for water supply (Rio Blanco), water diversion (Mineral Creek) and drainage during operations (Ok Tedi).

In the early 1990s, a TBM was used for the development of more than 12 km of tunnels at the San Manuel Mine in Arizona. A 4.6-m-diameter open main beam type of TBM was used and was mobilized underground into the mine via a shaft and launched from an underground chamber. Figure 2 shows the TBM used at the San Manuel Mine.

The construction of the Rio Blanco water diversion tunnel to supply water for the El Teniente Mine in Chile was also launched from a large underground chamber within the underground mine, as shown in Fig. 3.

The open type TBM used for the Rio Blanco water diversion tunnel at the El Teniente Mine was underpowered, which initially resulted in low rates of progress for the competent and very strong dioritic rock. Upgrades were completed on the TBM during the early stages of the project and resulted in sustained production rates of 30 m/day.

A most recent and notable use of a TBM at a mine has been

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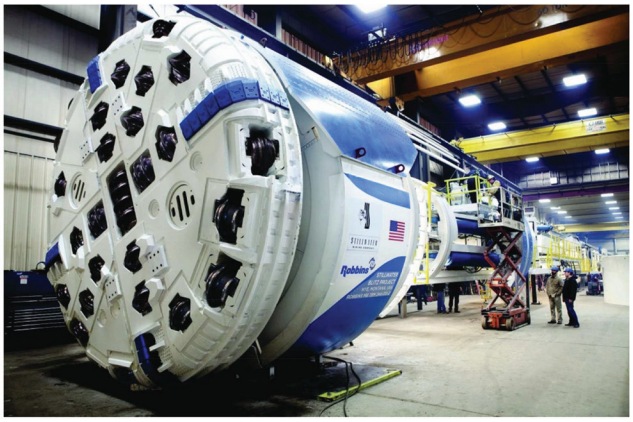

Figure 1 — New TBM for the Stillwater Mine.

Figure 2 — 1993 TBM at the San Manuel Mine.

at the Anglo American Los Bronces Mine in Chile, located at an elevation over 4,000 m, where an 8-km exploration tunnel was constructed between orebodies to facilitate exploration drilling. Figure 4 shows the specially designed TBM that was used at the Los Bronces Mine in Chile.

A notable current use of a TBM is at the Stillwater Mine in Montana, where additional tunnels are being constructed as part of the mine expansion. TBMs were first used at this mine for the development of nearly 30 km of tunnels for the main mine access in the late 1980s and the late 1990s. Figure 5 illustrates the open main beam type of TBM that was used in the past at the Stillwater Mine.

Recent key technical advances have been developed for TBMs for future consideration in the excavation of tunnels for complex mining layouts. Aker-Wirth has developed a tunnel boring system (TBS) that is currently undergoing an initial 2 km trial at the Northparkes Mine in Australia. The TBS will be operated by Strabag, an experienced civil engineering tunnel contractor from Austria (Fig. 6).

Table 1 – TBM use at mining projects.

Project	Location	Year[a]	Length, km	Size, m
Step Rock Iron	Canada	1957	0.30	2.74
Nchanga	Zambia	1970	3.2	3.65
Oak Grove	USA	1977	0.20	7.4
Blyvoor	South Africa	1977	0.30	1.84
Fosdalen	Norway	1977	670	3.15
Blumenthal	Germany	1979	10.6	6.5
Westfalen	Germany	1979	12.7	6.1
Donkin Morien	Canada	1984	3.6	7.6
Autlan	Mexico	1985	1.8	3.6
Kiena	Canada	1986	1.4	2.3
Stillwater EB	USA	1988-91	6.4	4
Fraser (CUB)	Canada	1989	1.5	2.1
Rio Blanco	Chile	1992	11.0	5.7
San Manuel	USA	1993	10.5	4.6
Cigar Lake	Canada	1997	> 20	4.5
Port Hedland	Australia	1998	1.3	5.0
Stillwater EB	USA	1998-01	11.2	4.6
Mineral Creek	USA	2001	4.0	6.0
Amplats	South Africa	2001	0.35	2.4
Monte Giglio	Italy	2003	8.5	4.9
Tashan Coal	China	2007		4.9
Ok Tedi	PNG	2008	4.8	5.6
Los Bronces	Chile	2009	8.0	4.2
Stillwater Blitz	USA	2012-13	6.8 [b]	5.5
Grosvenor Coal	Australia	2013	1.0 [b]	8.0
Oz Minerals	Australia	2013	11.0 [b]	5.8
Northparkes	Australia	2013	2.0 [b]	5.0
El Teniente	Chile	2014	6.0 [b]	10.0

[a] Year of start of project.

[b] Planned TBM excavation.

Key technical considerations

Geological conditions. Mining environments are commonly associated with highly altered rock conditions that can present some unique challenges for consideration for the planning of tunnels.

Deleterious minerals, including zeolites containing smectites, gypsum/anhydrite or vein filled laumontite, are also commonly present within the host bedrock of many economically mineralized areas. The main concern about deleterious minerals is their susceptibility to scour and/or erode unlined water conveyance tunnels. Deleterious minerals will also typically result in moderate to low rock strengths.

TBMs are most appropriately applied in homogeneous rock conditions that are conducive for excavation, including very strong rock varying from 150 MPa to 250 MPa. Extremely strong, massive (widely jointed) and abrasive rock will impact TBM progress; however, larger (19 in. or 483 mm) cutters in conjunction with high-power capacity can result in attractive TBM progress rates.

TBMs are also most appropriately applied along tunnel alignments, where there exists a relatively low percentage of poor quality rock associated with faults/shears and/or highly altered rock.

TBMs are not ideally suited to places where a significant amount of poor quality rock conditions are anticipated or sig-

Figure 3 — TBM Launch Chamber at El Teniente.

Figure 4 — TBM for the Los Bronces exploration tunnel.

nificant and sustained ground water inflows may occur, such as that associated with permeable fractured or porous rock, since unmanageable ground water inflows will impact TBM operations. A thorough evaluation of the anticipated ground conditions should be performed as part of the decision whether to adopt a TBM for a mining project.

Depth of cover/potential overstressing. One of the key considerations for the use of TBMs is the depth of rock cover along the tunnel alignment and the potential for overstressing. Overstressing will occur under the following conditions:

- High rock cover.
- Low/moderate rock strength.
- High in situ stresses.

Evaluation of the potential for overstressing requires knowledge of the uniaxial compressive strength and in situ stresses. Estimates of rock strength can be made by field observations at bedrock outcrops and knowledge of the type of rock and the presence of alteration. Ideally, laboratory testing of rock block or drillcore samples should be undertaken.

TBMs are typically not considered to be appropriate for long, deep tunnels, where extensive lengths may be subject to overstressing due to low rock strengths and/or high in situ stresses. Destressing ahead of the advancing tunnel face does not occur for TBM excavation, but does for drill-and-blast tunnels, and significant amounts of high capacity tunnel support will be required to be installed close behind the cutterhead in a protected area for workers.

Under such high-stress conditions, there also exists the

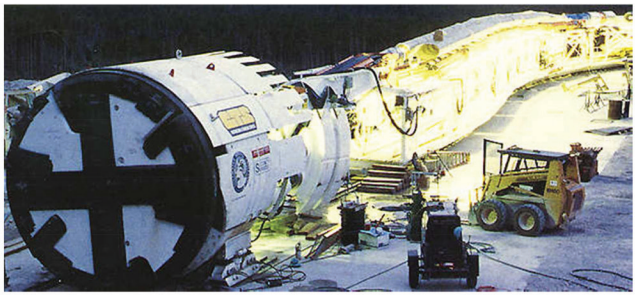

Figure 5 — Historical TBM at the Stillwater Mine.

Figure 6 — Tunnel boring system.

potential for the occurrence of rockbursts impacting worker safety. There is limited protection around the cutterhead area of the TBM, unless specific modifications have been made for this purpose. Brox (2012, 2013) presents a simple evaluation and classification for overstressing, including the potential for rockbursting based on the empirical spalling criteria, and has validated several deep TBM projects with the approach.

Successful support systems to address severe overstressing, such as rockbursting include the McNally TBM Support System, as illustrated in Fig. 7.

Site access and terrain. Appropriate site access and terrain with low-gradient roads must be considered to allow for the practical mobilization of TBM equipment. The weight of large size TBMs (> 8-10 m) can exceed 130 t, and special low-boy access vehicles are typically required to bring TBMs to portal areas for assembly. Alternatively, the maximum payload for high capacity helicopters (Mi26) is limited to 20 t and, therefore, restricts the use of TBMs to only small models in remote locations.

While many existing mine sites have well established access that will facilitate the use of TBMs via existing haul roads, declines and shafts, special access requirements will often be required for new remote mining projects, particularly in mountainous terrain.

TBM launching requirements. Practical locations with sufficient area must exist that facilitate the assembly of TBMs, unless large span caverns/chambers can be excavated to allow for the assembly of TBMs and for the starter tunnel. Tunnel portals are always sited at the base of slopes, where rockfall and/or avalanche hazards may exist. The site laydown for a TBM is much larger than that for a drill-and-blast operation and, therefore, there is greater risk for rockfall/avalanches to impact TBM operations during construction. Figure 8 shows

Figure 7 — McNally TBM support system.

Figure 8 — Los Bronces assembly chamber.

the TBM assembly chamber used at the Los Bronces Mine at an elevation of more than 4,000 m in the Chilean Andes, where mobilization and assembly was successfully completed in midwinter for protection.

As previously mentioned, the rock conditions around mine sites can include highly altered bedrock with extensive weathering near the surface. Under such conditions, large excavations may be necessary for the preparation of portals for safe tunnel construction. TBM launch chambers can typically be excavated within existing underground mines, as was done at El Teniente (Fig. 3).

Tunnel alignment and inclination. The vertical alignment for TBMs is typically kept below a maximum grade of 3%; otherwise, special braking systems have to be included. Horizontal alignments also have similar limitations, with typical minimum radii of curvature of about 250-300 m.

However, the TBS that has been recently developed by Aker-Wirth and is undergoing trials at the Northparkes Mine has been specifically designed to operate at a minimum radius of curvature of 30 m for the construction of complex mining geometries.

Tunnel alignments should be planned to avoid poor quality rock conditions, deep sections and intersecting geological fault zones at high angles to minimize additional ground support. With highly specialized setups, TBMs have been used for the construction of inclined shafts for hydropower projects and escalator tunnels for metro stations, with typical inclinations of 45°. Figures 9 and 10 show setups and launching of upward and downward inclined TBMs. Notable inclined examples for TBMs include upward 35° shafts for hydropower projects in Switzerland and India and downward 30° escalator tunnels in Moscow.

Figure 9 — Upward-inclined TBM setup.

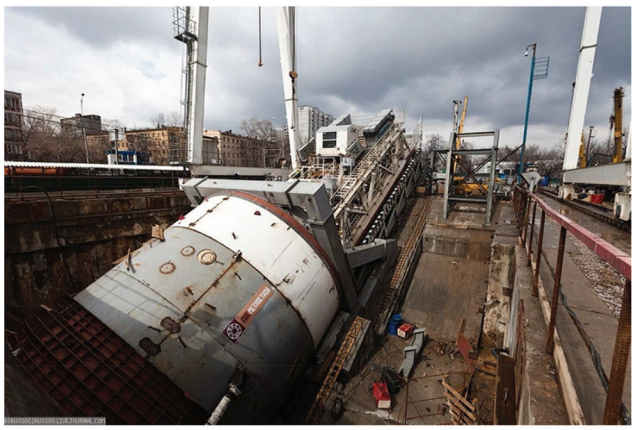

Figure 10 — Downward-inclined TBM setup.

Contractor experience. Experience with the use of TBMs is a key requirement for successful tunnel construction. The selection of a TBM contractor should be based on a pre-qualification process, whereby previous experience with similar size tunnels and similar geological environments should be part of the evaluation criteria. There exist several international TBM contractors that have excellent experience from civil engineering and other large infrastructure projects.

A related challenge is the need to have skilled labor to operate a TBM and provide the support services necessary for efficient progress. In some cases, the TBM contractor will include key skilled labor positions, such as TBM operators, mechanics and electricians, who are highly trained specifically for operating TBMs.

Project schedule and procurement. Early or on-time completion is nowhere more vital than for major mining projects at the startup of operations. These projects may mandate the use of TBMs in order to provide an overall shorter construction schedule. In some cases, it may be attractive for owners to consider pre-purchasing TBMs for an earlier start of tunnel excavation, rather than wait the full procurement period for a TBM after the award of contract. Typical procurement time for new TBMs is 12-14 months.

Figure 11 – Support installation in small TBM tunnel.

Figure 12 – Final support as shotcreting.

Minimum TBM size. One of the key issues with regard to the application of TBMs is the minimum acceptable tunnel diameter to meet the minimum internal clearance requirements that are dictated by the purpose of the tunnel, as well as practical construction considerations for the effective installation of initial tunnel support and also, importantly, for any final support and lining for long-term protection. An evaluation of the minimum acceptable TBM diameter for a proposed mining tunnel should be carried out, recognizing the minimum clearance requirements, the maximum anticipated initial tunnel support requirements (Class 5 support with shotcrete), maximum anticipated deformation/closure under weak rock conditions and maximum final support/lining requirements. In some cases, it is prudent to oversize the TBM diameter above the minimum size requirements to achieve higher productivity than would be achieved with a small tunnel size due to space constraints for installing rock support.

A TBM diameter of about 4 m is considered to be a practical minimum size based on the above mentioned criteria. Figure 11 shows the minimized space for the installation of heavy steel rib support for poor rock conditions for a 4-m TBM.

Final tunnel support and lining. The final support and lining requirements for any proposed TBM excavated mining tunnels are subject to the durability of the encountered rock conditions as well as the performance of the initial installed support and overall stability of the tunnels after excavation.

The durability of most altered bedrock around mine sites is of particular importance in terms of their acceptability to remain unlined/protected for long-term serviceability of the tunnels. The durability of the altered bedrock can be initially evaluated from the results of rock strength and petrographic testing; however, further durability/slaking potential testing may be appropriate if there exist rock units of low strength and suspected limited durability.

The decision-making process for final support and lining for mining tunnels should only be made after excavation and initial support, in order that the performance of the tunnels can be evaluated after the encountered rock conditions have been exposed to any possible effects of humidity. The decision-making process for final support and lining should be made by the owner's representative during regular and routine site inspections during tunnel excavation, such that instructions can be provided from the construction management team to the tunnel contractor to complete the works in a timely manner and concurrently with ongoing tunnel excavation, rather than at the completion of all tunnel excavation. With this approach, it is necessary to have unit rates from the tunnel contractor for various forms of final support and lining.

Typically, it will be necessary to provide shotcrete and/or concrete linings over areas where low strength and/or altered/non-durable rock is encountered during construction. If left untreated, significant deterioration may occur within these areas during mining operations and may require appreciable maintenance. An ongoing evaluation of rock durability will be required during tunnel excavation to further assess the durability of all encountered rock units. Figure 12 shows shotcreting as part of final support works. If required, shotcrete is typically applied only within the backup section of a TBM, where it will not impact the hydraulic components of the TBM and overall operations. Shotcrete robot application systems have now become standard equipment incorporated into the backup section of TBMs to achieve optimal application and quality control for enhanced tunnel support.

The 5.7-m-diameter, 11-km TBM that excavated the Rio Blanco diversion tunnel constructed for Codelco's El Teniente Mine in 1992 represents an interesting case history with regard to final support and lining requirements. The geology along the tunnel alignment is believed to have been andesites that were of good quality, as indicated by the minimum support requirements during excavation. However, shortly after operation, severe problems occurred due to deterioration of the andesite rock, and it was subsequently recognized that zeolites containing swelling clays were present within the andesite. This case example provides an important lesson to be learned that adequate petrographic and other associated rock testing should be completed and carefully evaluated prior to construction to identify all final support and lining requirements. Significant increases to lining requirements and/or changes during construction can typically lead to major delays and cost overruns.

Concrete lining for TBM tunnels. An increasing number of mines are being planned as well as extended with life spans in excess of 40 years. For such projects, it may be prudent to consider adopting design standards that are commensurate with civil engineering tunnels. In some cases, it may be cost-effective to design the tunnel lining with concrete in order to minimize maintenance requirements over the life of mine. Precast concrete segmental linings are commonly used for major urban metro and water/waste water projects, as well as for hydropower tunnels in mixed bedrock conditions. Figure 13 presents a typical precast concrete segmental lining.

Spoil disposal and handling. Tunnel muck or spoil produced from the excavation of mining related tunnels can be expected to have a high to very high acid-generating potential due to the alteration associated with the mining ore body as well as the surrounding bedrock. A specially designated spoil site will be required to be identified and evaluated during the planning stages for any new tunnels as part of the environmental approval process. Spoil generated by TBM excavation typically comprises well-graded materials ranging from 100-mm-long rock chips to fines, which can serve as road base after compaction.

Spoil can be removed from a tunnel either using rail-based muck wagons or by conveyor. Spoil is typically removed for medium (6 m) and large (10 m) tunnels using conveyors due to the large volume of material to transport efficiently without impacting mining. Conveyor systems require a significant amount of power, especially for long tunnels where booster drives are commonly installed along the tunnel. Typical TBM conveyor capacities vary from 600 - 1,200 t/hr. It may, therefore, also be practical to utilize the TBM conveyor system after the completion of tunnel construction for initial mining production purposes.

Spoil from TBM tunnels may be used as backfill for the tunnel invert to construct a flat bottomed roadway, as commonly required for many tunnel uses. With appropriate established equipment, it is possible to spill TBM generated spoil close to the front end of the TBM ahead of the backup section to allow a one-pass operation of the construction of a compacted roadway.

Logistics. The main logistics to consider for the use of TBMs at mine sites is the availability of power. Power requirements for TBMs vary with size and can range from 1.5 MW for a 4-m-diameter TBM up to 8 MW for a 10-m diameter TBM. Additional power requirements for TBM tunnel construction include ventilation and lighting. Substantial savings on the order of millions of dollars can be realized by operating TBMs from a main electrical supply such as a national grid in comparison to diesel-fueled generators.

Advantages and disadvantages of TBMs

The main advantages for the use of TBMs for mining projects are as follows:

- Significantly higher and sustainable progress rates for generally good quality hard rock conditions.
- Less rock support due to less damage caused to tunnel profile.
- Long single drives where no intermediate access adits are possible in steep terrain.
- Lower ventilation requirements, allowing smaller tunnels to be constructed.
- Improved health conditions for workers without exposure to blast smoke/fumes.

Typical advance rates that were achieved in some of the historical TBM mining projects are presented in Table 2.

The main disadvantages for the use of TBMs for mining projects are as follows:

- Circular shape, which may introduce constraints for transport of large equipment into mines .
- Limited to use for relatively straight tunnels where curvature is restricted to about 50 m.

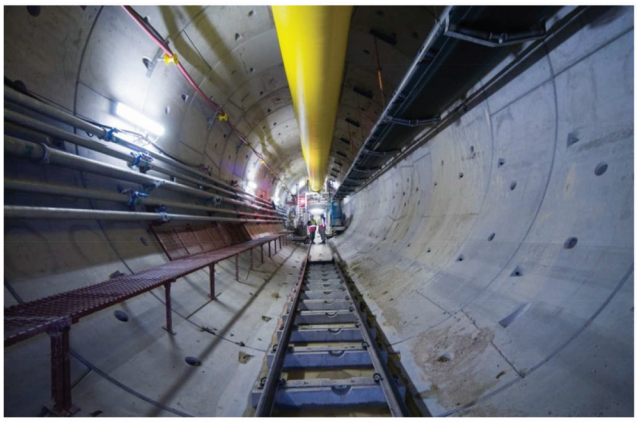

Figure 13 – Precast concrete segmental lining.

- The presence of a high proportion of highly altered and weak bedrock may result in significant tunnel support requirements, thus hampering TBM progress.
- Immediate stress relaxation and overstressing behind the cutterhead, requiring early support and protection of workers.
- Limited space available for the installation of high capacity tunnel support if very poor geological conditions are encountered.
- Limited space available for pre-excavation grouting to reduce ground water inflows.

Minimum specifications for TBMs

Precedent practice in the tunneling industry has demonstrated that it is not prudent to overspecify the requirements for TBMs such that most of the risks associated with the selection of any type or make of TBM remains with the tunnel contractor.

The minimum requirements for the application of TBMs on any given tunnel project should be based on consideration of the following key issues:

- Distribution of main rock types, strength, quality and durability.
- Quantification of number and extent of major fault and shear zones.
- Presence of weak rock units and potential for overstressing and squeezing conditions.
- Installation requirements for initial tunnel support.
- Final support and lining requirements.

A prudent list of minimum requirements are as follows:

- Minimum power requirement to effectively excavate strongest rock units (UCS > 250 MPa).
- Overcut capability with reamer cutter to prevent squeezing of cutterhead in weak rock conditions and facilitate timely changing of gauge cutters.

Table 2 – Historical TBM advance rates.

Project	Location	Year	Size, m	Rate, m/day
Stillwater EB	USA	1988-91	5.5	15
Rio Blanco	Chile	1992	5.7	30
San Manuel	USA	1993	4.6	17
Mineral Creek	USA	2001	6.0	18
Ok Tedi	PNG	2008	5.6	30
Los Bronces	Chile	2009	4.2	17

- Fixed mounted rock bolting drills on either side of TBM close behind cutterhead.
- Mechanical ring-arm erector to facilitate installation of steel rib supports.
- Fix mounted probe drill capable of drilling ahead to a minimum of 30 m in the strongest rock unit through port facility in cutterhead.
- Reinforced canopy shield extending 180° over the top of TBM.

The above-listed minimum requirements pertain to the use of an open-type main beam TBM. Since the mid-1990s, a limited number of tunnel contractors have adopted the use of double-shielded and single-shielded TBMs with the concurrent installation of precast concrete segments and/or steel liner plates when a large proportion of poor rock conditions was inferred along the given tunnel alignment. The main advantage of these types of TBMs is that they can operate as a open-type main beam TBM (with sidewall grippers) for good rock conditions, but can also install full profile segmental support (with rear thrusters) for poor rock conditions.

Geotechnical investigations

An appropriate level of geotechnical investigation should be completed prior to the consideration of the use of TBMs. The typical tasks to be undertaken should include the following:

- Geological mapping/evaluation.
- Identification of main faults/shear zones.
- Seismic surveys at portals.
- Long horizontal drillholes at tunnel portals or into side valleys.
- Short (Hilti-type) drillholes to obtain core samples for testing.
- Rock testing for strength, petrology and abrasivity from cores and blocks.
- Evaluation of the distribution of rock quality along the tunnel alignment.

Geological mapping and evaluation is the first task that should be undertaken. This work can comprise a desk review of existing literature and historical reports and investigations. The key requirement is the identification of faults along the tunnel alignment and, then, field proofing of suspected features. The confirmation of such features may be difficult due to thick overburden in tropical areas or access in steep mountainous terrain. A fairly new method for the evaluation of fault zones is through the use of high-resolution airborne electric-magnetics. This relatively new method is attracting significant recognition, as it is able to delineate lineaments in difficult terrain and under thick overburden that may represent faults and sources of ground water that are important to identify for tunnel construction.

In the event that colluvium or rock blocks are present around a proposed portal site, it is prudent to undertake seismic surveys to determine the depth to bedrock for the design of a portal and excavation and stabilization requirements.

One of the most important requirements for the assessment of TBMs is the undertaking of a comprehensive rock testing program and the interpretation and presentation of representative data by a qualified person. Rock parameters in terms of uniaxial compressive strength (UCS) and tensile strength (Brazilian), as well as petrology (percentage of hard minerals) and abrasivity (Cerchar index) represent the key parameters that need to be characterized for the application of TBMs. Additional rock testing includes punch penetration, as well as drilling rate index (DRI) and cutter life index (CLI) that are only performed at the University of Trondheim in Norway. Extremely high rock strengths (> 250 MPa) will result in slow TBM penetration rates. Conversely, low rock strengths with high rock cover can result in extensive overstressing and the potential for rockbursts. Petrographic thin section analyses serve to define the mineral constituents and percentage of overall hard minerals (> Moh 6.5) that can also have a dramatic impact on TBM penetration. Petrographic testing will also identify the presence of rock alteration that is usually associated with a significant loss of strength. Rock abrasivity in terms of the Cerchar abrasivity index (CAI) has become a recognized parameter that can be correlated to TBM cutter consumption and is usually related to the amount of hard mineral content. Figure 14 shows a typical large rock block sample that was collected and drilled and tested for rock strength and other parameters.

As an alternative to traditional deep geotechnical drilling, it is appropriate to identify representative rock block samples that can be collected and transported to a laboratory where core samples can be drilled and tested under standard procedures. Another alternative to traditional deep drilling is shallow drilling of holes using a Hilti-type drilling machine into rock outcrops to obtain core samples for laboratory testing, as shown in Fig. 15.

Along steep mountain slopes that are difficult to access, rock block samples can be collected from tunnel alignments. A rock block sampling and testing program is significantly less expensive than geotechnical drilling with helicopter support.

The importance of providing bidders with representative and technically correct rock testing data cannot be overemphasized. All sample preparation and testing should be completed at an accredited rock testing laboratory and only by certified testing technicians. The specifications for the rock-testing machine should be carefully reviewed as part of the laboratory selection process. A site visit should be made to the proposed laboratory prior to selection for all testing, and a quality assurance visit should be made to witness the first uniaxial compressive strength (UCS) test. Photographs prior to and after failure, along with failure descriptions, should be provided with each UCS test result. A limited number of check tests should be completed during the early stages of the testing program at a different laboratory for an early comparison to confirm that all testing is valid and representative. Photomicrographs should be provided for each of the petrographic thin section analyses. The Rockwell hardness number of the testing pins used as part of the rock abrasivity testing should be noted on each of the CAI test results, as different testing pins are used at various laboratories.

Contract delivery and strategy

The two main forms of contract delivery that are typically used for the construction of tunnels comprise design-bid-build (DBB) and design-build. DBB is the traditional approach, whereby the owner engages a consultant to complete a final design, drawings and technical specifications that are used for a competitive bid process to select a preferred contractor. The main advantage of this approach is that the owner is completely involved in the design process, such that all of the requirements are included in the design and project specifications. The main disadvantage of this approach is that it requires an appreciable duration to complete the design and bidding process before construction can start. This is particularly applicable for mine access and conveyor tunnels where key fire, life and safety components need to be included in the design for safe operations.

In comparison, the DB approach offers the advantage of time savings to the overall project schedule, whereby the owner only completes a reference design along with performance specifications to outline the basic requirements that are expected. This approach also invites innovation from the DB consortium. A typical minimum time savings of six months can be realized with this approach. The main disadvantage of the DB approach is that key requirements may be omitted in the project specifications. This allows the DB consortium to provide designs and construction quality that only meet the minimum project requirements. This may lead to the procurement of a TBM that is not entirely suited for the project. A number of complex tunnel projects undertaken with this approach have suffered shortcomings in terms of basic designs and less than ideal construction quality, which resulted in earlier and greater maintenance requirements. In order to achieve success with the DB approach, it is imperative to complete a thorough reference design and review of the project performance specifications.

A number of contract strategy models exist for owners to consider for the construction of tunnels for mining projects. Contract models essentially vary by risk allocation, from cost-plus with no risk to the contractor, to fixed price, with no risk to the owner. Cost-plus contracts start with an estimated total price that can be highly uncertain, whereas fixed price contracts typically include significant cost and time-related contingencies by the contractor, since additional compensation is typically provided. Geotechnical baseline reports (GBRs) can be compiled and included as part of the project contract agreement to serve to establish a baseline for a risk-sharing approach, whereby the contractor is compensated for site conditions that are more onerous than expected at the time of bid and have clearly impacted productivity. GBRs are typically compiled by the owner based on a minimum appropriate amount of geotechnical data from ground investigations performed prior to construction.

Hybrid cases of the standard contract models can also be developed to include target prices and schedules with variable or sliding fees that are adjusted subject to the actual site conditions encountered during construction. Such hybrid target-based contract models can be attractive to bidders and are common in the mining industry, with lucrative incentives for early completion but also penalties for lateness. The most successful contract models in terms of fair risk allocation have historically been those for which the entire risk of the site condition is allocated to the owner, and the entire risk of productivity is allocated to the contractor. A typical payment mechanism incorporated with this approach is based on a series of well-defined excavation support classes with estimated quantities from the owner that is priced by the contractor, along with the submission of estimated rates of productivity for each of the defined excavation-support classes.

Conclusions

The applicability of TBMs for mining projects requires a careful evaluation of several key considerations, some of which are technical and some nontechnical. The key lessons that can be recognized from past mining projects where TBM tunnels were used are that every tunnel project and site location is unique in terms of geology, access, terrain/cover, experience of candidate contractors and project completion demands. A comprehensive evaluation of probable fault zones and the potential for overstressing should be carried out as part of any assessment for the application of TBMs.

TBMs offer key project schedule benefits with high rates of progress, which is a unique economic advantage recognized for mining projects where timing is of the essence in order to advance mining development and achieve early startup for operations. TBMs do not represent the best solution for major and long tunnel projects where high-risk geological conditions are anticipated, or where intermediate access adits are available for well-experienced drill-and-blast contractors.

Figure 14 – Rock block sampling and coring.

Figure 15 – Portable drill for core samples.

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