

Modern large diameter rock tunnels

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Recent experience and development of hard rock tunnel boring on most large diameter tunnels, especially above 8m in diameter, has shown that improved ground support is a prerequisite to improved monthly advance rates. The opinions and comments presented in this paper are heavily influenced by recent experiences on the 12.4m diameter Jinping project in China⁽¹⁾, the 10m diameter AMR project in India⁽²⁾, and the 14.4m diameter Niagara project in Canada⁽³⁾.

While it is accepted that TBMs can perform well in good rock conditions, the data is less conclusive about difficult ground conditions. Difficult ground can mean many things to the TBM designer. It can mean massive 350 MPa UCS quartzite with 75% silica. It can mean blocky conditions; severely jointed; squeezing; swelling; or fault zones. It can mean all or some of these adverse conditions coupled with varying amounts of water inflow. In a vast majority of long, large diameter tunnels, most of these conditions are encountered to a greater or lesser extent.

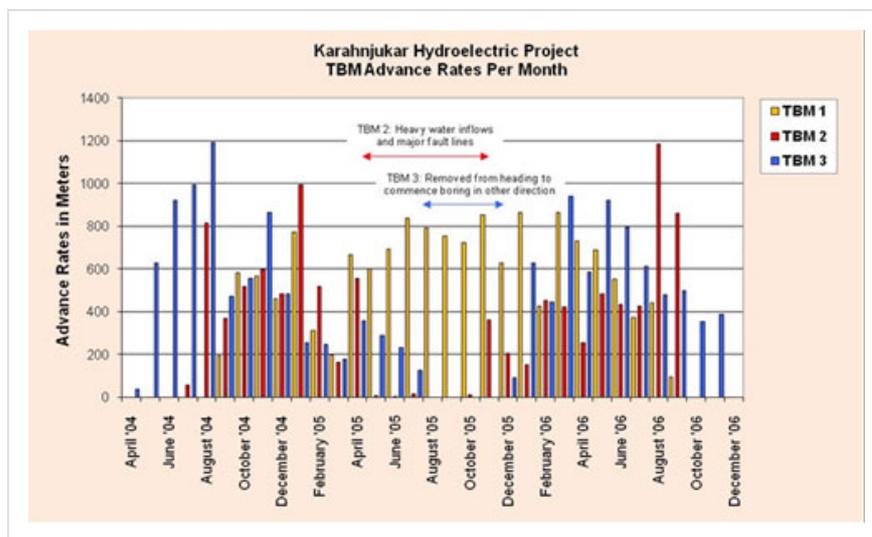


Fig 1. Kárahnjúkar, Iceland, TBM performance record

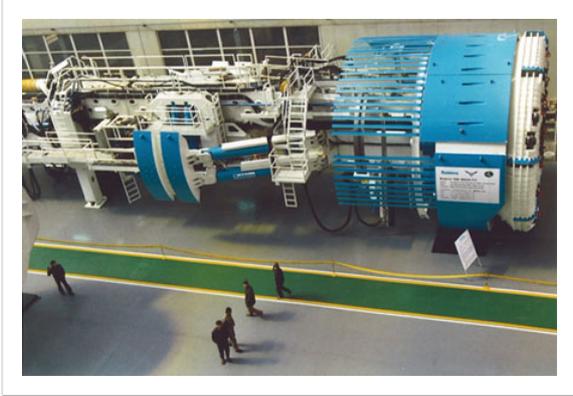
The fact is modern TBMs can effectively bore through all types of conditions and far exceed advance rates of drill and blast operations in each condition. For example, in good rock conditions of medium hard to soft stable rock, TBMs are without question able to achieve advance rates of 1,000m/month. Advance rates recorded at the Kárahnjúkar hydroelectric project in Iceland⁽⁴⁾, and on the Cabrera high-speed railway project in Spain⁽⁵⁾ confirm the achievement of more than 1,000m/month (Figs 1 and 2).

Fig 2. Cabrera Project, Spain: 9.6m diameter double-shield TBM performance record

Record Performance Figures	First tube	Second tube
Total excavation:	5,974.4m	5,966.4m
TBM started:	July 27, 2007	May 5, 2008
TBM holed through:	January 25, 2008	September 25, 2008
Average monthly advance	995m	1,330m
Top daily performance:	83.2m/52 rings (Dec 1, 2007)	105.6m/66 rings (July 19, 2008)
Top weekly performance:	430.4m/269 rings (Wk 47/2007)	435m/290 rings (Wk 30/2008)
Top monthly performance:	1,600m/1,000 rings (Nov 2007)	1,688/1,055 rings (July 2008)

TBM selection

There are five main types of TBMs that have been used to bore tunnels in rock: main beam, single shield, double shield, EPB, and slurry machines. The most classic or famous of these is the open main beam TBM. This open type system has been further standardized to the Robbins floating gripper type machine (Fig 3), now manufactured by German and Japanese manufacturers. The big advantage of the floating gripper type is the access it provides to rock immediately behind the cutterhead for rock support. The main beam TBM is normally used with temporary non-concrete lining, whereas most other types of TBMs are used with segmental lining.



8m diameter, floating gripper main beam TBM

The single shield is often used in softer formations, though in difficult or hard rock conditions the design has several drawbacks. The TBM relies solely on thrusting off the lining segments for advance, often requiring larger than necessary segments. The operation is also cyclic: while segments are being placed boring is discontinued. Another disadvantage is that there is no reverse force reaction to manipulate the shield when it starts to get trapped. A further drawback of the single shield is the very poor access to the cutterhead area for ground conditioning with foams and grouts.

The double shield TBM has in recent years come into fairly common use, with key advantages in hard rock tunnels. The machine body is fully shielded to hold rock in place until the lining is set, and boring and segment-ring building happen

concurrently. However, this TBM type also has its drawbacks. It is long and therefore prone to being trapped. The design is very poor with regard to access to the cutterhead for use of foams and grouts.

Though traditionally used in soft ground, EPB-type machines have also been used to excavate rock. In the past 40 years since the first use of EPB machines, there have been substantial developments in this type of TBM. Great advances have been made in cutterhead design, use and application of foams, and design of the auger itself. Modern EPBMs can be used with the correct additives in just about every type of ground from solid rock to flowing sand. With the correct additives they can also hold water pressure up to and exceeding 10 bars while obtaining good advance rates.

However, water pressure in most long, large diameter tunnels can exceed 10 bars. In addition, for EPB machines to work effectively they must have an opening ratio of at least 30%, which is not desirable in blocky or jointed rock. The most detrimental fault of an EPB type machine when used in most rock conditions is very high wear of all components in the cutterhead and the screw conveyor. These components are in constant contact with rock and for a lot of time, in contact with rock under pressure. This high wear normally results in numerous interventions, which involves stopping for several weeks or months for repair or replacement of components.

In addition to the above disadvantages, EPB-type machines also experience all the drawbacks of a simple single shield.

Slurry TBM machines are also used in rock excavation. The development in the design of slurry machines over the last 50 years has been significant. However, I believe there has not been one rock tunnel that has been excavated with a slurry TBM that would not have been more economical, and completed in a shorter time, using alternate methods. The high wear and complexity of operation in varying ground conditions make the slurry machine extremely difficult to operate and maintain constant face pressure resulting in very high costs.

Lessons learned in large diameter rock boring

In the past 10 years, there have been several key lessons learned in large diameter rock boring.



The main lesson is that in all but homogeneous sedimentary formations, there is a very high degree of rock fallout at the face. This means that at any one time, up to 50% or more of the face falls out in advance of boring. The effect is a result of jointing, bedding planes and fissures which occur normally in most rock formations. In these formations the forces of high-loading disc cutters in effect act as wood splitters. Small to large blocks of rock are wedged out, causing openings or



Rock fallout during boring

voids culminating in larger blocks and larger voids (Fig 4). This is typically not a big problem because modern cutterheads are designed for partial face loading; however, problems occur when the voiding progresses outside the cut diameter. This often occurs in severely jointed ground, causing voids or cathedralling above the TBM. This phenomenon occurs whether the machine is an open TBM or a shielded TBM. Such voids left untreated can cause the TBM to be stuck or, if not properly back filled, can eventually cause segment lining failure. This recently occurred on a project in Ecuador. As the diameter increases, the incidence of face fallout goes up exponentially.

The second lesson learned over recent times is that the TBM should have sufficient torque to start cutterhead rotation and keep rotation going even with a full face of loose rock against it. Such high cutterhead torque is common on EPB and slurry TBMs, as they are always operating with a full face of material against the cutterhead. Today rock machines are designed with such high torques.

However, unlike EPB or slurry machines, a rock TBM needs high cutterhead RPM to achieve good advance rates. With modern variable frequency drives (VFDs) these torque and speed characteristics can be achieved.

The third lesson learned is that the amount of material that ends up on the TBM conveyor must be controlled. The volume of rock conveyed out should never be more than what is contained in a normal advance (turned radius squared x π x 1.8 (expansion of rock)). If too much volume is excavated, then cathedralling is occurring and real problems can begin, requiring ground treatment or special ground support.

Ground support

With modern TBMs it is possible to advance with a full face of loose rock. There are two major types of ground support used in modern tunneling: continuous concrete segmented lining and temporary lining (shotcrete, rock bolts, etc.). Concrete segmented lining is very attractive because the TBM will hold the rock in place until all loose rock and soil can be supported by the segments. In some tunnels, depending on the geology, this process can be achieved successfully. In other tunnels, ground conditioning or temporary support is required even when using segments.

When using a temporary lining with TBM boring, there is a good general rule: hold the loose rock in place and limit the expansion. This same principle is used in NATM. In order to facilitate this procedure, rock access must be available immediately behind the cutterhead.

In a modern TBM, rock access is becoming more and more available due to several design innovations including:

- shorter front shields
- retractable shields
- shields that extend forward to immediately behind the gage cutters

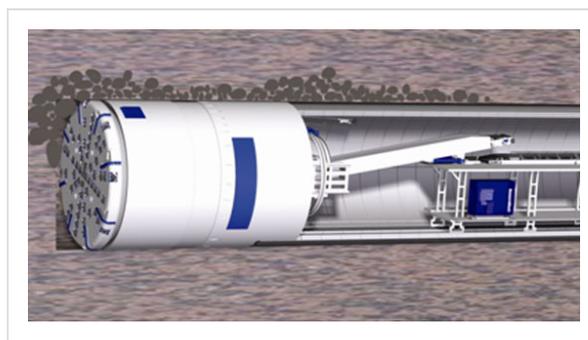
To keep the loose rock in place effectively, two main items are required:

- a closed, slowly rotating cutterhead ingesting a controlled amount of rock; and,
- the setting of rock support immediately behind the front shield.

In order to install lining immediately behind the front roof shield, rock anchors need to be placed into solid rock. The rock anchors support the wire mesh in combination with channels. Shotcrete should be used selectively if required.

The historic use of finger shields and 360° steel ribs is no longer advised, as their use permits ground expansion. In my opinion, there is limited justification for using 360° steel ribs in tunnels of larger than 7-8m in diameter. Steel ribs are complicated and difficult to erect. In addition the erector takes up valuable room needed for placing rock bolts, screens and shotcrete. The erected 360° steel rib is subject also to failure from point loading. It is far more practical and time-efficient to use good rock anchors, mesh and channels. For large tunnels, it is very conventional to use man cage booms to place the rock support, as these booms eliminate a lot of the difficulties in accessing the tunnel crown via platforms.

A good addition to modern rock support regimes is the



Schematic of a double shield TBM with loose rock at the face

McNally System. This system facilitates placing of lining immediately under the roof shield. The lining is pulled out of installed tubes as the TBM advances, supporting the rock and preventing its expansion.

An area of development required in large diameter rock boring is an intermediate lining between conventional temporary lining and full segment lining. This lining would have considerable use in Scandinavian rock conditions. We visualize lining which can be bolted to the crown and bored tunnel wall that would be sufficient to control or even prevent rock spalling and water ingress.

Extreme conditions

Extreme conditions are considered to be squeezing ground and water-filled fault zones. In such conditions features can be built into the TBM to make continuous progress through such zones possible and practical. For squeezing ground there are a number of options that can all be built into the TBM design, including overcutting capabilities, invert thrusting, the capability of placing yielding anchors, and the capability of placing yielding temporary support. In such conditions, advance rates of 2-3m/day are possible.

When encountering water-filled fault zones several measures are available. First, continuous probe drilling 30-50m in advance of the TBM is recommended in all conditions. 360° probe and grout drilling is an option, while drilling through the face is also available. With today's modern grouts just about any formation of difficult ground can be consolidated. The tunnel operation needs to have a plan plus available materials to grout off fault zones.

In some extreme conditions, foam in combination with forepoling has been used to support the crown in advance of boring. A good example of this was on the Abdalajis tunnels.

The Abdalajis tunnels at 10m diameter encountered a water-filled running ground condition. After some experimentation, the contractor was able to advance 2-3m/day using forepoling and foams⁽⁶⁾.

Under other extreme conditions, heavy shotcrete in the L1 area on the tunnel walls has been used. The shotcrete is used to reform the tunnel wall to permit adequate gripping forces. This was applied extensively on the Parbati tunnel in India. On the 6.8m diameter Parbati project tunnel, under more than 1,500m of cover, rock bursting was extensive and eventually caused a wall cave-in immediately behind the cutterhead.



Failed steel rib after a rock fall



TBM cutterhead for Kárahnjúkar, Iceland

Evolution of the cutterhead

The key part of the TBM is the cutterhead and these have gone through a tremendous evolution. Early designs were mounted with small 11in cutters on large spokes with large buckets. There was a generation of domed cutterheads which were thought to be more stable. Over the years, cutterhead bucket openings have gradually become smaller and more refined in shape, evenly ingesting the broken rock instead of gathering in large and small chunks. Modern cutterheads are crack resistant by the use of flex-acceptable materials and welding techniques. Strategically placed wear-resistant material is now commonly used. Rear-mounted cutters are now standard. The designs are more 'smooth' to reduce torque when against a face of loose rock or large blocks. A major step forward is the use of 20in cutters, which have a longer wear life and can withstand the tremendous forces of blocky, hard rock.

To summarize, key developments in larger diameter rock tunneling can be emphasized in a few main points:

- Be prepared, and expect large face fallout and the resulting cathedralling effect.
- Adapt modern rock support methods and strongly reconsider the specification of steel ribs as a temporary ground

support for large diameter tunnels.

- Expect 15-20m/day in good rock; 5-15m/day in difficult rock; and 2-3m/day in extreme conditions.
- Have a well-schooled operating team that is familiar with ground support methods including foams, grouts, shotcrete applications, and that understands well the interface between rock and rock boring.

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