Ground Support Equipment for Large Diameter TBMs in Difficult Ground Conditions

B. Khalighi
The Robbins Company, Kent, Washington USA

1 TBM DEVELOPMENT

1.1 TBM Diameter and Rock Support. Prior to the 1990s, TBM developments were mainly within a specific diameter range of 3 m to 7 m. Few large machines had been built with some exceptions.

The advance rates of several large diameter projects were analyzed, ranging from 7.7 m to 14.4 m in diameter. Data show that TBM projects over 7 m in diameter experience an abrupt drop in productivity (with some notable exceptions such as a 9.85 m machine at the TARP project that excavated 715 m in one month).For more background on these projects, see Sänger & Khalighi, STUVA 2009.

The level of geological difficulty per project can of course affect advance rates, which can account for advance rate variation among similar machine diameters. As machines become larger more time is spent on rock support and maintenance. While these factors explain differences in machine performance to some degree, they cannot account for an observed abrupt reduction in rate of advance in TBMs over approximately 7 m. A deeper consideration of the relationship between net advance rate and diameter will provide more answers. For this purpose, sub-categories of rock support and net advance rate were analyzed.

1.2 Rock Support versus Diameter. Typical rock support measures include mesh, steel (ring beams), rock bolts and concrete (shotcrete, in situ concrete, invert segments). To approach the problem, the contractual requirements for rock support of several projects were reviewed and analyzed.
The information provided in the rock support drawings of the reviewed projects was categorized by classes:

- total length of rock bolts per linear m of tunnel (m bolts/m tunnel)
- total surface area of mesh per linear m of tunnel (m^2/m tunnel)
- total volume of shotcrete or concrete per linear m of tunnel (m^3/m tunnel)
- total weight of steel per linear m of tunnel (kg/m tunnel)

A careful mathematical interpretation suggests in all cases that there is an exponential trend in the relationship between rock support and TBM diameter. Typically, in the small diameter range the curves are flat and close to a linear relationship. It is interesting to note that the ascent of the curves happens in the 7 m – 8 m diameter range, which is the area where significantly reduced “best monthly average” performance rates were observed (see Figure 1 for a generalized curve).

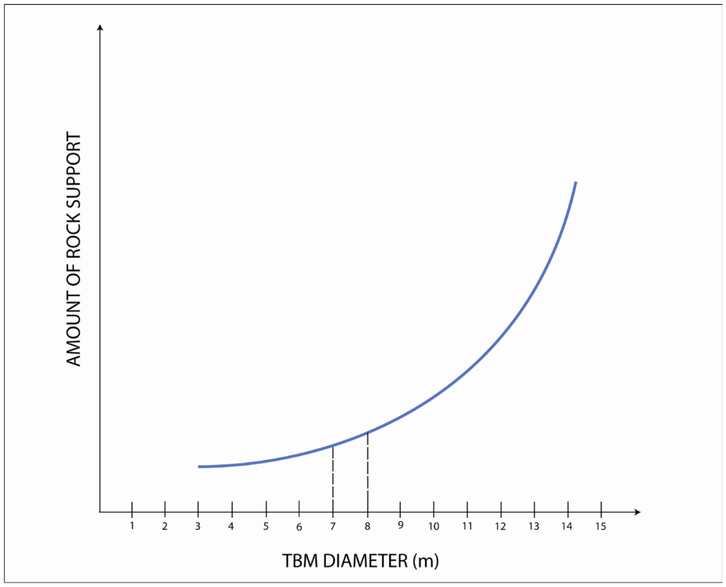

Figure 1. Generalized curve of TBM diameter vs. amount of rock support,

1.3 Definition and Conclusion of Analysis. The definition of a large diameter, open type TBM in acknowledged technical literature is ambiguous. Based on analysis, it appears reasonable to classify TBMs larger than 7.5 – 8.0 m diameter as “large diameter TBMs”. In the context of ground support design, this definition is supported by project experience. At the Kárahnjúkar Hydroelectric Project in Iceland, three open type TBMs were supplied with diameters from 7.23 m to 7.63 m. The machines were equipped with standard components for rock support (steel, mesh, rock bolts, shotcrete) that worked sufficiently and achieved high peak performance. At the DahuoFang Water Transfer Tunnel in China, two 8.00 m diameter open type TBMs were designed with the same machine core as the Iceland TBMs and the same ground support systems. In these tunnels, the system for handling and erection of ring beams turned out to be inadequate for the sizes and weights needed. The assembled ring beam was too large to be expanded from the bottom against the tunnel wall. Part of this problem was the excessive friction / drag forces on the ring beam segments when they came into contact with the tunnel prior to their full expansion.

Based on these data and field observations, it appears that the design of rock support equipment for large diameter, open type TBMs needs a different approach from that used on smaller diameter machines. This statement applies to all rock support classes, not only the rock support used in difficult rock classes.

2 CASE STUDIES – NIAGARA TUNNEL PROJECT

The Niagara Tunnel Project (NTP) is a 10.4 km long, 14.4 m diameter tunnel that will run from the Upper Niagara River to the Sir Adam Beck Power Station. The geology consists of limestone, dolostone, sandstone, shale and mudstone. The rock strength ranges from 15 to 180 MPa UCS, with most of the rock in the 40 to 100 MPa range. With the exception of sandstone, the geology is basically non-abrasive. Up to 80 percent of the rock consists of Queenston shale.

Design requirements stipulated several different support systems based on the type of ground encountered. The client’s requirement is to scale down / bar down any loose rock in the tunnel prior to application of any ground support.

2.1 L1 Rock Support. The L1 area, located directly behind the TBM cutterhead support, is approximately 5 m from the rock face. The equipment at the time of delivery included:

- *Rock Drills*

  Two 6.4 m long BMH 6000 series hydraulic drills COP 1532 hydraulic hammers on a rotary manipulator to allow independent operation of each drill.
- *Work Platforms*

  Stationary and mobile work platforms located in the L1 area to allow rock scaling, wire mesh and other ground support functions to be performed.
- *Shotcrete Robot*

  A shotcrete robot to cover the top 180 degrees of the tunnel was installed and integrated into the work platforms (see Figure 2).
- *Ring Beam Erector*
- *Mesh Erector and Mesh Transport System*

2.2 L2 Rock Support.

- *Rock Drills*

  To compliment the forward L1 drills, two additional 6.4 m long BMH 6000 series hydraulic drills were installed on a rotary drill manipulator to allow installation of 6 m long bolts.
- *Shotcrete Robots*

  Two remote controlled shotcrete robots to provide 360° coverage were installed in the L2 area.

2.3 Tunnel Excavation. During the first 200 m, problems were encountered including water inflows and handling of the water due to the 7.82% decline. The TBM also encountered problems with fines clogging cutters and muck buckets. A foam spraying system was added and the progress increased gradually up to 18 m / day in April 2007.

After about 800 m of excavation, the TBM entered the Queenston shale formation. Large rock blocks fell from the crown before rock support could be placed, creating over-break up to 3 m behind the roof shield in the L1 area, to the point a man could stand on top of the roof shield (see Figures 3-4).

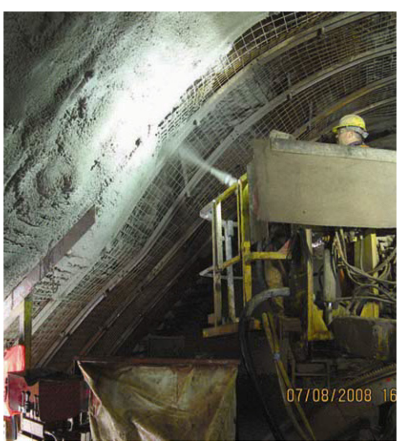

Figure 2. Shotcrete application Figures 3 and 4. Overbreak – Niagara Tunnel Project.

The contractual obligation to have no loose rock behind the supports meant systematic scaling of the rock. The volume and size of the scaled rock was proven to be beyond expectations at the time of ground support design. Eventually the contractor (STRABAG) designed a special ground support method using 9 m long grouted umbrella spiles to mine through the difficult geology (see Figure 5).

Figure 5. Spiling in Difficult Geology

Subsequently Robbins and STRABAG modified the ground support installations.

Equipment that was removed from the TBM:

- Ring Beam Erector
- Mesh Erector
- Roof Fingers
- Work and Access Platforms
- Muck lift buckets (initially supplied by Rowa)

Equipment that was installed on the TBM:

- 2 telescopic man baskets on top of the main beam.
- Crown mounted hoist for delivery of straps and mesh.
- 2 drill jumbos for spilling, bolting, and rock scaling (bar down). The original roof drills mounted on the machine are also used to install rock bolts.
- Drapes made of conveyor belt material were installed behind the cutterhead support to protect the motors from shotcrete rebound and falling rock.
- 2 invert cleaning chain conveyors that deliver broken rock and debris in the invert to a cross conveyor, which dumps onto the aft end of the TBM conveyor. One conveyor is for cleaning the area behind the cutterhead support and the other for cleaning the area in front of the back-up decks.
- Mini excavator to load the invert conveyors.
- Controls for the man baskets and drill jumbos were relocated to an area that would always be under supported rock. Therefore all equipments are operated without personnel being exposed to unstable areas of the tunnel.

These changes were made incrementally as TBM progress allowed it. The ground support method being performed today is as follows:

- Bore for half the stroke
- Scale down the loose rock
- Install rock bolts
- Finish the stroke
- Scale down the loose rock
- Install more rock bolts
- Install mesh and apply shotcrete to the entire area bored in one stroke

With the new spiling method, the over-break could be limited to 0.5 m to 1.0 m. Excavation rates slowed, however, to a maximum of 5 m / day and an average production rate of 3 m / day. Nearly 500 m of very difficult ground was excavated using this method. After tunnel chainage 1,970 m, the rock conditions improved to a point that spiling was no longer required. The TBM progress has since significantly improved in spite of continuous over-break from the tunnel crown.

3 CASE STUDIES – JIN PING II HYDROELECTRIC PROJECT

The Jin Ping II hydroelectric project consists of four parallel headrace tunnels, each approximately 18 km long. Tunnel geology consists of massive to blocky marble with limestone, sandstone, slate and chlorite schist with UCS between 50 and 85 MPa. The high overburden, with over 70% of the cover greater than 1,500 m and a maximum of 2,525 m, is a known risk for squeezing ground and rock bursts. In response to the core test results and high cover, an aggressive ground support program was developed with various support designs specified based on the rock mass classification.

4.1 TBM Features and Design Criteria. Robbins originally designed the 12.43 m diameter TBM for the specified ground conditions (see Figure 6).

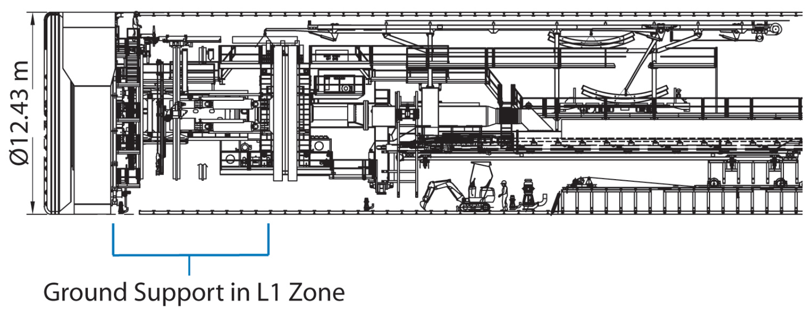

Figure 6. Original Ground Support in L1 Zone

4.2 Initial Ground Support System. Primary rock support activities were performed from platforms on top of the TBM. Ring beams were delivered in the top of the tunnel, through the back-up and over the top of the TBM main beam to the ring beam erector. A panel erector was specially designed to install steel panels over fissures in the rock where water entered at high pressure, in order to deflect and redirect the water spray.

Rock bolting was initially done in two locations on the TBM with two drills and two more drills in the L2 zone. Shotcrete could be applied in both the L1 and L2 areas.

4.2 Operational History. The Robbins 12.43 m diameter TBM was launched in late October 2008. During the commissioning bore, increased ground support was required at the interface between the starting chamber and the bored tunnel, which took some time to be agreed on. The resulting design included ring beam installation every 900 mm and a 17-bolt pattern of rock bolts every 1.5 m. Progress was slow from the outset due to very poor rock conditions. During the consecutive months, the bored tunnel continued to experience severe fractures and collapses (see Figures 7-8).

Figure 7. Roof collapse

Figure 8. Ring beam failure

Given that the geology encountered was much worse than expected at the time of design, engineers opted to design a new ground support system. In several site visits and meetings with the customer, Robbins Engineering developed a total system modification concept to cope with the reality of geological problems. According to this concept, steps were taken to rebuild the ground support system inside a modification chamber excavated by drill and blast ahead of the machine.

Equipment removed from the TBM:

- The original ring beam erector.
- Mesh / Panel erector; to open up the space in L1.
- The chain falls and the Presenter of the material delivery system.
- Roof shield fingers.
- Work and access platforms.
- Material delivery system.
- Probe drilling function separated from the roof bolting function.
- Winch and cable operated flat cars.

Equipment installed in the modification chamber:

- New and totally redesigned ring beam erector.
- 2 telescopic man baskets attached to either side of main beam. These units will provide access to the entire tunnel area as far forward as possible for rock bolting installation and shotcrete application.
- 1 roller bed and 1 telescopic presenter boom to replace the original presenter and chain fall hoists.
- Boom crane, mounted to the water canopy ceiling.
- Self propelled electric drive flat cars.
- 1 invert cleaning chain conveyor, which delivers broken rock and debris in the invert to a cross conveyor that then dumps onto the Banana conveyor. This is for cleaning the area in front of the back-up decks.

- Provisions for manual installation of mesh or corrugated steel panels attached to the inside radius of the extended shields.
- Continuous support system (McNally patented system) for support of broken rock at the tunnel crown. This system consists of rows of steel pockets installed to the outside surfaces of the roof shield and roof side supports. Steel or wood slats (~150 mm wide x 5 m long are inserted into these pockets. The exposed end of the slats is fixed to the tunnel by straps / ring beams. As the TBM moves forward the slats come out of the pockets. Before the slat is fully out, the next slat is fed into the pocket and the overlapping joint is fixed to the tunnel.
- Strategically installed work and access platforms to facilitate mesh installation.
- An adapter to install the probe drill (when probing is required) to the carrier for the shotcrete nozzle.
- Redundant controls for the man baskets and presenter boom were relocated to an area that would always be under supported rock. Therefore all equipment can be operated without personnel being exposed to unstable areas of the tunnel.

Since installation of the new system, conditions have improved markedly. The McNally support system is not in full use by the contractor yet, but systematic mesh panel installation has contained large blocks of rock. As the machine moves forward, panels of wire mesh are pulled back through the annulus. Welded castellations allow the roof drill to fit beneath the McNally system pockets to bolt each panel in place (see Figures 9). At the time of paper writing, the new system had not been 100% installed, but advance rates had already improved (see Figure 10).

5 Summary and Conclusion

The evaluation of rock support classes and the analysis of advance rates suggest that there is a critical region beyond which an open type TBM must be considered a large diameter machine with special ground support needs. The fundamental point underlying this perspective was experienced on the NTP and Jin Ping projects. It was observed that most large rock falls begin with some small rock pieces falling first – this is a much more significant phenomenon than on smaller diameter tunnels. These small pieces act as the lynchpins that hold the large pieces in place. The main task is to prevent these smaller pieces from falling out in the first place. This requires systematic installation of mesh panels, rock bolts, and application of shotcrete. In the author's opinion, the most effective method is one that provides immediate and continuous support of the ground behind the cutterhead support. Both mesh installation and the McNally system provide such immediate and continuous support. Any other methods are secondary to the mesh installation and are used for further reinforcement and strengthening of the rock support.

The problem with previous ground support equipment used on large TBMs was that the design of the delivery system and access / work platforms took a back seat to the design of the main components of the TBM. This often limited the space and freedom needed to design an effective ground support system once other machine components were already in place. It is necessary that the design of TBM and ground support system, including the delivery methods and the access / work platforms, are combined with the TBM design work from day one.

Figure 9. New ground support system showing wire mesh panels and McNally system in place.

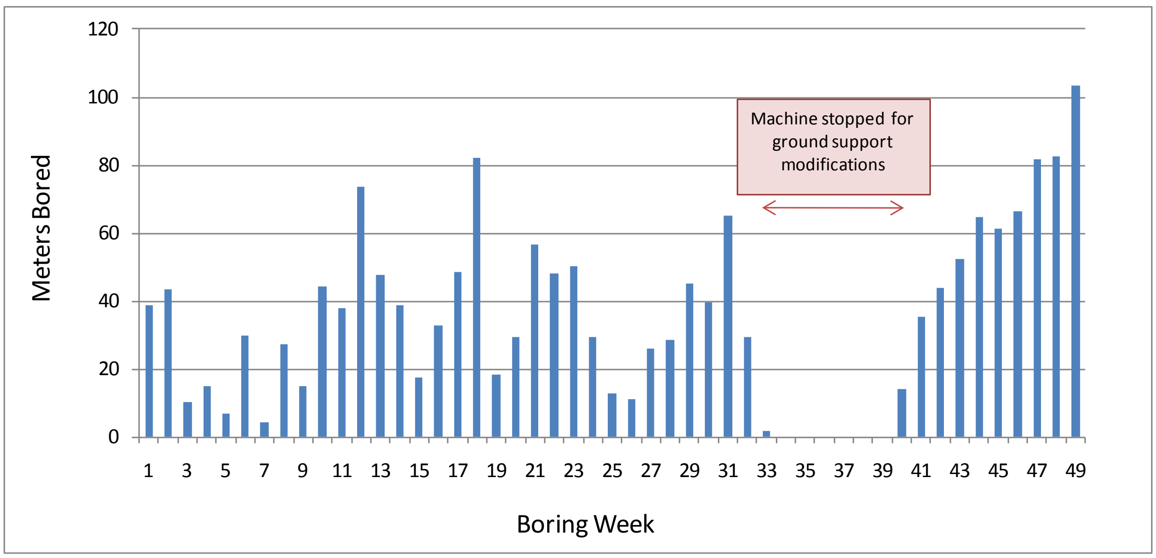

Figure 10. Meters bored per week at the Jinping II Hydropower Project

6 References

Sänger B, Khalighi B, and Eckert M.(2009). TBM-O with Large Diameter: The Challenge of Securing Rock. *Proceedings of the STUVA Conference*,190-197.