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# Rescuing and rebuilding TBMs in adverse ground conditions

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ABSTRACT: Modern TBMs deliver high performance with availability rates that are beyond 90%. The TBM design concepts make the machines highly versatile for employment in varying soil and ground conditions. Machines can now withstand extreme loads and impacts in rough underground environments because of the components made for longtime use. Regular maintenance and planned service is the vital element in prolonging a machine's life and for high performance and availability. A well-serviced machine provides excellent performance as well as active project safety. Proper operation in variable conditions is also key. For instance, a hard rock TBM may run into zones of swelling rock. The most appropriate method to overcoming the swelling rock is to keep going, avoiding any unnecessary stops. Worn disc cutters that have not been maintained in due course are a prominent example of such avoidable stops, which may result in long downtimes and severe damage to the machine. However with modern and advanced techniques to underground tunneling, rescuing and rebuilding TBMs is possible to save the project This paper will discuss methods and tools for modern TBM service and maintenance using present case studies about TBM rebuilds in extreme project conditions.

## 1 INTRODUCTION: THE TBM LIFE CYCLE

It is essential to consider the total life cycle of a machine, even in its beginning design stages—this is by far the most economical and sustainable way of thinking. Designing machines with ease of rebuilding in mind ensures that the manufacturer does not have to start from scratch every time a machine needs work. It also results in time, cost, and energy savings when the time does come to rebuild a machine, which is then passed on to the customer.

Perhaps even more important than that is the way a TBM is maintained during its project. It is important to remember that the basic structure of a TBM is metal—as long as the structure is intact, one can then check on the bearings, conveyor, hydraulics, and other components. Particular attention should be paid to components that are hard to reach. The main bearing is one of those parts that is difficult to replace during tunneling.

When developing a maintenance plan, it is critical that TBM crews are properly trained on how to operate the machine in the entire gamut of ground conditions that may be encountered on a given tunnel project. Plans must be in place to deal with a wide range of ground conditions as well (e.g., fault zones, water inflows), with protocols as to how the machine should be operated in such conditions. Once the machine has been launched, regularly scheduled maintenance based on tunnel length and geological conditions is also essential. While there are no special guidelines for long-distance tunnels, crews must be diligent and conduct more detailed inspections the longer a TBM is in operation.

Planned cutter inspections are a regular part of maintenance, which is recommended daily. Checking of oil levels, and all fluids, greases and hydraulics, is also of primary importance. Daily logs are recommended for monitoring of all major systems on the TBM. A daily maintenance regime typically involves routine checks without TBM downtime. Protocols for more in-depth monthly, semi-annual, and annual checks of systems should also be in place. These full checks of various systems do require downtime but are all the more critical when tunneling over a long distance or in variable conditions. These checks are also typically based on the rigors of the project schedule—in hard rock, a week is assumed to be equivalent to 100 m of advance while a month is assumed to be equivalent to 500 m as a baseline.

Depending on the tunnel length, some maintenance may be done beyond what is considered normal. Gearboxes, for example, may be designed for long tunnels but if it is known that the tunnel length will exceed the life of the gearboxes then planned refurbishment should occur during tunneling. This procedure has been done on several tunnels including India's AMR tunnel—what will be the longest tunnel without intermediate access at 43.5 km once complete.

Maintenance while storing the TBM between projects can also maximize equipment life—such as storing components indoors, coating the equipment with anticorrosive spray, and making sure the main bearing is filled with oil. Owning and using a new TBM has added hidden benefits including familiarity of machine operation and proven performance for that particular piece of equipment.

## 1.1 *Maintenance in the Digital Age*

Modern TBMs are making maintenance and replacement of consumables more efficient with monitoring technology. A typical TBM will include sensors and detectors for all manner of functions and will activate an alarm or other type of notification that can shut down the operation or parts of the operation if a critical threshold is reached.

Even disc cutters can be monitored to determine when cutter changes are needed. Sensors can deliver information wirelessly about cutter RPM, vibration, and temperature, indicating when cutter changes are necessary and allowing the operator to avoid cascading cutter failures known as wipeouts (see Figure 1, Mosavat 2017).

However, a visual inspection of the cutterhead is still ideal. Cutter rings are not the only thing that need inspection in this high-wear area of the TBM. The cutter assembly bolts, the seals, the surrounding structure, the wear coating – all this needs to be inspected by trained and experienced cutter technicians.

Data reading and logging systems provide operators further clues as to when maintenance is required. Real-time data loggers can transmit to the surface where crew members can interpret the data, or the data can even be stored on a website where the TBM supplier can monitor the machine's behavior and consult the crew. An example of this would be a high pressure reading at the main thrust rams combined with low torque at the cutterhead—this can be an

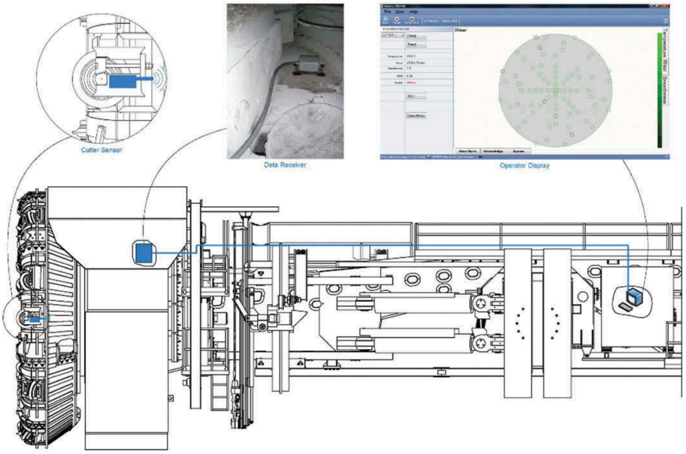

Figure 1. Remote monitoring system for disc cutters.

Figure 2. TBM data screens in operator's cabin.

indication of worn gauge disc cutters that in conditions like swelling rock could result in the machine becoming jammed (see Figure 2).

## 2 TBM DESIGN FOR MULTIPLE PROJECTS

Over the years, Robbins has built a quality assurance system that ensures when it delivers a rebuilt machine, either to the original configuration or a modified one, it still adheres to a design life of 10,000 hours. This standard also includes checks to make sure that all the components are in a functional condition of 'as new' or 'new'.

In order to guarantee the same design life and same warranties on a rebuilt machine, the initial design of the TBM will need to consider that the TBM will be used on several projects. This means that the major structures will need to be strong enough to survive even the toughest conditions and that worn parts can easily be replaced. If the machine is not properly designed for multiple projects, there will be a need to do major work to get the TBM in a working condition, either in its original or modified configuration.

One can argue that project owners typically only have one project and that the condition of the TBM and the suitability of its rebuild is therefore not essential. This is something that is also reflected in many of today's tunneling projects, where the commercial consideration is often given far more attention than the technical one. We would argue, however, that an initially sturdy and robust design of the TBM will give the project more uptime, higher production rates and better flexibility if unexpected conditions are encountered, making it a good and effective insurance against many types of obstacles. Some examples of design aspects that enable longer TBM design life are given below (Khalighi, 2015).

### 2.1 *Robust Cutterhead and Machine Structure*

A machine designed with multiple projects in mind relies on a heavy steel structure that can stand up to the harsh environments often encountered underground. Designs that take into account high abrasivity of the excavated material or the possibility of high abrasivity are even more robust. Ideally, the cutterhead should be designed with regular cutter inspections and changes in mind. It must also be built to last: this can be difficult with a back-loading cutterhead design, which is full of holes not unlike Swiss cheese. In order to build up the structure, much of the strengthening occurs during the manufacturing process. Full penetration welds are recommended for the cutterhead structure to battle fatigue loading and vibration. Rigorous weld inspections and FEA stress analysis checks can then be made for vulnerabilities in the cutterhead structure.

### 2.2 *Main Bearing and Seals*

Large diameter 3-axis main bearings, with the largest possible bearing to tunnel diameter ratio have larger dynamic capacity, and therefore are capable of withstanding more load impacts and giving longer bearing life. It is important to retain as high a ratio as possible (see Figure 3).

The bearing and ring gear are in a difficult-to-access spot on the TBM, so they must be designed for longevity, with a super robust structure and high safety factor. Safety factor is defined as any surplus capacity over the design factor of a given element, and overbuilding such structures is of necessity in long distance tunneling.

Robust seal design is also essential. The Robbins Company provides a proven seal design using hardened wear bands. Many other manufacturers don't use wear bands, and so as the TBM operates, it wears a groove into the seal lip contact zone. Robbins sacrificial wear bands can be switched out or replaced, making repairs easier. The abrasion-resistant wear bands, made of Stelite™, can be changed in the tunnel in the unlikely event of excessive wear, or can be relocated on the carrier to ensure that damage is not done to the TBM structure itself on long drives.

In addition to the seal design, other elements of the main bearing such as the internal fasteners must be designed to be durable and of high reliability, as these fasteners are difficult to access and are not easily replaceable. The studs connecting the cutterhead to the main bearing seal assembly must also be closely analyzed for strength, deflection, and adequate fastening/clamping force, and protection against abrasive muck must be provided for the fasteners.

## 2.3 *Lubrication*

Dry sump lubrication is a critical way of keeping the main bearing cavity clean by filtering and recycling the oil at a constant rate. Any contamination is cleaned from the cavity, prolonging bearing life. The system also has an added benefit: The oil can be monitored and analyzed for any indications of distress in the main bearing or gears. This monitoring has the potential to allow for correction or intervening maintenance of critical structures/components before a failure occurs.

## 2.4 *Drive System*

The right drive system is also important for heavy TBM usage. Variable Frequency Drives (VFDs) and planetary gear reducers allow for infinitely adjustable torque and speed control

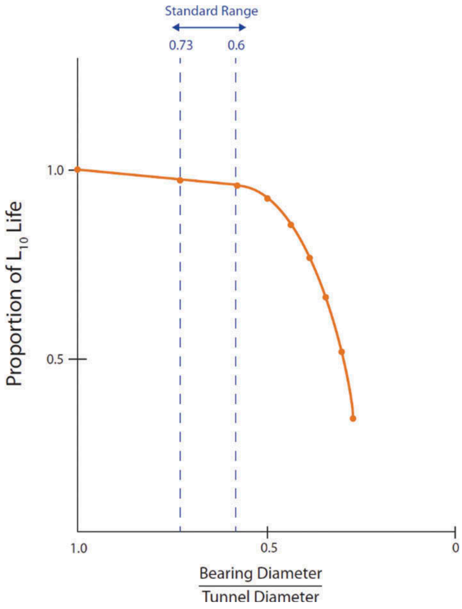

Figure 3. As the ratio falls below 0.6 bearing life is reduced.

based on the encountered ground, which optimizes the TBM advance rate and reduces damage to machine components. This is in comparison to older style drives: In older model TBMs, often the drive system was single speed or 2-speed. If a machine bored into a fault zone, for example, there would be no way to slow down the cutterhead. Such drives would often result in undue wear to the TBM, or even damage to structural components.

Drive motors must also be designed to withstand high vibration as a result of excavating through hard rock conditions. Cantilevered motors must be able to withstand the high g-forces applied to them by violent machine vibration, which is induced by the rock cutting action.

### 2.5 *Load Path*

A uniform load path, from cutterhead to main bearing to cutterhead support, is always desirable. However, for long distance tunnelling or for multiple uses, the load path can be crucial as high stresses occur wherever the load path shifts. A cutterhead with a cone-shaped rear section can help with this problem by evenly distributing the load across the circumference of the main bearing. In general, everything must be designed in a more robust fashion, and the loads generated by the cutterhead must also translate into a heavier overall structure of the machine.

## 3 KEY FACTORS IN REBUILDING TBMS

The rebuilding of TBMs—both, the process and the standardization of rebuilds–has become a focus for the industry as more projects with multiple machine requirements and short time frames are being proposed. The focus has been further highlighted by the ITAtech, a technology-focused committee for the International Tunneling Association (ITA-AITES) that produced guidelines on rebuilds of machinery for mechanized tunnel excavation in 2015. While the guidelines are relatively new, Robbins has a long history of delivering robust machines, many of which are rebuilt (many are also 100% new).

In general, Robbins' experience with rebuilding machines has yielded some key insights. As long as the TBM is well-maintained, there will be jobs it can bore economically. Optimal TBM refurbishment on a used machine requires a broad knowledge of the project conditions, and there are some limitations:

- Machine diameter can be decreased within the limits set by free movement of the grippers and side/roof supports
- Machine diameter can be increased subject to the structural integrity of the machine and the power/thrust capabilities
- Propel force can be increased only to the level supported by the grippers' thrust reaction force
- Cutterhead power must be adequate to sustain the propel force in the given rock, but cannot be increased beyond the capacity of the final drive ring gear and pinions
- Cutterhead speed increases must not exceed the centrifugal limits of muck handling or the maximum rotational speed of the gage cutters

Increasing the power of the TBM is one way to make the design more robust for a longer equipment life. Strong designs have been developed in recent years, including Robbins High Performance (HP) TBMs, and have been used on a number of record-setting hard rock tunnels. The HP TBM is designed with a greater strength of core structure and final drive components. They can be used over a much wider range of diameters, whereas older machines (from the 1970s and 80s) are typically limited to a range of less than 1 m of diameter change plus or minus their original size.

HP TBMs have the capability of operating over a broad range. For example, a 4.9 m TBM can be refurbished between 4.3 m and 7.2 m diameters—a range of 2.9 m. Main bearing designs have allowed for greater flexibility, evolving from a 2-row tapered roller bearing to the 3-axis, 3-row cylindrical roller bearing used today. This configuration gives a much higher axial thrust capacity for the same bearing diameter and far greater life in terms of operating hours or revolutions.

Overall, what determines how long a TBM will last is a function of the fundamental design, such as the thrust and gripper load path through the machine and the robustness of the core structure. On older model TBMs, the ring gear and pinions can be strengthened, and larger motors can be added. With sufficient core structure strength, it is also possible to increase the thrust capacity. The limitation is the capacity of the gripper cylinder to handle the increased power and thrust. Once replacement of the gripper cylinder and carrier are required, TBM modification costs are generally considered uneconomic.

## 4 TBM REBUILDS IN ADVERSE GEOLOGICAL CONDITIONS

Service, maintenance and operation of a TBM can be dramatically impacted by the ground strata, which may appear in the form of rock bursting, swelling and squeezing rock, face collapse, mixed face conditions, or other challenges. In some cases, the TBM operation must be interrupted to allow the machine to undergo substantial reconditioning.

### 4.1 *Case Study: Kargi HEPP, Turkey*

The Kargi Kizilirmak Hydroelectric Project involved the excavation of an 11.80 km headrace tunnel at 10.00 m bore diameter. Due to expected variations in geology, a Robbins Hard Rock Double Shield TBM was selected with specific features to bore the tunnel in mixed ground formations.

As expected, the machine ran into adverse ground conditions, but these were much worse than initially predicted during site investigations. The crew employed various well-proven techniques to keep the machine from becoming stuck, including boring half strokes to keep the gripper and rear shield from sitting idle for too long. This worked well for a time, but the machine came to stop when a face collapse occurred followed by a crown cavity. In total, eight bypass tunnels were needed in the first 2 km of boring.

It was determined the machine needed to be reconditioned to continue the drive, and it also needed to be furnished with supplementary features and equipment to enable tunneling in highly variable geologic conditions. Some of the most significant features are listed below (Clark 2015).

#### 4.1.1 *Supplementary means for ground support installation*

The possibility of installing ground support such as fore-poles or a pipe roof canopy ahead of the tunnel face was investigated as a means of supporting loose and fractured ground. A custom designed canopy drill was delivered to site and installed in the forward shield for installation of a tube canopy. The space in the forward shield area was limited; hence, the extension section of each tube was only 1.0 m in length. However, the advantages of drilling closer to the tunnel face more than compensated for the time spent adding extensions to the tube length. The location of the canopy drill reduced the length of each canopy tube by more than 3 meters when compared to installation using the main TBM probe drills (see Figure 4).

#### 4.1.2 *Modification of Cutterhead Drive Characteristics*

To further mitigate the effects of squeezing ground or collapses, custom-made gear reducers were ordered and retrofitted to the cutterhead motors. They were installed between the drive motor and the primary two-stage planetary gearboxes. During standard boring operations, the gear reducers operate at a ratio of 1:1, offering no additional reduction and allowing the cutterhead to reach design speeds for hard rock boring. When the machine encounters loose or squeezing ground the reducers are engaged, which results in a reduction in cutterhead

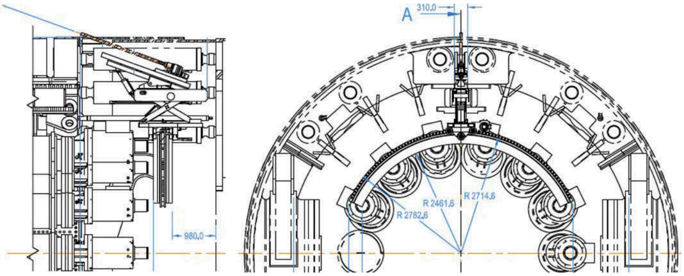

Figure 4. Custom canopy drill in the forward shield.

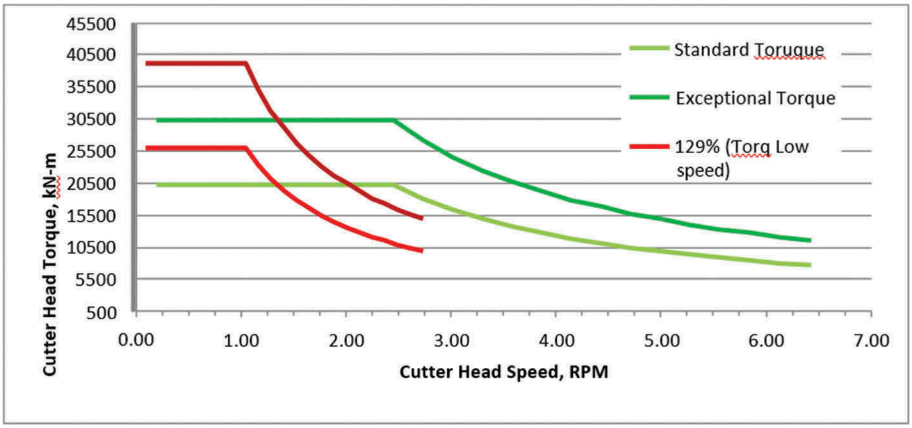

Figure 5. Cutterhead torque curves after modification.

speed but the available torque is increased. Figure 5 shows the torque curves for both standard and reduced gearing. After the installation of the canopy drill and the increase in available cutterhead torque, the TBM traversed several sections of adverse geology including stretches of severe convergence without becoming trapped.

### 4.2 *Case Study: Namma Metro Phase 1 Project*

The Namma Metro Phase 1 Project in the Indian City of Bangalore included dozens of TBMs, many operating in mixed face conditions. One of the sections—a 1.0 km drive from Mantri Square to the central hub station of Majestic Gowda, as part of the North-South Corridor—utilized a 6.23 m diameter European-manufactured EPB. The TBM employed experienced severe wear at the cutterhead with the result that the TBM could no longer excavate a tunnel of sufficient diameter for the shield to pass through. In general, the TBM excavated in weathered granite having approximate compressive strength of 130 MPa with a high content of quartz and feldspars (see Figure 6).

The initial plan was to determine how to dismantle the TBM underground to allow another TBM to excavate the tunnel from the opposite direction. After an intense survey and inspection, it was found that the entire machine was in good enough condition to be refurbished in-situ, permitting completion of tunnel excavation (a further 630 m) with the same machine. The cutterhead and screw conveyor were completely worn out and needed changing (Willis 2017).

To enable the reconditioning effort, a rescue shaft was built to gain access to the front of the machine. While this happened, TBM parts and components were refurbished and repaired.

Figure 6. Rock sample taken from the face.

Figure 7. Extreme wear of helix measured at 230 mm to inside of casing & cracks at screw helix shaft.

The plan was to inspect the cutterhead and drive systems once the shaft was finished and the front of the machine could be accessed. Other components such as the screw conveyor were removed inside the tunnel for subsequent replacement with a combination of new and refurbished parts (see Figure 7).

Once in the shaft, the cutterhead of the machine showed evidence of the extremely abrasive rock encountered. Disc housings, buckets and drag cutter mounts were completely gone. This damage resulted after only 370 m of tunnelling (see Figure 8).

Repair of the cutterhead was not an option anymore, so it had to be replaced in full by a new one. The basic configuration was kept. The new head was dressed with extended wear coating and protection and flown in for installation to make the tight schedule.

Full refurbishment began in January 2015 with a programme of dismantling components such as the screw conveyor, hydraulic system, PLC, and checking the main drive. These actions uncovered even further signs of damage than earlier seen. A completely new drive system for the screw conveyor as well as the top helix section of the screw was ordered from Italy. The refurbishment was completed and re-commissioning began in August 2015.

The TBM was re-launched in late September 2015. Though various challenges were faced, tunnel excavation was completed on 19th April 2016. The remaining 630 m drive was bored in especially challenging geology and completed in seven months, with minimal cover in many places (down to less than 2 metres even in back-filled areas). Significant stretches of mixed face conditions were also encountered where cutter ring damage was frequent along with hub

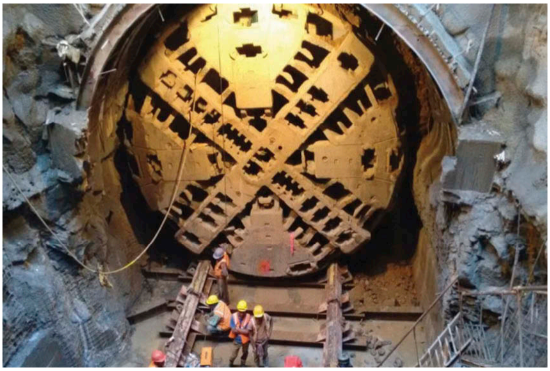

Figure 8. Cutterhead condition when machine was pushed in the shaft.

Figure 9. Condition of the new cutterhead after breakthrough into the final receiving shaft.

seal failure—filling the hubs with an oil/grease mixture helped overcome this problem. However, a disciplined programme of proactive service and maintenance kept the machine in good shape and at high availability. The service company in charge of the machine's repair actively supported the contractor on site, demonstrating that even in the worst cases when machines are heavily damaged and have suffered extreme wear, they can be rescued and repaired in-situ (see Figure 9).

## 5 CONCLUSIONS

Regular service, good housekeeping and efficient organization of maintenance periods on site are essential to maximize a TBM's performance, its availability and safe employment on a project.

Suppliers can help and provide guidance and support – in paper and in person. Modern tools and data communication can support maintenance service, but they don't replace intervention by experienced crews on site. TBMs can be reused economically for multiple projects given that the machine design is robust and the equipment is operated and maintained according to requirements.

Machines operating in adverse geological conditions can run into stoppages and need reconditioning or in-situ modification. Suppliers have engineering knowledge and the technical know-how to adjust the machine to the new requirements and bring the TBM back on route.

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