TBM Design for Long Distance Tunnels: How to keep Hard Rock TBMs boring for 15 km or more

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1. Introduction

Today's Tunnel Boring Machines are often required to bore longer tunnels in harder rock at a faster pace—a trio of challenges that can be daunting for any contractor. With proper design, operation, and maintenance, however, modern TBMs are very capable of reaching their 10,000-hour design life or more. TBMs in the industry today have already accomplished the feats of boring upwards of 50 km on multiple tunnels over decades, and of completing single TBM drives totaling 27 km. With new capabilities, even greater feats may be possible.

From abrasive rock to fault zones to water inflows, geologic challenges become more common as tunnel lengths increase. In rock tunnels over 15 km long, a host of challenges may meet a TBM, requiring a versatile design. General wear and tear is an issue on machines boring long stretches of tunnel, and thus minimization of downtime is key. In order to counteract these challenges, a number of design features can be added during the manufacturing process, and these, combined with regular maintenance and well-designed logistics during tunneling, can result in TBMs lasting for the tunnel length and possibly over multiple projects.

2. Basic Tenets of Long Distance TBM Design

In order to design machines for such conditions, consideration must be given to the harsh aspects of tunneling in hard rock over long distances. These considerations can be broken down into what can be done at the TBM design stage, and what can be done during TBM operation and maintenance. Overall, oversizing components like the hydraulics and lube systems is a good idea, and overbuilding of steel structures is key.

2.1 Cutterhead and Cutters

Much of long-distance TBM design centers around areas directly in contact with the rock face, namely, the cutterhead and cutters. High strength materials, wear protection on the cutterhead, and cutter spacing all affect cutterhead wear in dramatic ways. For example, Hardox plates can be used in less abrasive rock, while in very abrasive rock replaceable chromium carbide plating becomes a necessity. Depending on the geology, this plating can cover the entire face, periphery, and back of the cutterhead. 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.

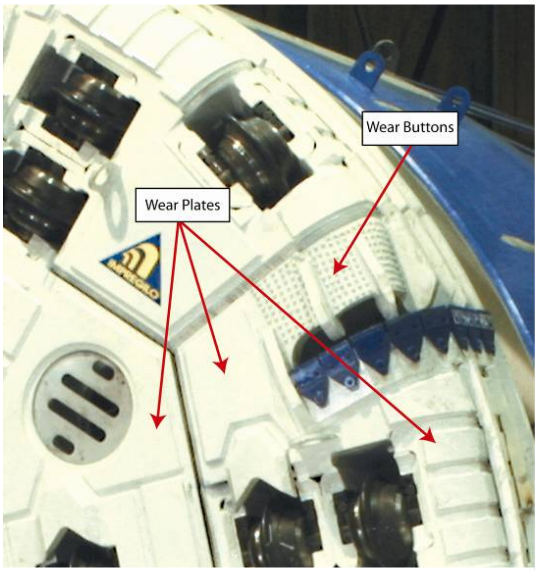

Fig. 1. *Example of a cutterhead designed for very hard rock conditions*

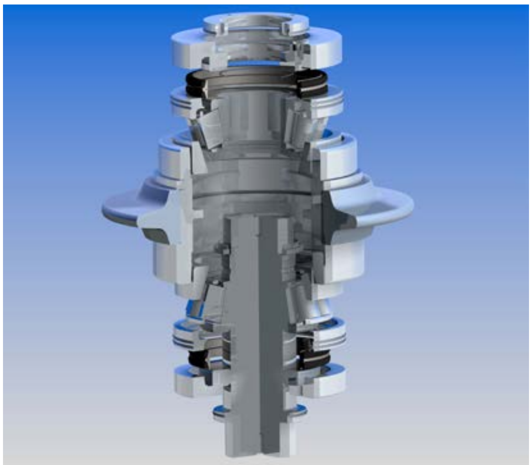

Fig. 2. *20-inch cutter assembly, exploded view*

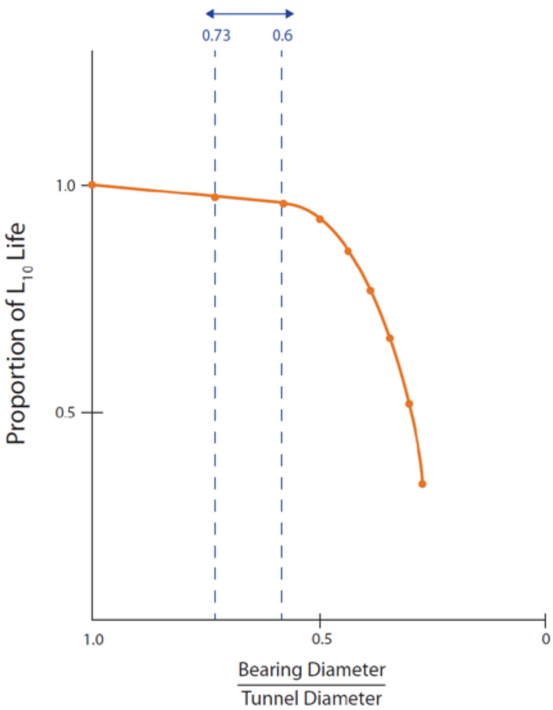

Fig. 3. *As the ratio falls below 0.6 Main Bearing life is reduced*

During operation, deflector plates on the cutterhead can bulldoze rock away from the leading edge of disc cutters, minimizing the impact of loose rock on cutters that might otherwise cause chipping or spalling. Adequately-sized muck buckets are also a crucial component to allow for a smooth flow of muck, along with the right quantity and location on the cutterhead. Durable, replaceable bucket lips are also of key importance in these high-wear areas (see Figure 1).

In terms of rolling disc cutter design, larger diameters are manufactured with larger bearings capable of withstanding heavier loads while also offering more wear volume. 19-inch or 20-inch cutters are preferable to smaller cutter diameters such as 17-inch (see Figure 2).

The material of the disc rings themselves is also crucial—exceptionally clean steel ensures high resistance to fatigue, for instance. Metal-to-metal face seals are also the industry standard in eliminating ingress of foreign materials, while silicone torics maintain elasticity at high temperatures. These temperatures can often rise to 75-85ºC when excavating very hard rock or when in very hot climates, and cutter designs must be able to withstand repeated heating and cooling.

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 over-building 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. Other manu-

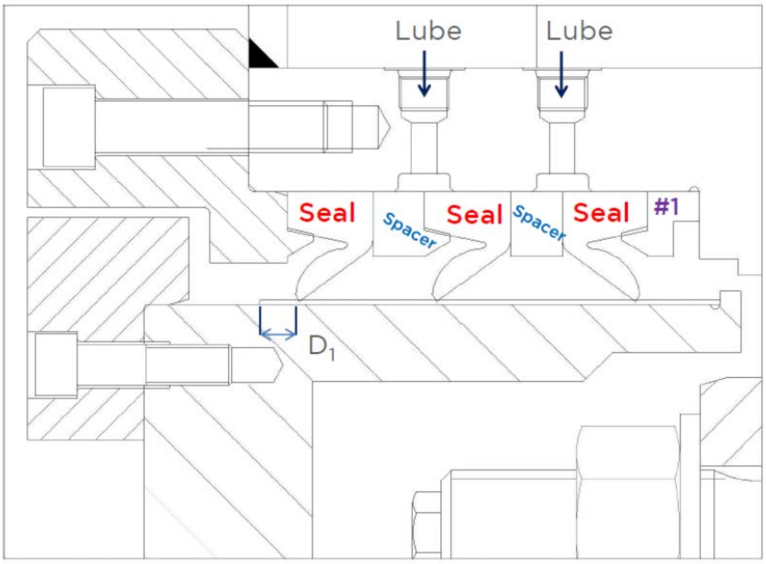

Fig. 4. Normal seals diagram

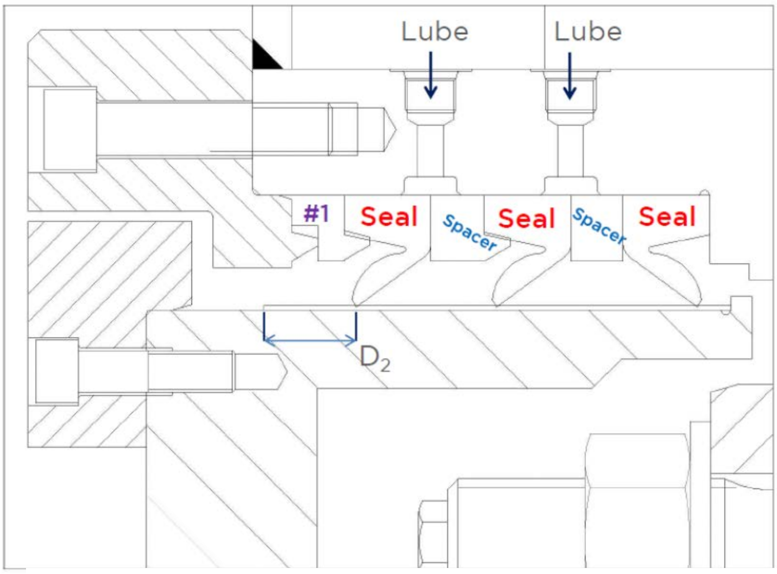

Fig. 5. Moved seals diagram

facturers utilize a ring of low-carbon alloy steel instead, which is non-replaceable. To change the seal location in the tunnel, the seal is moved axially relative to the wear band. The spacer between the seals can be relocated so that wear bands do not have to be changed at the same time as the seals, effectively doubling the life of the wear band (see Figures 4-5).

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 in long-distance TBM design. Variable Frequency Drives (VFDs) and planetary gear reducers allow for infinitely adjustable torque and speed control based on the encountered ground, which optimizes the TBM advance rate and reduces damage to machine components (see Figure 6). 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.

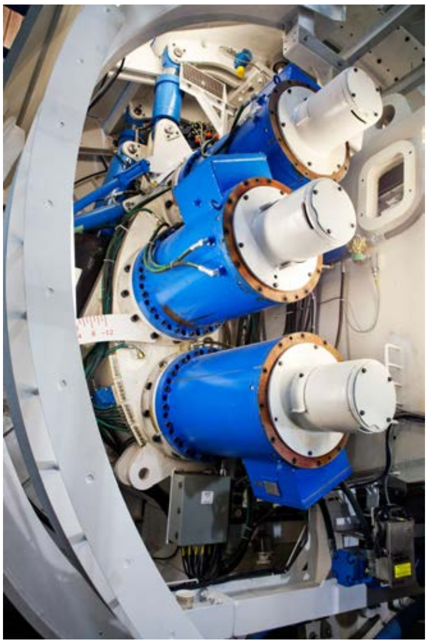

Fig. 6. *VFD setup in a hard rock TBM*

2.5 Load Path

A uniform load path, from cutterhead to main bearing to cutterhead support, is always desirable. However for long distance tunneling, 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.

2.6 Efficient Muck Removal

The path of muck, from the muck bucket to the chute to the machine belt conveyor, must also be as smooth as possible. Smooth muck flow not only increases efficiency, but also prevents the problem of re-grind on the cutterhead. It can also reduce wear on both the external and internal surfaces of the cutterhead. One way of achieving smooth flow is to oversize the TBM belt conveyor, allowing for increased capacity while reducing the overall belt speed, thereby reducing wear on the conveyor over a long period of time.

2.7 Continuous Conveyors

Similarly, a smooth muck flow path all the way out of the tunnel is critically important. Use of continuous conveyors limits downtime when compared to the downtime experienced when a locomotive and muck cars are used. As a tunnel gets longer, the time to transport muck cars in and out of the tunnel becomes less and less efficient. Continuous conveyors for long distances must be designed with robust transfer points to allow for a soft landing of the muck in order to reduce wear and tear. A good maintenance system including muck scrapers to keep the belt clean and flashings to prevent spillage is also of critical importance.

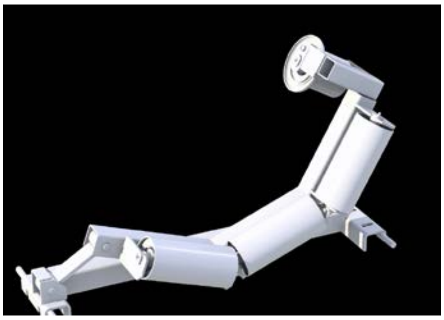

Fig. 7. *Self-adjusting curve idler*

For efficient load transfer through curves, ultimately reducing wear on the system, Robbins has developed a patented self-adjusting curve idler. The idler senses the changing load conditions and accommodates by adjusting the belt tension (see figure 7).

3. Operation and Maintenance

While TBM design for long distance is crucial, proper TBM operation and maintenance may be even more so. 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. These checks are also typically based on the rigors of the project schedule—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. Gear boxes, for example, may be designed for long tunnels but if it is known that the tunnel length will exceed the life of the gear boxes 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.

4. Case Study: Liaoning NOW Water Transfer Project

One of the longest tunnels currently under construction is Northeastern China’s Liaoning NOW Water transfer project, measuring a whopping 120 km in length. The project is a good example of long-distance TBM design and operation. The government-commissioned tunnel, for irrigation and drinking water, has been divided into nine lots, designated T1 through T9 (for Tunnel No. 1 to 9, etc.). Each lot, except for T7, is utilizing a tunnel boring machine--lot T7 is utilizing drill and blast. Lots T1 and T2 purchased new non-Robbins Main Beam machines. Contractor SinoHydro Bureau 3, responsible for lots T3 and T4, elected for new Robbins Main Beam TBMs, 8.53 m in diameter. Similarly, T5 contractor Shanxi Hydraulic Engineer Construction Bureau ordered an 8.53 m Robbins Main Beam. Chinese equipment supplier NHI contracted with Robbins to supply Main Beam machines of the same diameter for T6 and T8, and a rebuilt Robbins machine was provided for lot T9. All eight machines, including the non-Robbins TBMs, were ordered with Robbins continuous conveyors for muck removal.

Each of the eight TBMs excavating the Liaoning NOW project is boring two consecutive tunnels ranging from 6.5 to 8.0 km long, totaling about 15 km each. The difficult and long tunnels pass through mainly granite, granite gneiss, and schist geology of varying abrasivity. Mountainous terrain including valleys and rivers requires versatile ground support. Cover varies widely, from as little as 97 m to as high as 590 m at T6.

4.2 Liaoning TBM Design

A flexible ground support system was provided for all six Main Beam TBMs at Liaoning due to the long tunnel lengths and variable conditions. The machines are capable of installing a wide variety of ground support, from wire mesh and rock bolts to ring beams and McNally slats. The TBMs are among the first to be designed with McNally pockets during fabrication, and the first to use 20-inch disc cutters in China. The McNally roof support system, developed by C&M McNally for exclusive use on Robbins TBMs, is a unique solution: In the past, roof support fingers provided limited protection to the crew working at the front of the machine and also to a degree prevented damage to cutterhead drive motors and other equipment installed on the front of the machine. However, when poorer or blocky ground conditions were encountered these fingers would simply bend out of shape and more often than not the contractor would end up removing them altogether. With the removal of the roof support fingers, the bored tunnel is exposed at the back of the roof support where more effective ground support is easier and quicker to install. The fingers are replaced with a curved assembly of pockets known as McNally pockets, and as the TBM advances, workers load the pockets with steel slats that are then extruded during a TBM stroke. The slats are bolted in place, providing continuous and maximal support to the tunnel crown in difficult rock conditions (see Figure 8).

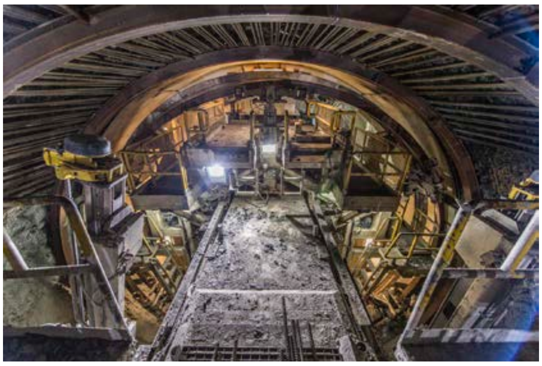

Fig. 8. *McNally slats installed in the tunnel crown at Liaoning T5*

Several other unique aspects were designed in order to accommodate multiple ground support options within an 8. 53 m diameter space. Materials handling takes place in the tunnel invert, requiring a 180-degree rotating backhoe scoop that can be moved out of the path of the cart. A bridge crane and jib crane pick up materials such as mesh panels, new disc cutters, etc. and transfer it to the bridge area. Invert cleaning is ongoing when the cart is not in place (see Figure 9).

The ring beam erector and roof drill system are both mounted on the same rail system, but are capable of independent movement. The ring beam erector consists of the assembly ring and expander. The rotating assembly ring is fixed axially and used to loosely assemble five ring beam components. Once the components are loosely assembled and pinned to the assembly ring, the expander, which moves fore and aft, expands the components to a preset pressure against the tunnel wall. A sixth Dutchman piece is installed in the resulting space, and the ring beam with tightened connections is bolted to the tunnel wall. The assembly and expander can also be easily converted for installation of steel straps, rather than full rings.

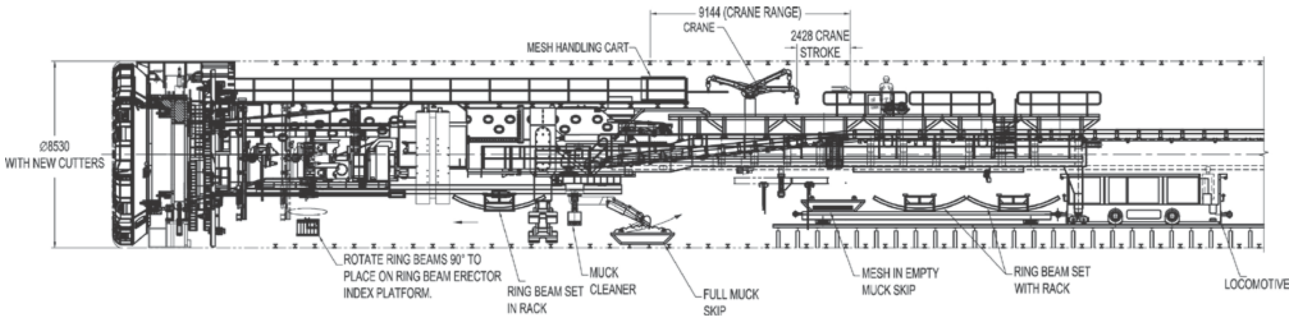

Fig 9. *Liaoning NOW TBM Materials Handling System*

Previous assembly methods required that the fully assembled ring beam be transported to a pocket before being expanded against the tunnel wall. The method is not as fast, and does not give the flexibility often needed in changing ground that may only require steel straps.

4.3 TBM Excavation

The machines were launched between October 2013 and February 2014 from adit tunnels, with the exception of the refurbished T9 machine, which was launched earlier in 2013. Field Service crews at the sites provided mechanical, electrical, and hydraulic system supervision, TBM operation during site assembly and commissioning, and training on proper operation and maintenance of the machine.

The project is allowing for a unique opportunity to analyze various cutter sizes and manufacturers in varying geologies. Three Robbins TBMs were supplied with 20-inch cutters, as well as two Robbins/NHI machines with 20-inch cutters. Two Non-Robbins TBMs were launched with 19-inch cutters, and one rebuilt Robbins TBM was fitted with 19-inch cutters. Despite launching two months later than a Non-Robbins machine on the same project, a Robbins TBM with 20-inch cutters completed its first section of the excavation in October 2014, at a point nearly 2.7 km ahead of the Non-Robbins machine.

Similarly, the average monthly boring meters using Robbins TBMs and cutters have been as high as 675 m per month and nearly 1,300 cubic meters bored per cutter. Excessively abrasive ground on the Non-Robbins (NR) TBM jobsites created excavation problems that resulted in rates as low as 322 m per month and only 139 cubic meters bored per cutter. The project owners insisted the contractor switch to Robbins 19-inch discs with the end result that Robbins cutters were installed on the two machines. After the new cutters were installed, excavation rates have steadily increased to a high of 610 m per month on average and overall cutter performance increased to 877 cubic meters per cutter. These great results were similarly echoed when locally manufactured 20-inch cutters were installed on a Robbins/NHI TBM—high cutter wear (only 198 cubic meters bored per cutter) ultimately resulted in the contractor switching back to Robbins discs (see Figures 10-11).

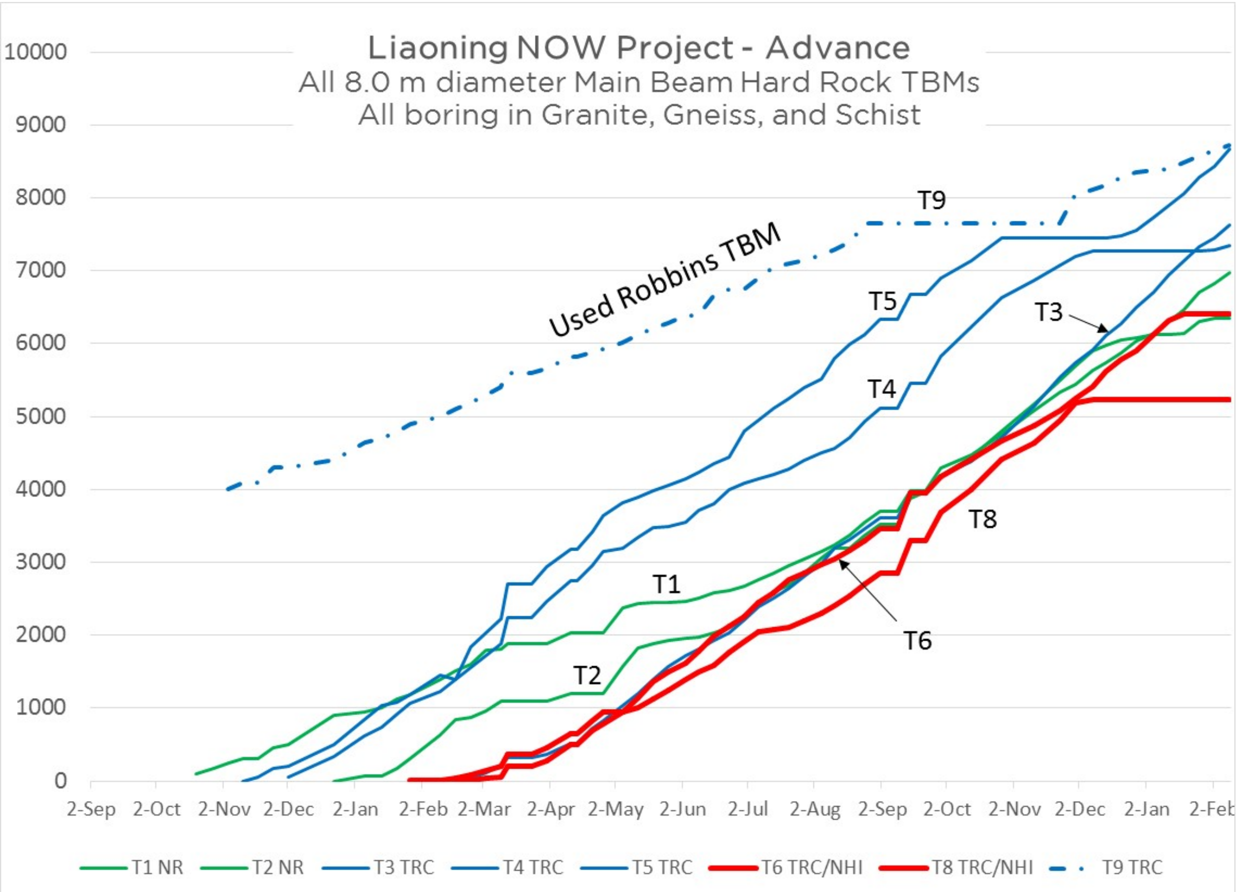

Fig 10. *Current advance of Liaoning NOW TBMs (as of February 2015)*

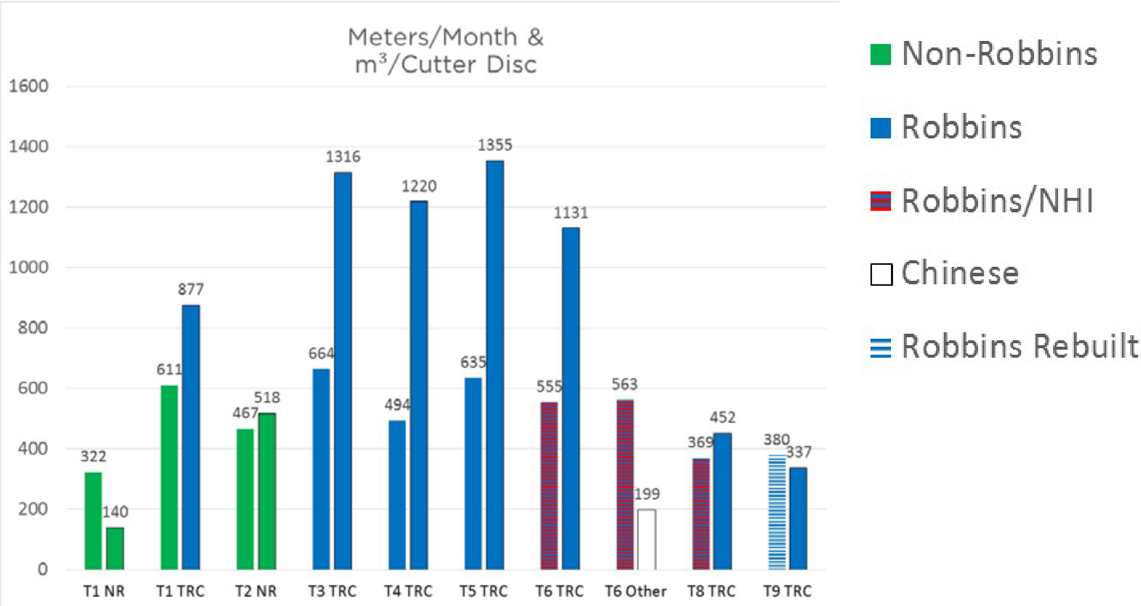

Fig 11. Meters per month (left column) and cubic meters per cutter disc (right column) of each TBM drive at Liaoning

At T5, fractured ground conditions have required the use of McNally slats to consolidate the ground in over 50% of the tunnel. The contractor at T5 has taken steps to extend the coverage of the original McNally system to the gripper shoes area and both side supports in case difficult ground is encountered. The contractor is reinforcing tunnel walls under the gripper shoe position by using a combination of McNally slats, ring beams and a top layer of shotcrete so the gripper shoes can react against the reinforced shotcrete face. The process allows for fast and continuous boring without the need for continual reinforcement of the gripper pads.

Overall, the machines are progressing well, with the continuous conveyors being a particularly important part of the overall system. Continuous conveyors transfer muck to adit conveyors, which are between 600 m to 1.3 km long, and then onto radial stackers for temporary muck storage onsite. Tunneling on the massive project is expected to be completed by early 2016.

5. Olmos Trans-Andean Water Tunnel

A second example of long distance tunnel in hard rock can be seen at Peru's Olmos Trans-Andean Tunnel. The 13.9 km long tunnel is the world's second deepest civil works tunnel with 2,000 m of cover (second only to the Gotthard Base Tunnel). Launched in 2007 with a 5.3 m diameter Main Beam TBM, ground conditions deteriorated as cover increased, with rock falls and rock bursting events becoming more common. By the time tunnelling was completed in 2011, more than 16,000 rock bursting events had been recorded, ranging from mild to very severe.

5.1 TBM Design for Long Distances at High Cover

The Olmos project was the fifth tunnel with the refurbished machine—by the end of tunnel completion the machine, originally built in 1994, had completed almost 35 km of tunnel. The TBM design for Olmos included a back-loading cutterhead mounted with 17 inch (432 mm) diameter disc cutters, and was tailored for excavation in a mix of schists, argillaceous rock, quartz mica schist, quartz porphyry, andesite, dacite, tuff, and pyroclastic breccia.

As the rock cover increased in 2008, the frequency of broken rock, overloads of ring beams and mesh, as well as rock bursting events, also increased. Engineers suspected that this was a consequence of cutting a tunnel in a stressed rock mass, resulting in a local increase in stress around the tunnel opening. The shape of the opening, the support system used, and the timeliness of its installation were affecting the distribution and intensity of the stress changes caused by the tunnel excavation.

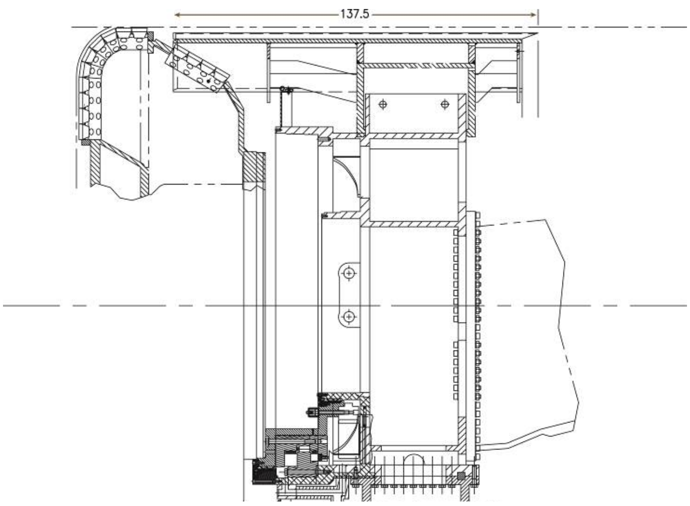

Figure 12. *McNally roof support pockets for slats*

Despite employed methods including probe drilling and Tunnel Seismic Prediction, a 20-tonne rock fall occurred, which was not for-seeable. Engineers determined that due to the rock stresses ground conditions were literally changing as the machine excavated through them.

In order to cope with the extreme geology, the contractor and manufacturer elected to make changes to the TBM allowing installation of a novel type of TBM ground support. The machine's roof shield fingers were removed and replaced with the McNally Support System, designed and patented by C&M McNally of Ontario, Canada.

The McNally system requires modifying or replacing the roof shields. The curved finger shield plate is replaced by a curved assembly of pockets with rectangular cross-sections. The pockets extend axially aft from the rear side of the cutterhead through the cutterhead support, in the area where roof drills can work. Before a TBM stroke, crews slide pre-fabricated steel slats (consisting of four pieces of steel reinforcing bar welded together) into the pockets, such that the slats are two rows deep inside each pocket. The ends of the slats protrude from the pockets and are bolted to the roof of the tunnel using a steel strap. As the machine advances, the slats are pulled from the pockets and continuously bolted to the roof using subsequent straps. Slats are reloaded and used throughout excavation to prevent deformation and rock falls (see Figures 12 & 13a-c).

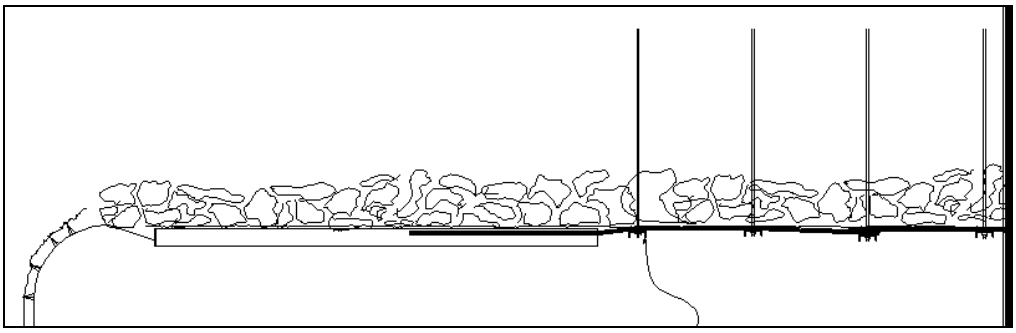

Figure 13a. *McNally –system - slats installed*

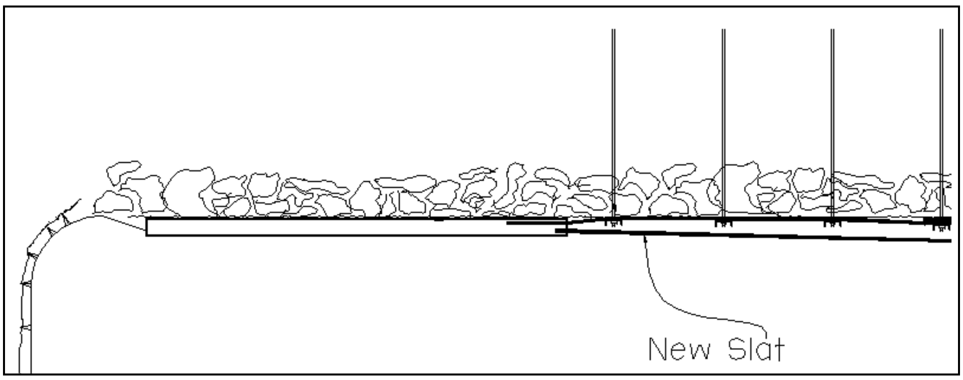

Figure 13b. *McNally system – new roof slat inserted into pocket*

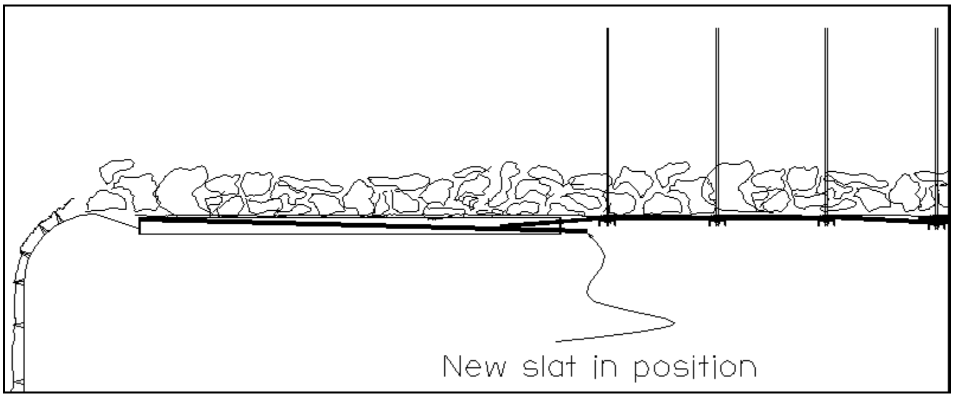

Figure 13c. *McNally system – new roof slat fully inserted, overlaps last installed slat*

The McNally support system provides the benefit of continuous support along the roof area of the tunnel, retaining smaller pieces of broken rock in place and helping to sustain the natural rock arch, ultimately protecting workers from falling rock. Due to the high pressures in the Olmos tunnel and the requirement for steel as part of the final lining, the contractor opted for steel slats as the continuous support (see Figures 14 & 15).

Figure 14. *In-tunnel install of the McNally system*

Figure 15. *Steel Slats containing Rock Bursting*

5.2 Secondary Modifications

Despite improvements in production, with up to 674 m per month excavated, rock bursting events continued to hamper progress into 2010. Crews experienced large over-breaks and cathedralling in over 7,000 m of highly fractured and unstable ground. Large cavities that formed during tunnelling had to be injected with cement and stabilized with spiling. In addition, a major rock bursting event occurred in 2010 that severely damaged the TBM, burying parts of the machine near the left gripper shoe and twisting ring beams. As a result of this sequence of events, secondary modifications were proposed.

After the large rock bursting event, new changes were proposed in June 2010 in order to control severe rock bursting encountered in the L1 area (directly behind the cutterhead support) and extending down the tunnel sides (see Figure 16):

- Extensions fore and aft, of the side portions of the roof canopy, the side supports and the bottom shoe (vertical front support)
- Additional pockets for McNally slats on the outside of the side supports to the bottom, to contain rock bursting in these areas
- Platforms modified for workers to more easily install rock bolts in the tunnel crown.
- Installation of “yieldable” bolts to enable energy absorption of rock bursts and to prevent or reduce collapses of the rock mass
- Operator’s control station was removed from the L2 area (gripper carriage), and installed on back-up deck #2, to protect operators from severe rock bursts

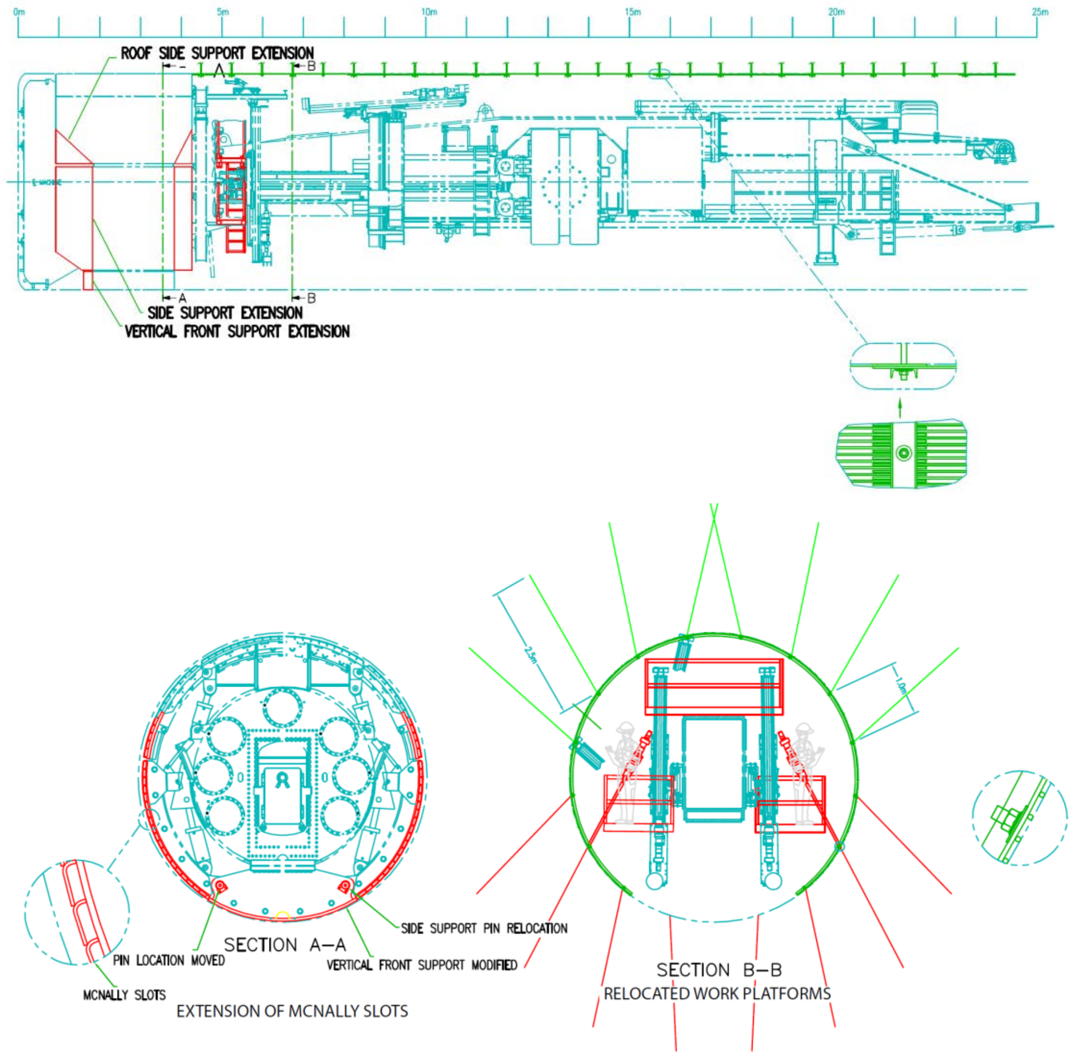

Figure 16. Secondary modifications to the ground support program

While some of these proposed changes were made, namely the extensions of the side supports, roof canopy, and bottom shoe, and the relocation of the operator's control station, others were foregone in the interest of maintaining the tunneling schedule. Though only partial modifications were done, safety in the severe rock bursting conditions was greatly improved. By the time of breakthrough in 2011, the machine's excavation rate had improved to 4 m per hour. The project stands as a testament to human engineering overcoming long odds in a deep mountain tunnel.

6. Conclusions

Intelligent, robust machine design for purpose, combined with a rigorous maintenance program performed on a regular basis, are the fundamental tenets of building TBMs for long distance tunnels in hard rock. With today's technology and skilled workers, there is no reason why TBMs can't excavate longer tunnels in excess of 25 km, and last over multiple projects and decades of use.