Long Haul TBM: Use of a Rebuilt Main Beam Machine at the DigIndy Tunnel System in Indianapolis, IN

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ABSTRACT: TBMs can last for decades and be rebuilt project after project with proper maintenance. How successful can rebuilt TBMs be? At the DigIndy Tunnel System in Indianapolis, Indiana, USA, a rebuilt TBM was used to great effect. The 6.2 m diameter Main Beam, originally manufactured in 1980, bored 40+ km of tunnels and set three world records in its size class of 6 to 7 m, including a best month of 1,754 m. In this paper, the authors analyze the TBM rebuild, performance and lessons learned to make recommendations for future projects seeking to use rebuilt TBMs over long distances.

INTRODUCTION

Time and cost savings for a rebuilt machine can be highly variable, depending on the extent of the rebuild and the number of projects the machine is used on. But there is general agreement that under the right conditions, savings and advantages can be significant.

TBMs are still in operation in the industry that have lasted over five decades—in particular a 2.7 m diameter Robbins Main Beam TBM originally built in 1968 is still in operation in Canada. The machine has been used on many projects, and with contractor-led refurbishment at the start of each project the TBM can continue boring tunnels for many more years. With each subsequent tunnel the savings in terms of time and cost multiply.

As for the savings of using rebuilt machines vs. new ones for each project, this is highly variable and can range from 75% cheaper for a simple machine and a tunnel project with tried and tested ground conditions, to around 20% cheaper for a project with more complex requirements (a high-pressure EPB for example).

The advantages of rebuilt machines aren't just in the costs, however. Contractors have stated that the time savings of using a rebuilt machine can be six months or more (as long as the TBM truly fits the project specifications and is not a compromise, and major changes aren't required).

The other benefit is in owning the machine itself: Familiarity of the TBM is a big plus, and operators and maintenance crews are familiar with the equipment, all of which can greatly improve performance during the initial learning curve.

HOW LONG CAN TBMs LAST?

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, used on a number of 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 (Roby & Walford, 1995).

DIGINDY TUNNEL SYSTEM: PROJECT BACKGROUND

A great example of just how long a TBM can last can be found at the DigIndy Tunnel System in Indianapolis, IN, USA. One TBM was used on the project to bore a vast network of 40+ km of tunnels below the city (see Figure 1).

Tunnel System Map

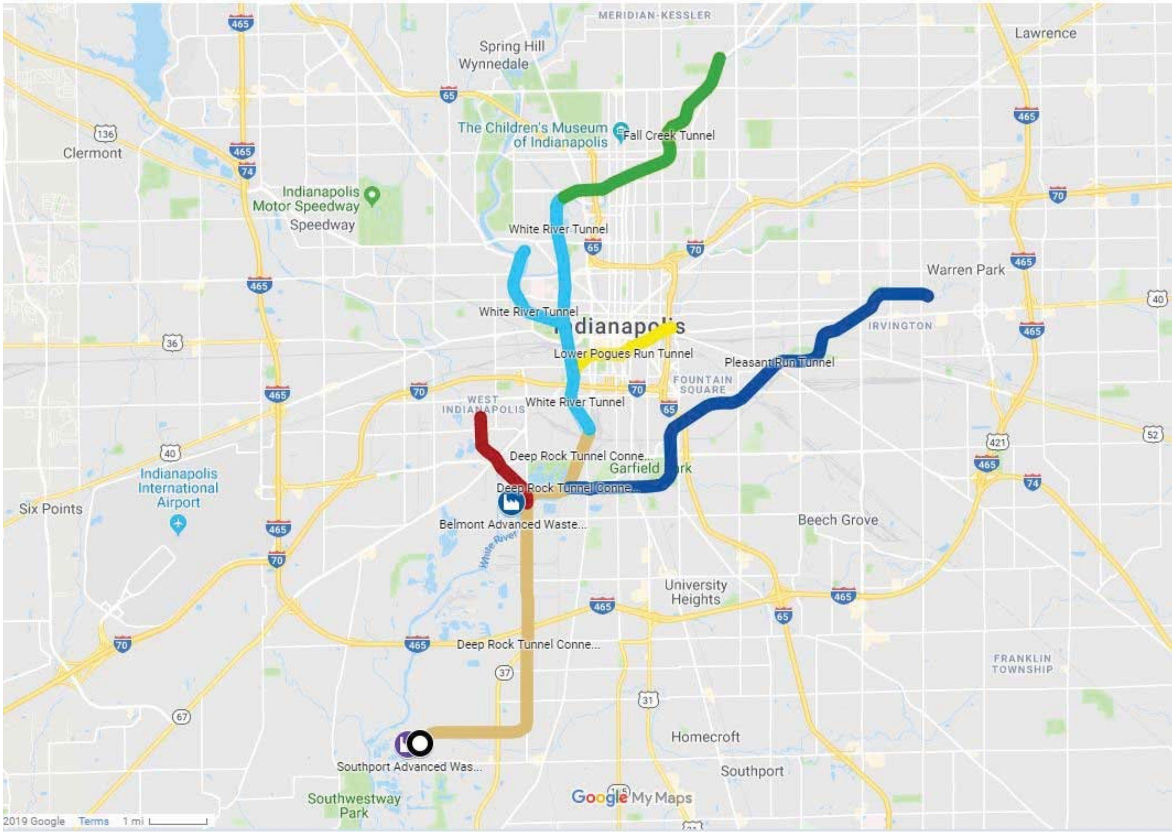

Figure 1. The DigIndy Tunnel System consist of the Deep Rock Tunnel Connector (orange), the Eagle Creek Tunnel (red), the White River Tunnel (light blue), Lower Pogues Run (yellow), the Fall Creek Tunnel (green) and the Pleasant Run Tunnel (dark blue).

All in all, the DigIndy Tunnel System consists of the following, all bored with one machine:

- Deep Rock Tunnel Connector: 39,362 lf of tunnel; 3 CSO connecting structures/deaeration chambers and adits. Put into service in 2017.
- Eagle Creek Tunnel: 9,175 lf of tunnel (added as a change order to the Deep Rock Tunnel Connector project); one CSO connecting structure/plunge drop. Put into service in 2017.
- White River Tunnel: 30,628 lf of tunnel; 2 bifurcations; 7 CSO connecting structures/deaeration chambers and adits. Put into service in 2021.
- Lower Pogues Run Tunnel: 10,182 ft, bifurcates from White River Tunnel; 2 CSO connecting structures/deaeration chambers and adits. Put into service in 2021.
- Fall Creek Tunnel: 20,244 lf of tunnel; 10 CSO connecting structures/deaeration chambers and adits. Tunneling and lining complete.
- Pleasant Run Tunnel: 41,472 lf of tunnel; eight CSO connecting structures/deaeration chambers and adits. Tunneling complete. (Rush, 2023)

The $2 billion DigIndy program is the result of planning efforts to address Combines Sewer Overflows (CSOs). It comprises a network of 28 miles of 18-ft ID tunnels, in addition to other sewer system and treatment plant improvements. The program resulted from a consent decree signed by the U.S. EPA and the City in 2006. The DigIndy program is administered by Citizens Energy Group, which became party to the consent decree when it acquired the water and wastewater systems in Indianapolis in 2011.

Not surprisingly, planning a $2 billion program that includes more than 28 miles of large diameter tunnels is quite the undertaking. Planning and design began in earnest in 2006 as the city entered into the consent decree with EPA, which stipulated that the work was to be completed by 2025. Once online in 2025, the DigIndy tunnel system will reduce the amount of raw sewage overflows and clean up tributaries along the White River.

Early activities included geotechnical exploration, which identified a zone of limestone and dolomite approximately 250 ft deep that was conducive to tunneling. Identifying the alignments presented the challenge of real estate acquisitions and third-party interactions that inevitably occur on a project of this magnitude (see Figure 2).

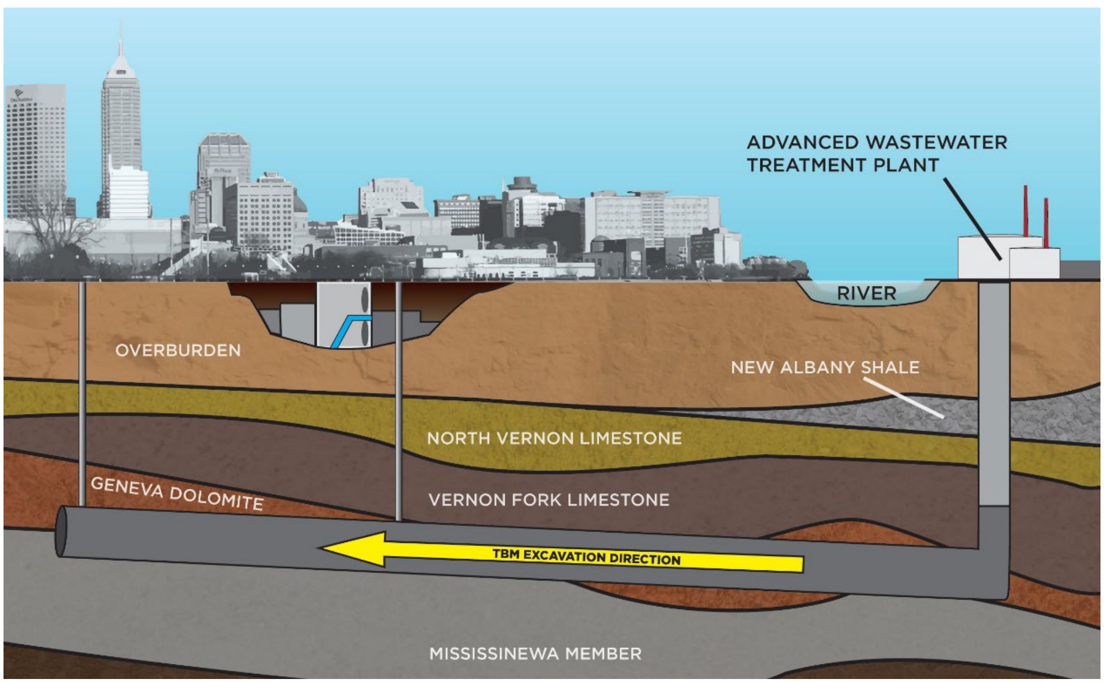

Figure 2. The limestone and dolomite layers deep below Indianapolis (drawing shows the DRTC, the first leg of DigIndy).

THE DEEP ROCK TUNNEL CONNECTOR

The 7.8 mi (12.5 km), 18 ft (5.5 m) diameter Deep Rock Tunnel Connector (DRTC) has a capacity of 250 million gallons (946 million liters) for overflow events, and has enough slope to be self-cleaning with minimal maintenance.

The 6.2 m (20.2 ft) diameter Robbins Main Beam TBM, owned by contractors Shea- Kiewit (S-K) JV, was refurbished and redesigned in 2013 for the DRTC. Originally built in 1980, the TBM had previously bored at least five other hard rock tunnels including New York City's Second Avenue Subway. Design updates for the DRTC included new 19-inch disc cutters, variable frequency drive (VFD) motors, a back-loading cutterhead, and a rescue chamber. The age of the machine wasn't a concern for the contractor, who saw it as a positive that the machine had been proven to perform well in harder, more abrasive rock (see Figure 3).

Figure 3. The DigIndyTBM, originally built in 1980, was fitted with a new back-loading cutterhead and VFD motors, among other upgrades.

The 36-year-old Robbins machine was launched from a deep shaft and utilized a unique continuous conveyor system, also manufactured by Robbins. The system spanned 25 km (82,000 ft—two times the tunnel length) of belt and two unprecedented 90-degree curves, hauled muck up a 76 m (250 ft) deep shaft using a vertical belt and deposited it in piles using a radial stacker. The system –considered one of the most complex conveyor systems in tunneling construction in North America—consisted of conveyor belt traveling through two 90-degree curves in opposite directions and S-curves in other places.

The conveyor system also played a part in multiple world records that the machine would achieve in limestone and dolomite rock. The records, achieved in the 6 to 7 m (20 to 23 ft) diameter range, included "Most Feet Mined in One Day" (124.9 m/409.8 ft), "Most Feet Mined in One Week" (515.1 m/1,690 ft), and "Most Feet Mined in One Month" (1,754 m/5,755 ft). Crews were able to keep up the good advance rates despite significant water inflows that hovered around the 2500 GPM rate for months and an extensive grouting program. Ultimately the TBM broke through one year ahead of schedule, and the Eagle Creek Deep Tunnel was added onto the contract as a change order. That 2.8 km (1.7 mi) stretch was completed in less than a year—before the original contract date to complete the DRTC.

NEXT PHASES OF DIGINDY

TBM Refurbishment

With the initial phase of work completed, S-K JV set about refurbishing the TBM for the nearly 28 km (17 mi) of tunnels the TBM would bore. They put in a new bearing, motors, gearboxes, electronics, chillers, and more. The machine was removed from the tunnel in May 2016, and the refurbishment lasted through August 2016, about four to five months.

In addition to the refurbishment, S-K JV, with the assistance from Robbins, added an automatic grout system and three extra decks to the back-up system. Based on what was experienced at the DRTC, S-K JV knew they would encounter water and needed to replace the manual grout system used on that job. The system will allow use of a cement pre-excavation grout with an automated grout plant. The new high-capacity grout system was very similar to one that S-K had previously used on California's Arrowhead Tunnels. The system was fitted with new components manufactured by Hany, including a grout mixer, agitator, and pump, as well as new PLC controls to automatically adjust the auger feed rate, water, additives, mixer discharge rate, and the rate of material flowing to the high-pressure grout pump. The system also measured grout volume and pressure as it was injected into the probe holes. Robbins designed a system to move grout bins into place on the back-up in order to feed the mixer. With the new design elements in place, the Robbins TBM was ready to be launched.

White River and Lower Pogues Run Tunnels

The machine was launched in September 2016 to bore the White River Tunnel from the 67 m (220 ft) deep DRTC retrieval shaft. Geology was similar to the DRTC, limestone and dolomite rock. The tunnel also included a bifurcation approximately 1.6 km (1.0 mi) into the White River Tunnel, where the tunnel turned eastwards and the machine bored the 3.0 km (1.9 mi) Lower Pogues Run Tunnel in front of Lucas Oil Stadium in downtown Indianapolis.

On the Lower Pogues Run Tunnel, a section of weaker rock was encountered where water inflow was different from other sections. Brierley Associates was called in to assess the situation and make recommendations for future tunnel works. In this section, a unique solutions was devised. Water inflow through the walls led to a welded PVC liner (supplied by Renesco) being installed prior to concrete final lining. After completing the 3.0 km, the machine was then backed up to the bifurcation point before continuing north for completion of the White River Tunnel. Despite the challenges the Robbins TBM achieved advance rates as high as 298.2 m (978.4 ft) in one week and 84.0 m (275.6 ft) in 24 hours. Completion of the White River Tunnel occurred on April 10, 2019 (see Figure 4).

Figure 4. Breakthrough at the White River Tunnel in April 2019.

A Note on Tunnel Wyes

The tunnel wyes are one of the more unique aspects of the DigIndy tunnel system and occurred in several places. Spurs headed off from the main tunnel at angles and required a complex process of boring and machine retraction. Each time an offshoot was bored, the machine then backed up, a concrete plug was poured, and the machine then mined through the concrete/rock mixture. Concrete, with a lower psi than rock, must be mined through slowly. Crews used high-strength concrete, which puts out a lot of heat and takes about 24 hours to pour. In areas where the machine needed to be backed up crews used swellex bolts and split sets for ground support in the limestone and dolomite rock. These types of support fit tighter against the rock so the ground support didn't hit the side and roof supports during TBM retraction. Each time the machine was backed up the crew also had to remove the side-mounted tunnel conveyor directly behind the TBM.

Fall Creek and Pleasant Run

With the breakthrough at White River behind them, the S-K JV began work on the 6.2 km (3.9 mi) Fall Creek Tunnel, which included 11 drop shafts to depths of over 60 m (200 ft). The White River Tunnel retrieval shaft was also the launch shaft for the Fall Creek Tunnel, meaning none of the equipment had to be removed to the surface.

The conveyor system was dismantled and moved to the Fall Creek Launch shaft as the machine bored forward. All in all, the conveyor system was dismantled and installed three times during the course of boring, with the last instance at Pleasant Run, a final 11.9 km (7.4 mi) deep leg consisting of 8 drop shafts that will capture 30 combined sewer overflows.

Once the mining was completed for the Fall Creek Tunnel the TBM was removed and transported to the Pleasant Run launch shaft site and was completely rebuilt again. This included a few modifications to the conveyor system in anticipation of a short section of tunnel that would be similar to the Lower Pogues Run tunnel geology. Mining began in April of 2021 and was completed in August of 2022 (see Figures 5 and 6).

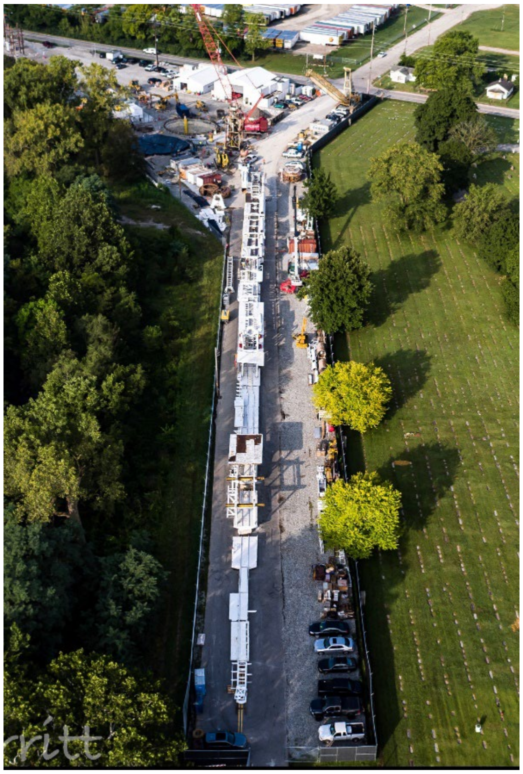

Figure 5. TBM rebuild at the Pleasant Run launch site.

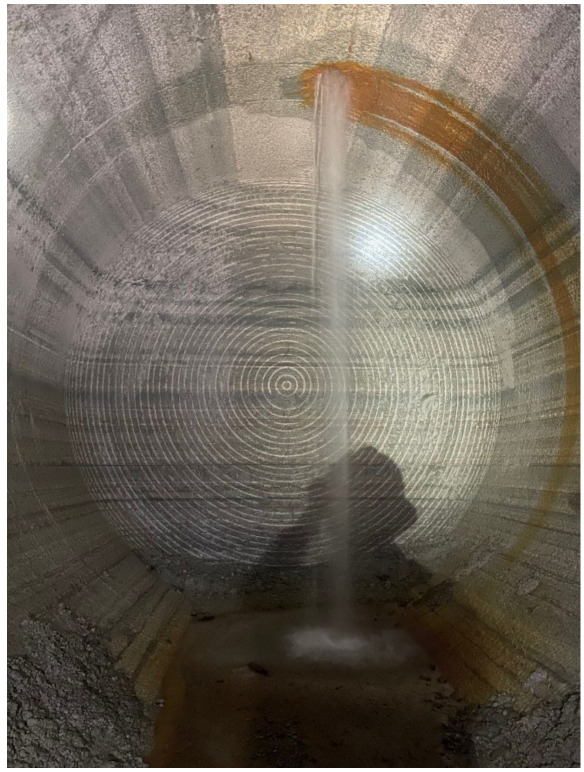

Figure 6. The end of the tunnel at Pleasant Run.

OPTIMIZATION OF TBMs FOR MULTIPLE USES

What has allowed the DigIndy machine to bore more than 50 km of tunnel in the course of its storied career?

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.

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).

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 (see Figure 7).

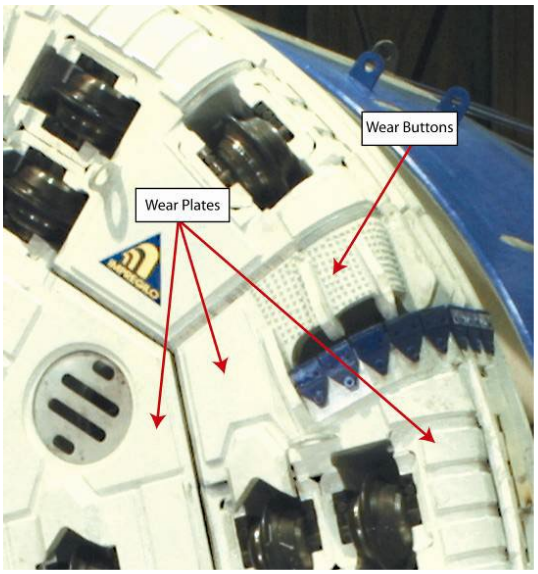

Figure 7. Example of a cutterhead designed for abrasive hard rock conditions

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 8).

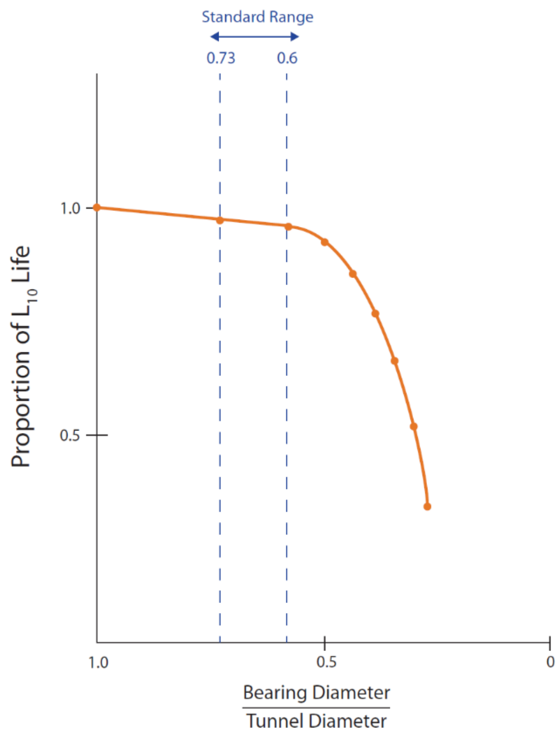

Figure 8. As the ratio falls below 0.6 bearing life is reduced

The bearing and ring gear are in a difficult-to-access spot on TBMs, so they must be designed for longevity, with a 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 when a TBM is planned to be used over multiple, long tunnel drives.

Robust seal design is also essential. Robbins 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.

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.

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 based on the encountered ground, which optimizes the TBM advance rate and reduces damage to machine components (see Figure 9). 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.

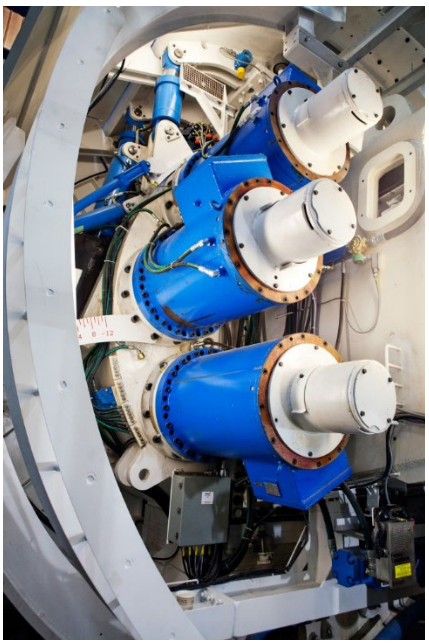

Figure 9. VFD setup on a hard rock TBM

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.

ON THE IMPORTANCE OF MAINTENANCE

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. When it is planned to use a machine on multiple projects or on long tunnel drives, this is all the more important. In general, the total life cycle of a TBM should be considered and care can be taken during a tunnel drive above and 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.

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 or machines being used on multiple 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.

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.

CONCLUSIONS

So is newer really better? In many cases the record shows that they are equivalent. If the age and number of projects bored by a TBM is seen by some as an issue, a history of record-breaking projects achieved using rebuilt machines does exist. More than one third (36%) of currently standing world records have been broken using a refurbished TBM, some of them in service for decades. That has certainly held true at DigIndy.

The machine's rebuilt specifications should fit that project's geology and unique requirements. With a proper design and rebuild, a used machine has advantages: The design is proven, the cost is usually lower and there is an advantage in faster delivery times. The risks are only when the TBM is not properly built or when a machine is put into geology where it is not suitable.

Overall, there are many benefits, both obvious and hidden, to using a rebuilt machine, but the rebuild should be done within certain design restraints to remain economical. There is always the possibility to upgrade power and thrust on a machine but there are strict engineering limits. When increasing the cutterhead drive motor power, the gear reducers and final drive ring gear and pinions must have the capacity to take that increase in power. When increasing thrust, the bearing life must be checked to make sure that the bearing can take the increased forces. If the project requires exceeding gripper capacity on a hard rock TBM, then another machine must be considered.

Overall TBM design and usage for the long haul is simply a cost effective, energy efficient, and sustainable way of thinking about tunnel boring. Used machines can and have shown their ability to excavate projects at world-class rates of advance and complete many kilometers of tunnel with success.

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