Rebuilding TBMs: Are Used TBMs as Good as New?

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ABSTRACT

Much has been made worldwide of the difference in performance between new and rebuilt TBMs. Worldwide, a bias exists that seems to favor new machines, but is the bias warranted? The reuse of machines can, if done to exacting standards, reduce costs and time to delivery while also reducing the carbon footprint. But guaranteeing the quality of TBM rebuilds is another issue—one that seems only minimally improved by the existence of international guidelines.

This paper will discuss the process of machine rebuilds and the use of rebuilt TBMs with performance examples from projects worldwide. It will seek to establish guidelines and recommendations based on real experiences of success in the shop and in the field.

INTRODUCTION

International guidelines have been developed to standardize the process of reusing a TBM for another project. But is standardization truly possible, and what makes a TBM perform successfully in the first place?

There is no reason why a used machine shouldn’t perform as well as a new machine if the operational history of the machine is known and the geology is suitable for its design. In fact, contractors may opt for a used machine for its proven performance, although this view is certainly not the case in every market (see Figure 1).

Large metro projects worldwide often employ dozens of TBMs working simultaneously, resulting in a glut of secondhand machines on the marketplace at any given time. But contractual constraints often form barriers towards using these machines on subsequent projects. Consultants employed by project owners can over-specify technical specifications, often in an attempt to lower risk, but these specifications are not always necessary.

If owners were to instead specify a minimum quality of a rebuilt machine required, this would prevent rebuilt machines from being excluded from projects. This type of specification would require a certain level of TBM knowledge—for example, things that could be specified include main bearing requirements, either that the bearing is new or that it has to be certified for a certain number of hours. A cutter load could be specified for hard rock tunneling, but details like thrust and torque would not be necessary and could be too exclusive.

Not only can rebuilt TBMs result in significant cost savings, but they can also be the answer to aggressive delivery schedules. That, combined with their proven track record, and the reduction in carbon footprint by using an existing machine, makes them an attractive solution for the tunneling industry moving forward.

Figure 1. A main beam TBM originally built in 1979 was refurbished and successfully completed the Albany Park Stormwater Diversion Tunnel in Chicago, IL, in late 2017

QUANTIFYING TIME AND COST SAVINGS

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, the savings 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.

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, 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).

OPTIMIZATION OF TBMs FOR MULTIPLE USES

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).

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 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 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.

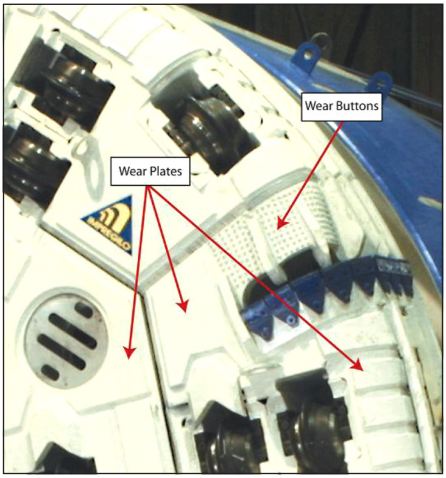

Figure 2. Example of a cutterhead designed for abrasive hard rock conditions

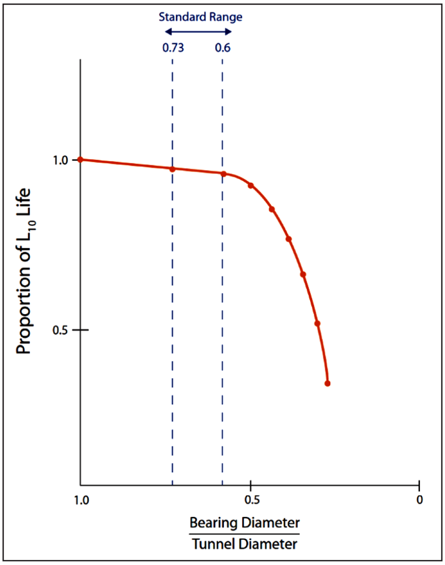

Figure 3. As the ratio falls below 0.6 bearing life is reduced

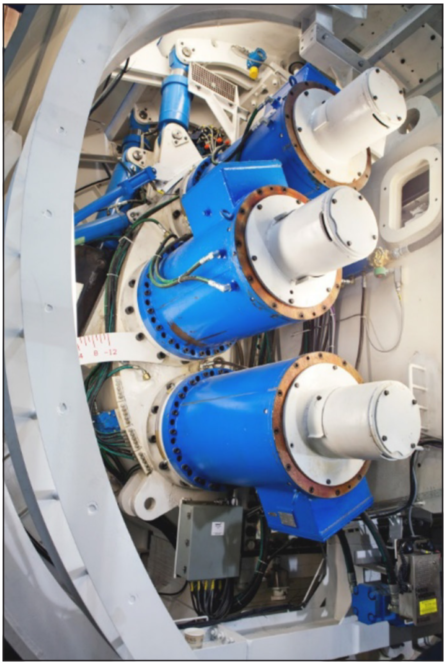

Figure 4. VFD setup on a hard rock TBM

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.

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 4). 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.

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.

CASE HISTORIES

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.

In cases where it is believed that new TBMs will perform or have performed better, this is often an experience bias based on the result of a TBM employed where it wasn't suitable or where it wasn't rebuilt properly. For example if an older machine was initially built for sandstone, it will not have enough power to work well in granite 25 years later without modifications.

A custom design, for a project's specific requirements and geology, is just as important on a rebuilt machine as a new one. For example, a contractor may wish to save money by purchasing a used TBM and rebuilding it to its original specifications. A 3 m diameter Main Beam TBM, rebuilt to the same diameter and specifications, will cost less than rebuilding the same machine but increasing the size to 4 m and adding custom elements. But are the savings truly obtained if the original TBM specifications do not fit the geology? Cutterhead configurations are a particularly important example, with cutter spacing, cutting tools, cutterhead geometry, and muck openings all coming into play and greatly affecting the rate of penetration.

The DigIndy Tunnel System

A good example of custom modifications resulting in success can be seen at the DigIndy project in Indianapolis, Indiana, USA. The TBM, originally manufactured in 1980 for New York's East 63rd Street Subway, had then gone on to bore at least five other hard rock tunnels including New York City's Second Avenue Subway. The 6.2 m diameter Main Beam TBM was chosen for the Deep Rock Tunnel Connector, the first phase of DigIndy, with design updates that included a new back-loading cutterhead with 19-inch disc cutters, variable frequency drive (VFD) motors, and a rescue chamber. The TBM made a record performance for TBMs in the 6 to 7 m diameter range, including "Most Feet Mined in One Day" (124.9 m), "Most Feet Mined in One Week" (515.1 m), and "Most Feet Mined in One Month" (1,754 m). The machine is currently boring the next phases of the DigIndy network—a further 28 km in addition to the 12.5 km of the DRTC already completed (see Figure 5).

Túnel Emisor Poniente II

What about shielded machines—is the rebuild process equally applicable? A good example of this process can be seen at Mexico City's Túnel Emisor Poniente (TEP) II. The TBM was originally manufactured as a 7.23 m diameter Single Shield Hard Rock TBM for Morocco's Abda Doukkala project in 1995. It was then converted to a Double Shield machine for Cleveland, Ohio's Mill Creek Tunnels in the early 2000s and then back to a Single Shield at 8.7 m diameter for a hydropower tunnel in Laos. In 2015 the machine underwent another transformation when it became a hybrid-type Crossover TBM for the TEP II project (see Figures 6–8).

The 8.7 m diameter Crossover (XRE) TBM was designed for a 5.6 km long tunnel in ground conditions including andesite and tuff with major fault zones containing water-bearing ground. Design components included a convertible cutterhead that could be changed from a Hard Rock to EPB design, a removable

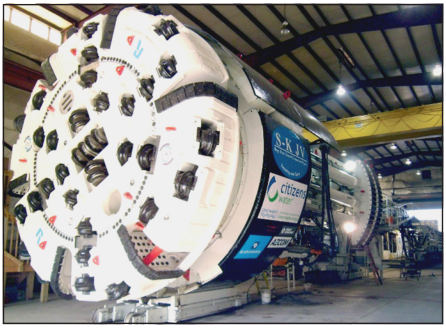

Figure 5. The DigIndyTBM, originally built in 1980, was fitted with a new back-loading cutterhead and VFD motors, among other upgrades

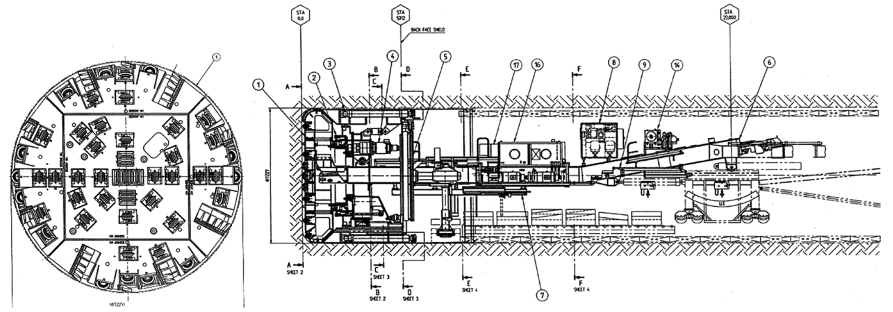

Figure 6. The original machine as a 7.23 m diameter Single Shield Hard Rock TBM in 1995

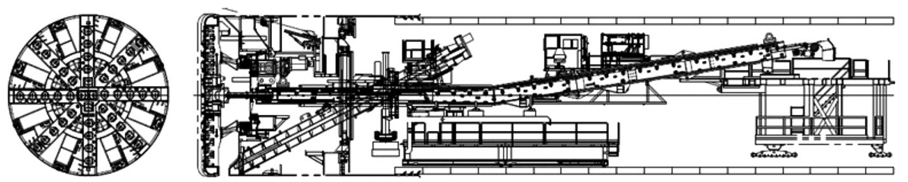

Figure 7. The modified TBM as an 8.7 m diameter Crossover XRE for the TEP II project in 2015—shown in EPB mode

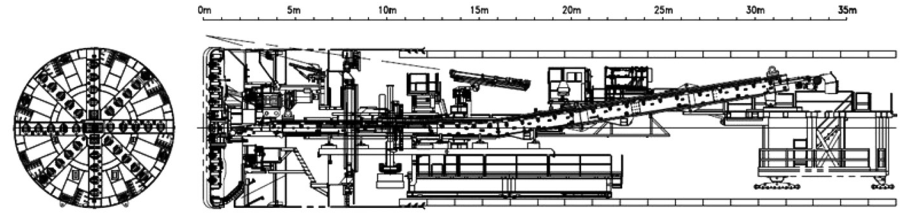

Figure 8. The modified TBM as an 8.7 m diameter Crossover XRE for the TEP II project in 2015—shown in hard rock mode

belt conveyor and screw conveyor, and multi-speed gearboxes to increase torque for tunneling through difficult ground. The machine's performance was highly successful, achieving national records for TBM tunneling after boring 57 m in one day and 702.2 m in one month despite difficult conditions.

CONCLUSIONS

Is a used TBM as good as a new one? In short, the answer is yes, with qualifications. 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. The type of TBM and whether it is shielded or not also matters. For example, if an EPB is being used, changing the diameter of an EPB such that it requires new shields may not be the best choice economically. Purchasing a larger EPB would make better sense in that application.

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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