Evaluating TBM Design and Performance, 30 Years Apart: The Lesotho Highlands Water Tunnel, Phase 1 and Phase 2

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Abstract: Two massive tunnel projects 30 years apart: The Lesotho Highlands Water Project (LHWP) is a multi-phased project that has taken place over decades to provide water to the Gauteng region of South Africa and to generate hydroelectricity for Lesotho. Phase I tunneling began in 1992 and utilized multiple Main Beam TBMs to bore long tunnels in basalt and dolerite ground conditions.

Phase II, now under construction, consists of 38 km of transfer tunnel to be excavated by both TBM and drill & blast. Water from the Polihali reservoir will flow by gravity through the Polihali Transfer Tunnel on its way to Katse Dam. Two 5.4 m diameter Double Shield TBMs will bore 17 km long sections of the Polihali Transfer Tunnel, one designated Polihali-West and the other Katse Outlet-East. The tunnels will travel through basalt and dolerite with some sections of breccia, pillow lava, tuff and agglomerate at depths ranging from 91 to 994 m below the surface.

In order to bore in the challenging conditions, the machines are fitted with 19-inch disc cutters and two-speed gearboxes that efficiently use power to generate high torque at low RPM when in sections of squeezing geology or fracture zones.

This paper will detail the design for the TBMs to be used on the Phase II tunnel, while comparing the modern-day machines to the history-making Main Beams used in the 1990s. It will derive some conclusions and lessons learned about boring in volcanic rock at depth utilizing Main Beam vs. Double Shield TBMs.

Keywords: Tunnelling; Hard rock; Main Beam; Africa

1 Introduction – Project Background

The Lesotho Highlands Water Project (LHWP) is decades in the making. A cooperative effort between Lesotho and South Africa, Phase 1 of the project sought to rejuvenate South Africa's heavily populated and arid Gaucheng Province. Its first phase began in 1992 and involved construction of the 180 m high Katse Dam, part of the Orange (Sequ) River system in Lesotho. The dam, finished in 1998, supplies water to South Africa's Vaal river system via a water transfer tunnel and two delivery tunnels. A total of 82 km of tunnels were constructed between 1992 and 1996. The project went online in 2003.

Today, the contribution of Phase 1 of the LHWP to the economic activity of Lesotho has been remarkable. Royalties, the sale of electricity, construction activities and other project-related revenue have provided an important economic boost to Lesotho. In 2002, it was calculated that the project's contribution to the economic activity of Lesotho was 5.4% of the GDP (lhda.org.ls, 2023).

The water from the LHWP is used in six provinces of South Africa. It cools the Eskom power stations in Mpumalanga, keeps Sasol and Free State gold mines operational, supplies the vast industries and sprawling urban areas of Gauteng, provides water to some of the southern towns of Limpopo and the platinum mines of the northwest, as well as the diamond mines and people of Kimberley and surrounding areas. Under drought conditions, emergency water can, and has, been transferred to the Caledon River and to the Eastern Cape and southern Free State through the BloemWater network.

Phase 2 of the Lesotho Highlands Water Project, now underway by the Lesotho Highlands Development Authority (LHDA), builds on the successful completion of Phase 1 in 2003. It delivers water to the Gauteng region of South Africa and utilises the water delivery system to generate electricity for Lesotho. Phase II will increase the current supply rate of 780 million cubic metres per annum incrementally to more than 1.27 billion cubic metres per annum. At the same time, it will increase the quantity of electricity generated at the Muela hydropower station and is a further step in the process of securing an independent electricity source to meet Lesotho's domestic requirements (LHDA, 2020).

The water transfer component of Phase 2 comprises a Concrete-Faced Rockfill Dam (CFRD) and saddle dam at Polihali, downstream of the confluence of the Khubelu and Senqu (Orange) Rivers, and a gravity tunnel that will connect the reservoir at Polihali to the Katse reservoir. In addition, two 1 km long, drill and blasted river diversion tunnels were built prior to the construction of the Polihali Dam.

The 38 km long Polihali Transfer tunnel will be constructed by both TBM and drill and blast, and allows water from the Polihali Reservoir to flow by gravity to the reservoir at Katse.

2 Phase 1

The first phase of the massive project included approximately 80 km of tunneling and construction of two dams and an underground power station. The project's co-owners, the Kingdom of Lesotho and the Republic of South Africa, awarded the contract for the 13 km-long south delivery tunnel and the 45.6 km-long transfer tunnel, both located in Lesotho, to the Lesotho Highlands Project Contractors (LHPC). LHPC was a joint venture of Spie Batignolles (France), LTA Ltd. (South Africa), Ed Zublin AG (Germany), Balfour Beatty Ltd. (U.K.) and Campenon Bernard (France).

LHPC leased a refurbished Main Beam TBM to excavate the shorter delivery tunnel. The contractor also ordered three new open-type TBMs, manufactured by Robbins, to bore the longer transfer tunnel. Yet another Main Beam TBM, manufactured by Wirth, was ordered for the North Delivery Tunnel.

The 5.18 m diameter south delivery tunnel connects the Muela adit with ventilation shaft #5 to the north. At this point the excavation junctures with the 5.1 m diameter north delivery tunnel, which continues 22 km to the Axle River outfall in South Africa.

The transfer tunnel, proceeding from the Katse Dam to the Muela Power Station, is one of the world's longest water supply pressure tunnels. It is made up of three 4.99 m diameter drives with lengths of 10.9 km, 17.3 km and 17.4 km. The transfer tunnel diverts water from the dam to the power station (see Figure 1).

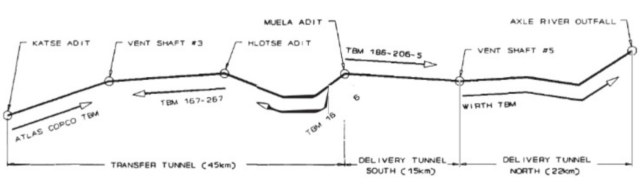

Figure 1 Schematic Overview of the Lesotho Highlands Tunnels (Finnsson, 1994)

2.1 Geology

The transfer tunnel route passes through basaltic flows of the Lesotho/Drakensberg formation, volcanic rock with variable amygdaloidal content. The area includes blocky conditions in faulted areas and within some of the doleritic dykes also found along the route. The unconfined compressive strength (UCS) of these rock formations ranges from 80 MPa to 176 MPa.

The south delivery tunnel site lies in sedimentary rock of the Stormberg Group, upper formation of the Karoo sequence, a deposit formation in the extensive Karoo Basin. Most of the tunnel route passes through the Clarens formation, located beneath the Lesotho/Drakensberg formation. The Clarens section consists mainly of horizontally layered sedimentary rocks composed of fine- to medium-grained siltstone and sandstone with occasional doleritic dykes and layers of claystone. The UCS of the softer rocks in this area varies from 10 MPa to 40 MPa.

3 TBM Design and Excavation

3.1 The South Delivery Tunnel

The 5.18 m dia machine, the first TBM to begin work at Lesotho, featured 37 cutters, each 432 mm in diameter. Six 185 kW motors provided 1,110 kW to the cutterhead, which operated at 7.28 rpm. The 270 metric ton machine had a 1.5 m boring stroke and a thrust of 7,400 kN. Manufactured in 1979, the refurbished Main Beam was already a tunneling veteran before its journey to Lesotho, having bored more than 24 km on projects in the U.S. and Canada.

The refurbished Robbins Model 186-206 began boring the 13 km-long south delivery tunnel in February 1992 and achieved break-through in August 1993, an astounding 20 months ahead of schedule. The tunnel excavation consisted of three drives: 2.1 km from Hololo south to Muela, 5.2 km from Ngoajone south to Hololo and 5.7 km from Ngoajone north to ventilation shaft #5.

The refurbished Main Beam achieved outstanding results on the south delivery tunnel despite two breakthroughs and start-ups of the TBM and back-up system along the way. The machine's average rate of penetration (ROP) was 3.86 m per hour (8.8 mm per revolution). The TBM advanced at an average 39.9 m per day in three eight-hour shifts and 878 m per 22-day month. The best day advance of the drive was 82.9 m, with a best week of 384.0 m and a best month of 1,324.4 m. Rock support measures in the south delivery tunnel included spot bolting as well as some systematic rock bolting with mesh and shotcrete (see Figure 2).

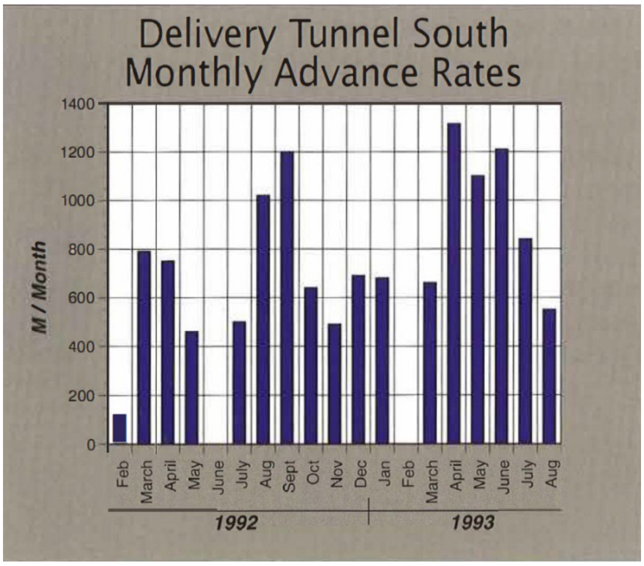

Figure 2 Advance rates in the South Delivery Tunnel

3.2 The Transfer Tunnel

3.2.1 Design of the TBMs

The new Robbins MK 15, an open hard rock machine, offered a bore diameter of 5.018 m. The TBM's cutterhead was dressed with four center cutters, 22 face cutters and eight gauge cutters, all 432 mm in diameter. Three 560 kW motors supplied 1,680 kW to the cutterhead, producing a torque of 1,588 kNm. The 320 metric ton machine had a 1 1.525 m boring stroke and a thrust of 8,300 kN. Cutterhead speed was 10.1 rpm (see Figure 3).

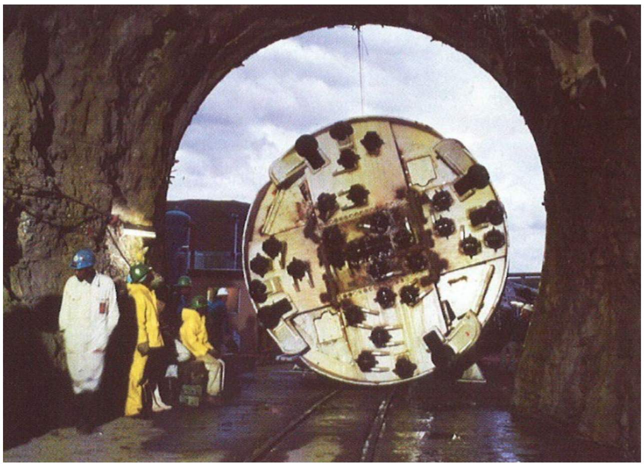

Figure 3 The MK15 open-type TBM at the tunnel portal

The two Robbins Main Beam TBMs were supplied with boring diameters of 5.03 m. At Lesotho these machines were equipped with 35 disc cutters, each 432 mm in diameter and load rated to 222 kN, producing a total cutterhead thrust of 9,723 kN. The machines were both equipped with back-loading cutterheads. The flexible design of these high-performance TBMs also allowed later installation of 483 mm dia cutters to achieve a cutter load of up to 312 kN for situations in which increased power was needed for superior performance on the job. The machines also featured five 315 kW water-cooled motors supplying a total of 1,575 kW to the cutterhead. The TBMs have a boring stroke of 1 .866 m and a cutterhead speed of 10.0 rpm.

Each of the four Robbins TBMs on the Lesotho Project had its own trailing back-up system, including a rock drill. The drill was part of an assembly mounted on a 7 m-long sliding deck about 20 m behind the cutterhead on the top level of each TBM's back-up. This arrangement allowed probe drilling concurrently with TBM advance (see Figures 4 and 5).

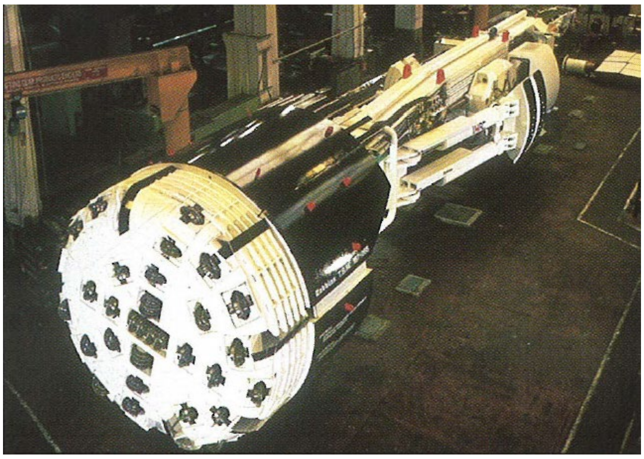

Figure 4 One of the 5.03 m diameter Main Beam TBMs supplied for the transfer tunnel

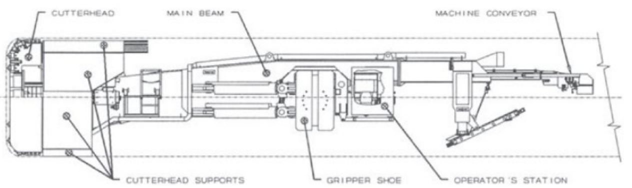

Figure 5 Schematic of the Main Beam TBMs provided for Phase 1 transfer tunnel

Locomotives and rotadump cars operated behind each of the TBMs to remove muck produced during tunneling operations. Each service train was made up of seven 12 m^3-capacity muck skips. Depending on the difficulty of the excavation gradient, either 25 metric ton, 180 hp or 35 metric ton, 200 hp diesel locomotives were used to haul the filled muck trains.

LHPC installed a precast concrete invert segment in each tunnel to support tracks for the muck-handling trains. These segments remained in the operating water delivery system
to facilitate tunnel maintenance and repair.

3.2.2 TBM Excavation

The Robbins MK 15 began boring the Katse tunnel section from the Katse Dam site to ventilation shaft #3, a distance of 10.9 km, in May 1992, and reached breakthrough in September 1994. With an average ROP of 3.89 m per hour (6.4 mm per revolution), the TBM achieved an average monthly advance of 364 m, with a best day, week and month of 62.9 m, 289.0 m and 987.0 m, respectively.

Difficult rock conditions prevailed in the non-amygdaloidal basalt areas of this section of the transfer tunnel. Blocky ground at the tunnel face and rock falls from the crown area resulted in substantial downtime to clean the invert and cutterhead and install appropriate rock support. In addition, some challenging conditions forced reductions in TBM thrust and ROP, decreasing the machine's advance rate in these areas to about 30 percent of the progress achieved in stable rock. Although the tunnel route also in-cluded two doleritic dykes, one 95 m long and the other 82 m long, the TBM advanced surprisingly well through these difficult sections. About 15 percent of total job time was devoted to rock support, which included bolting, rock straps, mesh and shotcrete. Overall, TBM utilization reached 31 percent (see Figure 6).

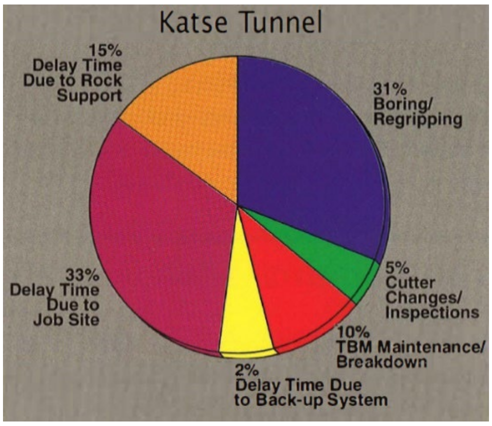

Figure 6 Katse Tunnel Utilization

The first Main Beam TBM (Muela tunnel section) began boring the 17.4 km-long transfer tunnel section from Muela south to the Hlotse adit in June 1992. Maintaining an average ROP of 4.59 m per hour (7.7 mm per revolution), the machine broke through in September 1994. The TBM's average advance rate was 33.4 m per day and 656 m per month. The Main Beam set world tunneling records for its diameter class with a best day advance of 86.3 m, a best week of 399.8 m and a best month of 1,344.3 m.

The TBM set these records despite some challenging geology along the tunnel route. Rock jointing necessitated rock support measures, especially at the beginning of the drive. Overall, rock support required 24 percent of total job time, with machine utilization reaching 29 percent (see Figure 7).

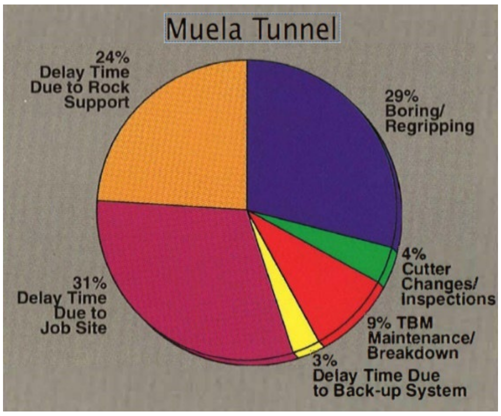

Figure 7 Muela Tunnel Utilization

In July 1992, shortly after boring began on the transfer tunnel's Muela-Hlotse section, the Robbins Model 167-267 TBM started its 17.3 km long drive from Hlotse to ventilation shaft #3. The machine achieved an average ROP of 4.10 m per hour (6.8 mm per revolution), while maintaining average advance rates of 27 .6 m per day- and 620 m per month. The TBM turned in a superior performance with a best day advance of 66.8 m, a best week of 325.0 m and a best month of 1221.0 m.

Challenging rock conditions in this section of the transfer tunnel required rock support measures accounting for 11 percent of total job time, with another substantial delay (29 percent) due to job site problems. Nevertheless, machine utilization reached 38 percent (see Figure 8). Final breakthrough occurred on October 14, 1994.

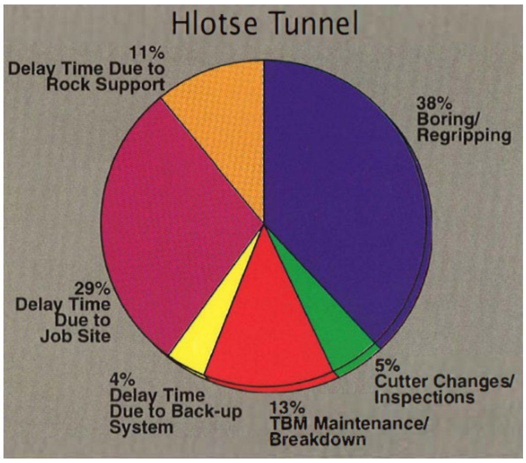

Figure 8 Hlotse Tunnel Utilization

4 Phase 2 Tunneling

In 2022, the 38 km long Polihali Tunnel was announced as part of the LHWP Phase 2. The approximately M9.2 billion Polihali Transfer Tunnel contract was awarded to the Kopana Ke Matla joint venture, which includes Yellow River Company (China); Sinohydro Bureau 3 (China); Unik Civil Engineering (South Africa) as the main joint venture partners. Subcontractors include Nthane Brothers of Lesotho, Esor Construction and Mecsa Construction of South Africa.

The Polihali Transfer Tunnel will transfer water by gravity from the Polihali reservoir to the Katse reservoir. From Katse, water is transferred via the delivery tunnel to the ‘Muela Hydropower Station constructed in Phase I, and then on to the Ash River outfall outside Clarence in the Free State on its way to Gauteng (see Figure 9).

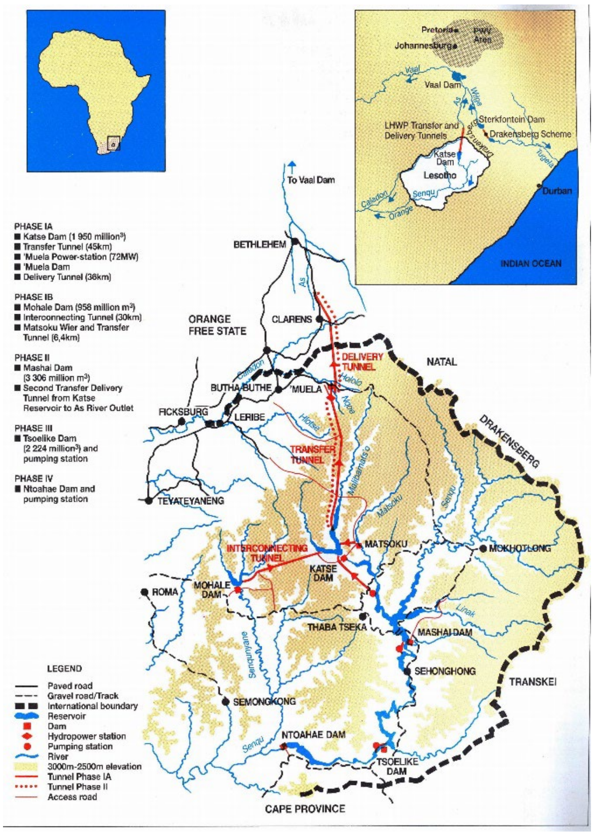

Figure 9 Map of LHWP works, Phases I and II (Lhda.org)

3.2 Tunnel Specifications & Geology

The Polihali tunnel includes two approximately 17 km long TBM-driven tunnels, designated as TBM Drive from Polihali-West and TBM Drive from Katse Outlet-East, and two approximately 1.5 km long D&B-driven connecting tunnels (one at each end), designated as Polihali Connecting Tunnel and Katse Outlet Connecting Tunnel. The Polihali Tunnel will have a finished diameter (ID) of 4.5 m and a relatively flat slope of 0.032%. The tunnel will be constructed in hard rock at depths to invert ranging from 91 to 994 m below ground surface. The TBM-driven portion of the tunnel will be lined with a drained, initially-bolted, gasketed, precast concrete segmental tunnel lining (PCTL) installed concurrently with TBM tunnel excavation (see Figure 10).

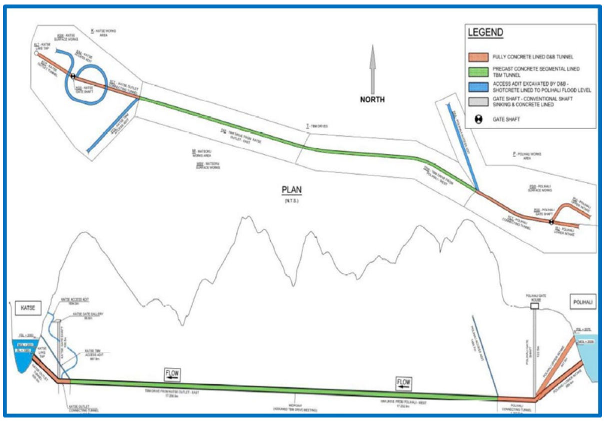

Figure 10 Schematic of Polihali Tunnel path

Geology along the tunnel alignment consists of highly amygdaloidal basalt (28%), moderately amygdaloidal basalt (28%), non-amygdaloidal basalt (28%), doleritic basalt (10%), and dolerite (5%). About 1% of the geology is estimated to consist of other rock types including breccia, tuffites, pillow lavas, olivine basalts, and agglomerate. These rock types are often associated with problems in terms of tunnel stability and excavation.

3.3 TBM Design for Challenging Conditions

In order to excavate in the challenging conditions, the two 5.4 m diameter Double Shield TBMs have been designed with advanced features.

3.3.1 Multi-speed Gearboxes

Customized cutterhead drives can be instrumental in getting through difficult ground. Designing a machine with high-torque, continuous boring capabilities allows that machine’s cutterhead to restart with break-out torque in difficult ground. The net effect is that the machine can keep boring in the event of a face collapse and can effectively bore through fault zones and running ground where the potential for cutterhead jamming exists. Multi-speed gearboxes give the machine the ideal EPB torque if larger sections of soft ground are anticipated (Figure 11).

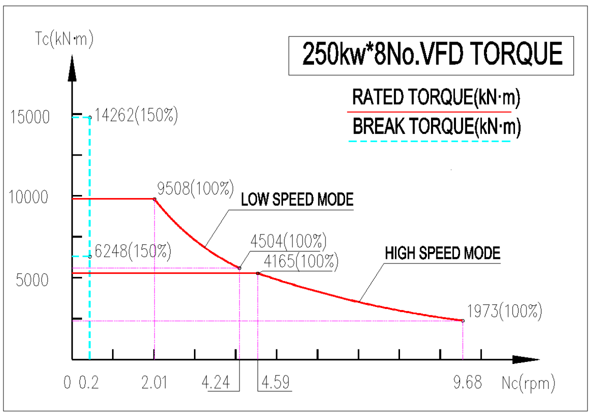

Figure 11 Torque-speed curve for the LHWP Phase II TBMs

When compared to the Phase I TBMs, the Phase II machines also have much higher thrust – in some cases nearly four times higher (see Table 1). The combination of higher thrust capabilities and multi-speed gearboxes is ideal for variable rock conditions.

Table 1. Comparison of 5 m diameter TBMs, Then and Now

	Cutterhead Power (kW)	Thrust (kN)
LHWP Phase I MB TBMs	1,110 to 1,680	7,400 to 9,473
Modern MB TBM	2,310	10,898
LHWP Phase II DS TBMs	1,920	29,500

3.3.2 Stepped shields and shield lubrication

When blocky rock or squeezing ground is expected, using a shielded TBM can be tricky. The risk of a machine's shield becoming stuck is real and can be the source of major delays. Designing for these conditions involves creating the shortest possible shield length, with stepped shields if necessary (particularly if a Double Shield TBM is used). Stepped or tapered shields involve each successive shield having a slightly smaller diameter than the last to accommodate for any squeezing or ground convergence as the TBM excavates. Radial ports in the shields can be used for application of Bentonite to provide lubrication between the shield and tunnel walls, again to avoid a stuck machine. Should the machine become stuck, there are additional solutions: hydraulic shield breakout can be used in trapped conditions. The radial ports can be made to inject pressurized hydraulic lubricants to free a shield that has already become stuck (see Figure 12). Lastly, additional thrust jacks between the normal thrust cylinders can supply added thrust in a short stroke to break loose a stuck shield.

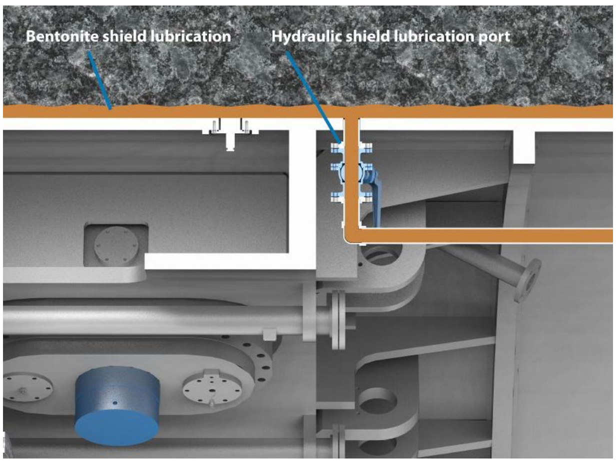

Figure 12 Shield lubrication system

3.3.3 Enhanced Probe Drilling and Grouting

One of the key lessons learned from projects in difficult ground is that more drill ports, and more types of drills, are necessary components of shielded tunneling in difficult ground. Multiple probe drills can be installed on the TBM, with ports to provide probing patterns in a 360-degree radius. High-pressure grout injection can be done through these same ports to stabilize ground up to 40 m ahead of the face (or more if using specialized drills). The type of grout injected can also be specialized—for example chemical or polymer grout can be used to seal off groundwater.

In order to minimize water inflows and increase water tightness of the segments, grouting can be done through the TBM tail shield as well.

3.4 TBM Supply

The two Double Shield TBMs are currently being built at Robbins partner facilities, CCCC Tianhe Mechanical Equipment Manufacturing Co., Ltd. (CCCCTH) in Jiangsu Province, China. A representative example of a Double Shield TBM is shown in Figure 14 below.

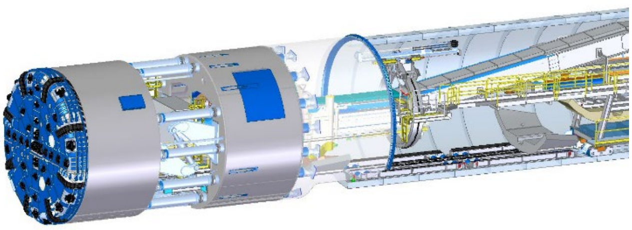

Figure 14 Example High-Performance Double Shield TBM Design

5 Conclusions

While the original Main Beam TBMs provided for Phase I were able to excavate in the challenging conditions, there were many delays and stoppages. Modern TBM design, from 360-degree probe drilling to multi-speed gearboxes, offers advantages in these types of challenging ground. They have been proven to get through fractured, and variable ground by detecting such conditions ahead of the TBM grouting to seal off water inflows and utilizing multi-speed gearboxes. While the Double Shield TBMs have not yet been launched at the Polihali Tunnel, these two epic projects, 30 years apart, clearly elucidate the advances of the TBM industry. Advance rates and utilization will be monitored throughout these tunnels in order to compare and contrast to the Phase 1 TBMs.

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