CARVING A PATH THROUGH EXTREME CONDITIONS: AN INTEGRATED GROUND INVESTIGATION SYSTEM OPTIMIZED FOR TURKEY'S DIFFICULT GEOLOGY

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ABSTRACT: Turkey's geologic framework, seated on an active tectonic belt, is made up of older rocks mixed with younger igneous rock. More than 80% of the country's surface is rough and mountainous, and the ground conditions can be highly variable and unpredictable. Today's adaptable TBMs are capable of tackling these tough conditions using cutting-edge technology coupled with modern ground investigation methods.

This presentation will explore several recent and ongoing projects in the tunneling industry that highlight the latest in TBM technology for difficult ground excavation. Whether smart features include a Measurement While Drilling (MWD) system, cutterhead inspection cameras, or sensors to monitor converging ground, today's TBMs equip contractors with knowledge. Specialized sealing systems can arm contractors with methods to successfully and safely treat water head pressure up to 30 bar.

The projects to be discussed, including Turkey's Kargi and Gerede Water Tunnels, as well as New York City's Rondout Bypass, exhibit the capabilities of TBM technology to guide contractors through a gauntlet of conditions. Even under demanding circumstances today's TBMs, paired with cutting-edge ground investigation and treatment, can forge a path in the most difficult rock.

KEYWORDS: Difficult ground, hard rock, water inflows, tunnel boring, Kargi, Gerede, Rondout, Turkey

1. INTRODUCTION

In many rock projects in high cover, mountainous regions, the occurrence of squeezing ground, high inrushes of water, blocky rock, and other challenges is a real possibility. Today's highly adaptable TBMs are capable of tackling these tough conditions using cutting-edge technology coupled with modern ground investigation and treatment methods. The story of how these methods concentrated our viewpoint and came into practice involves hardship and difficult ground conditions that tested the mettle of a shielded hard rock TBM on a recent project. What came out of those challenges is a new way to deal with both predicted and unforeseen ground conditions in rock and mixed ground tunnels.

1.1 Solutions Informed by Field Experiences

The project in question began its underground excavation in 2012 near Ankara, Turkey using a 10 m diameter Double Shield TBM (see Figure 1). Known as the Kargi Hydroelectric Project, the initial 11.8 km long tunnel was expected to be bored in softer yet self-supporting geology for the first 2.5 km, giving way to competent rock that would not require a fully segmented tunnel lining for the rest of the drive (see TBM DiGs 2015 proceedings). However crews immediately ran into much more difficult ground than they had anticipated—everything from running ground with sand and clay to blocky rock and water bearing zones.

After boring just 80 meters the TBM became stuck in a section of collapsed ground that extended more than 10 m above the crown, loaded onto and around the cutterhead.

Figure 1. 10 m diameter Double Shield TBM for the Kargi HEP.

As a countermeasure that was immediately put into place to avoid the cutterhead becoming stuck in the blocky material, crews began boring half strokes and half resets. Even with these measures, the machine encountered a section of extremely loose running ground with high clay content. A collapse occurred in front of the cutterhead and the cathedral effect resulted in a cavity forming that extended more than 10 m above the crown of the tunnel. The cathedral effect can be difficult to detect and control as loose rock can set on the shield and above the cutterhead, and the cathedral void can occur meters above this material. Injection of polyurethane resins via lances inserted through the cutter housings and muck buckets was the method utilized for consolidation operations; however, injection locations were restricted to the available openings and subsequent attempts to restart the cutterhead proved to be unsuccessful. A bypass tunnel was successfully used to free the TBM; however, this represented only the first of a total of seven bypass tunnels that would be excavated in the first 2 km of tunnelling (see Figure 2).

Figure 2. Bypass tunnel excavation.

It became apparent that much more drastic measures would be needed to get through the difficult conditions. In order to improve progress, the contractor, owner, consultants and Robbins engineers worked together to formulate a plan to improve advance by modifying the TBM for the now-known ground conditions. The contractor, with the assistance of the Robbins field service team, installed a custom-built canopy drill and positioner to allow pipe tube support installation through the forward shield. Drilled to a distance of up to 10 m ahead of the cutterhead, 90 mm diameter pipe tubes provided extra support across the top 120 to 140 degrees at the tunnel crown. Injection of resins and grout protected against collapse at the crown while excavating through soft ground. As a result of successful use of the probe drilling techniques, the contractor was able to measure and back-fill cavity heights above the cutterhead in some fault zones to over 30 m and, in addition, was able to help detect loose soil seams and fractured rock ahead of the face.

To further mitigate the effects of squeezing ground, face collapse, and trapped cutterhead, custom-made gear reducers were ordered and retrofitted to the cutterhead motors. They were installed between the drive motor and the primary two-stage planetary gearboxes. During standard rock boring operations the gear reducers operated at a ratio of 1:1, offering no additional reduction and allowing the cutterhead to reach design speeds for hard rock boring. When the machine encountered loose or squeezing ground the reducers were engaged, which resulted in a reduction in cutterhead speed but the available torque was increased by nearly double. The net effect of the modifications was to allow the Double Shield TBM to operate much like an EPB in fault zones and squeezing ground with high torque and low RPM—these methods effectively kept the machine from getting stuck. In addition, short stroke, high-pressure thrust jacks were installed between the normal auxiliary thrust to double total thrust capabilities in order to break loose a stuck shield.

Ultimately, after in-tunnel modifications, the machine at Kargi was able to excavate the ground very efficiently, even boring 723 m in one month. The average advance was more than twice the rate of a drill and blast heading proceeding from the opposite end of the tunnel (see Figure 3). The TBM broke through in July 2014 after boring 7.8 km total.

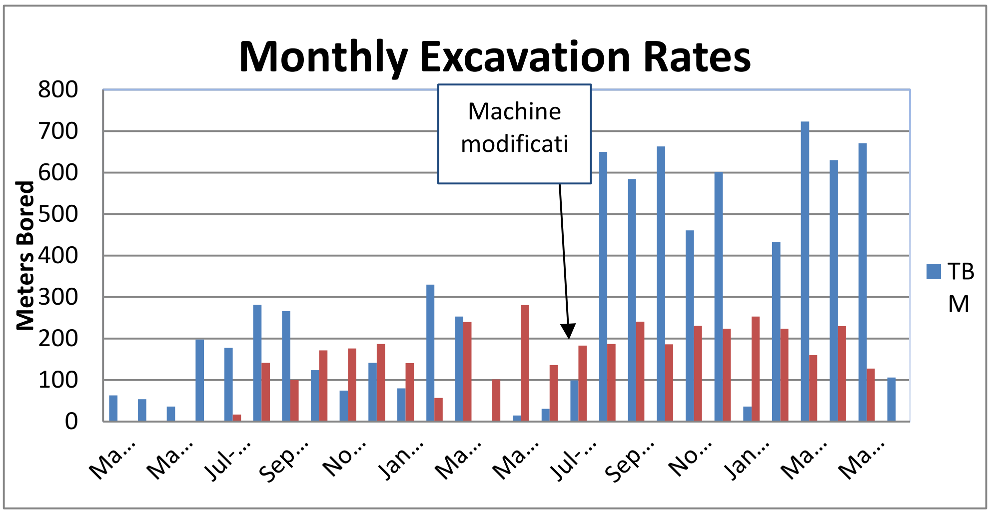


Figure 3. Monthly production rates

2. A PATHWAY TO SUCCESS IN DIFFICULT GROUND

After the lessons learned at Kargi, it was decided to create a comprehensive system that could tackle the various conditions faced by shielded machines in hard rock. The ground investigation system is known as Difficult Ground Solutions (DGS), and consists of a set of integrated features tailored to a specific project's geology. The main components of the system allow for ground investigation ahead of the TBM, increased monitoring, and methods to keep a machine shield from becoming stuck. The main components are listed below.

2.1 Multi-Speed Cutterhead Drives

As determined at Kargi, customized cutterhead drives can be instrumental in getting through difficult ground even when the TBM is designed for boring in mostly hard rock conditions. 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.

Going one step further, multi-speed gearboxes give the machine the ideal EPB torque if larger sections of soft ground are anticipated (see Figure 4).

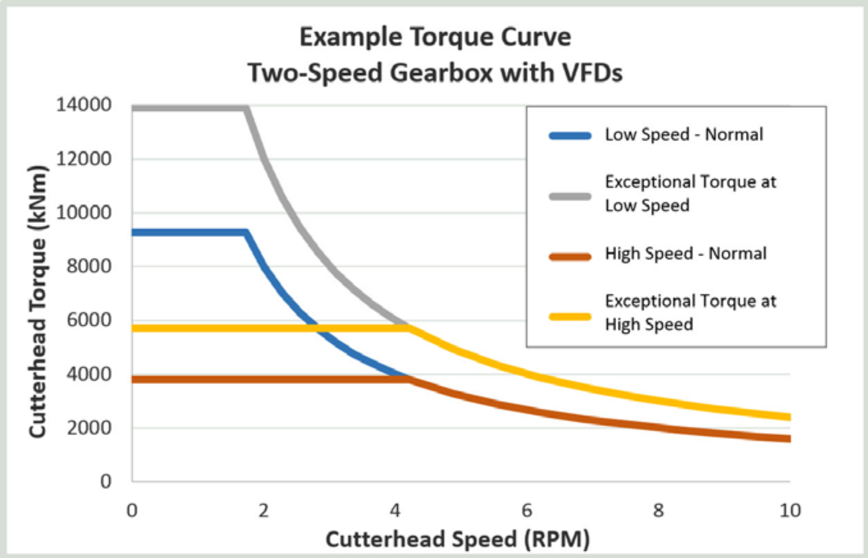


Figure 4. Example Torque-Speed Curve for TBM with Multi-Speed Gearboxes.

2.2 Continuous Advance Shield Design

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 5). Lastly, additional thrust jacks between the normal thrust cylinders can supply added thrust in a short stroke to break loose a stuck shield.

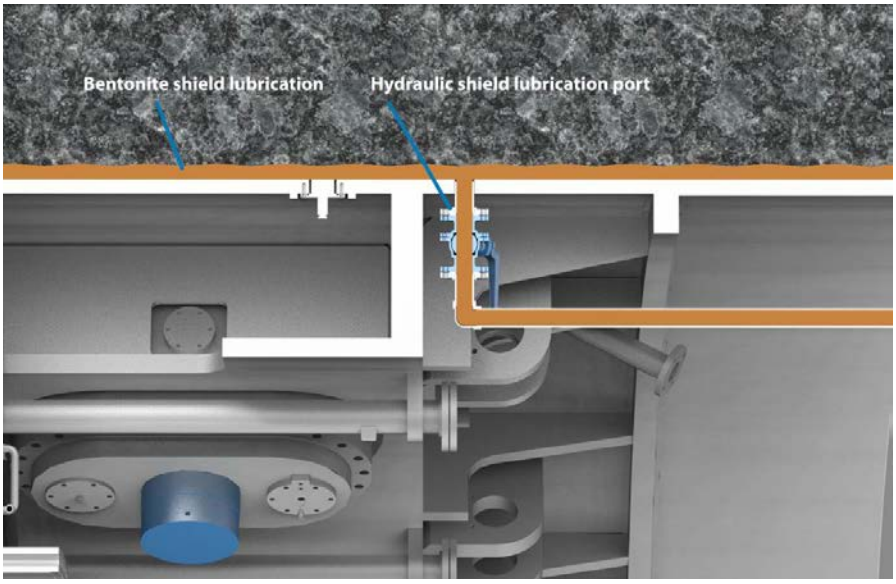


Figure 5. Shield lubrication system.

2.3 Convergence Measuring System

Again for use in squeezing or blocky ground, this system utilizes a hydraulic cylinder mounted on top of the shield and connected to the TBM's PLC. It measures the shield gap in the tunnel crown, so that if squeezing or collapsing ground is detected the crew can take countermeasures. These measures include using bentonite lubrication, crown or face rock conditioning, or planning ahead to use another system in the area before the machine can become stuck (see Figure 6).

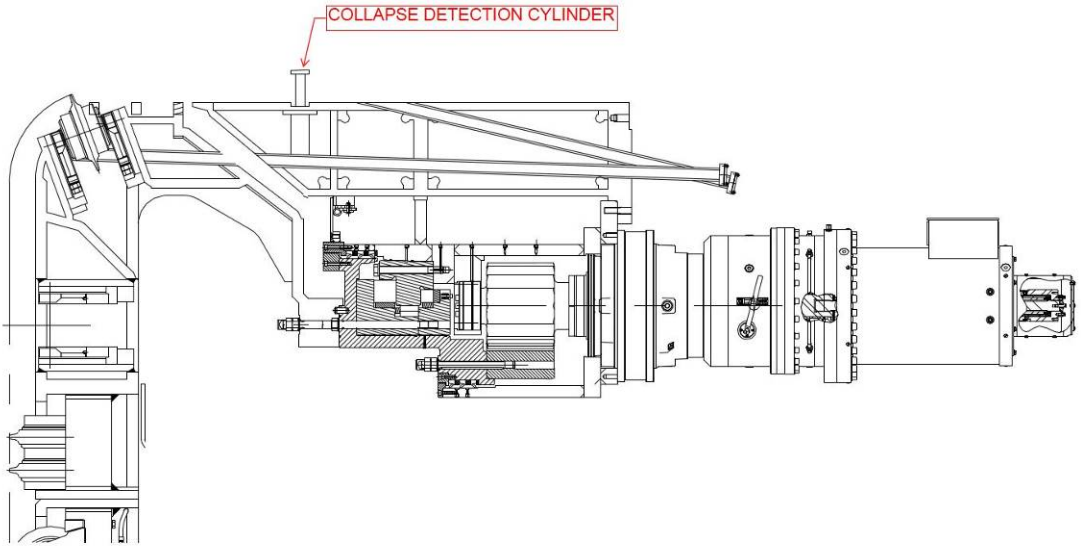


Figure 6. Convergence measurement using a hydraulic collapse detection cylinder.

2.4 Cutterhead Inspection Camera

The cutterhead inspection camera can be used to remotely inspect the boring cavity without intervention, and to check water levels ahead of the TBM. While these cameras have been used to monitor mixing chambers and perform cutterhead inspections in soft ground TBMs, their use in hard rock machines has been much more limited. In the new ground investigation system, the probe and injection holes in the cutterhead and front shield are specifically designed to accept these cameras (see Figure 7).

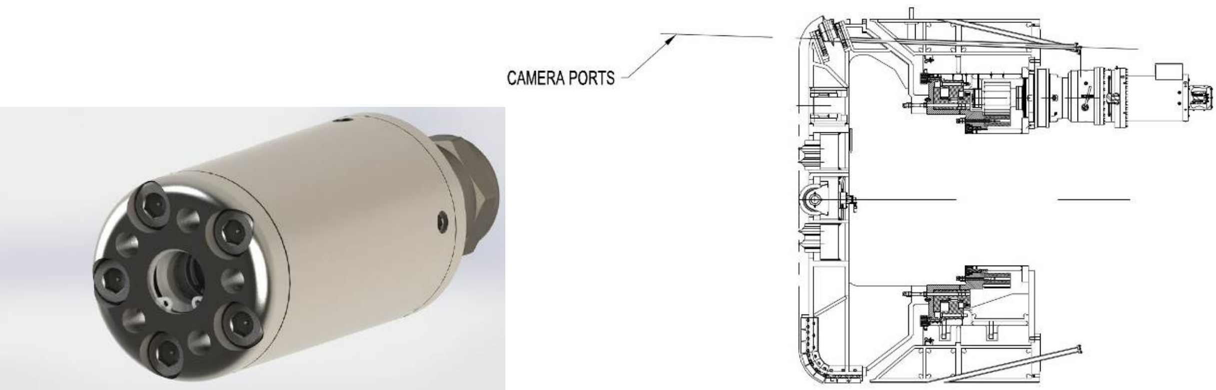


Figure 7. Face inspection camera (left) and camera ports in the cutterhead (right).

2.5 Water Inrush Control

In the event of a large inrush of water, a guillotine gate on the muck chute can effectively seal off the muck chamber to keep the crew safe as well as keep the machine from becoming flooded out. Additional inflatable seals can seal the gap between the telescopic shield and outer shields of a Double Shield TBM to keep everything water tight. This system is termed "passive" water protection because the TBM is stopped in place (not actively operating). During that time the crew can then work to grout off water inflows and dewater the chamber to control the flow before they begin boring again. The grouting crew also have the added assistance of back pressure to assist in grouting (see Figure 8). In this way TBMs can be designed to withstand inflow pressures up to 30 bar.

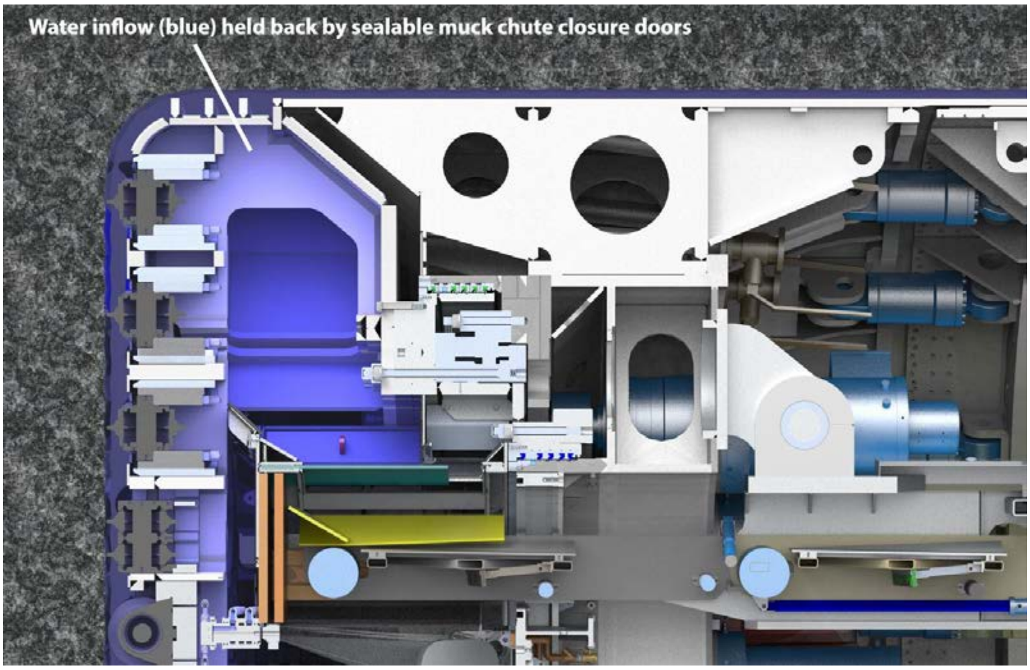


Figure 8. Water inflow (blue) can be sealed off inside the muck chamber using a guillotine gate.

2.6 Improved Ground Detection and Consolidation

One of the key lessons of Kargi was that more drill ports, and more types of drills, is a necessary component of shielded tunneling in difficult ground. Multiple probe drills can now 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. Lastly, a rotary forepole drill can be installed just behind the cutterhead support to allow for ground consolidation around the shield periphery. The forepole drill is of particular use in fractured rock and fault zones (see Figure 9).

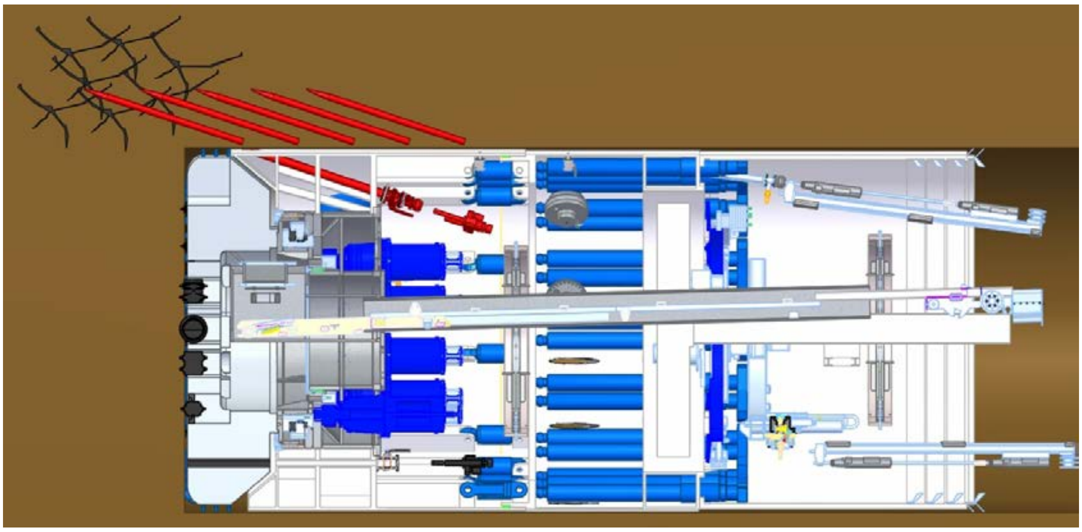
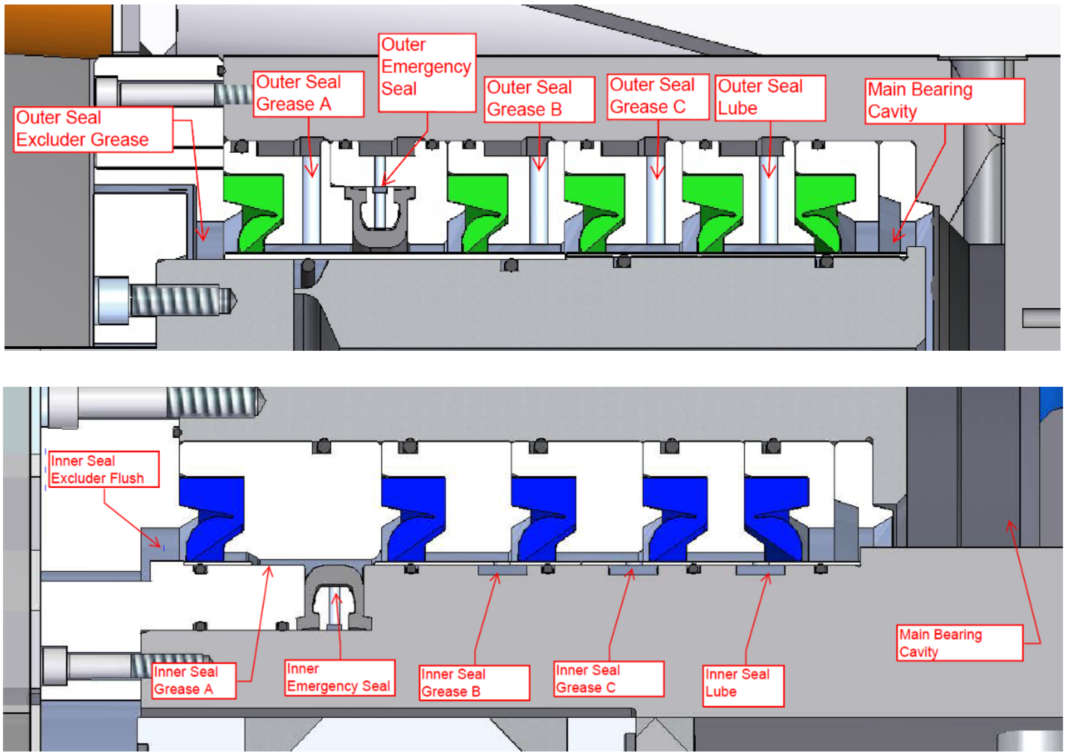


Figure 9. Forepole drilling (shown in red) for use in fractured rock and fault zones.

3. APPLICATIONS OF THE GROUND INVESTIGATION SYSTEM: NYC'S RONDOUT WEST BYPASS

The ground investigation system will be used on several TBM projects, including New York City's Rondout West Bypass Tunnel. Scheduled to begin in 2017, the project will use a 6.6 m diameter Single Shield TBM to excavate a 4 km long tunnel below the Hudson River. Ground conditions are expected to consist of shale with possible zones of intense water inflow with pressures building to 30 bar. The machine is being designed to passively hold the potentially high water pressure using a cutterhead drive sealing system and backfill grouting through the tailskin. In order to protect the machine from such high water pressure, an extensive sealing system was designed. Around the main bearing, there is an outer row of five seals and an inner row of five seals, plus an additional emergency seal in each row. Between each seal, the cavity is filled with pressurized grease to ensure a constant pressure in each of the cavities. In the event that the machine is shut down and an inrush of water overtakes the machine, a pressure sensor will detect this presence of water and pressurize each cavity with grease in order to continually protect the seals (see Figure 10).

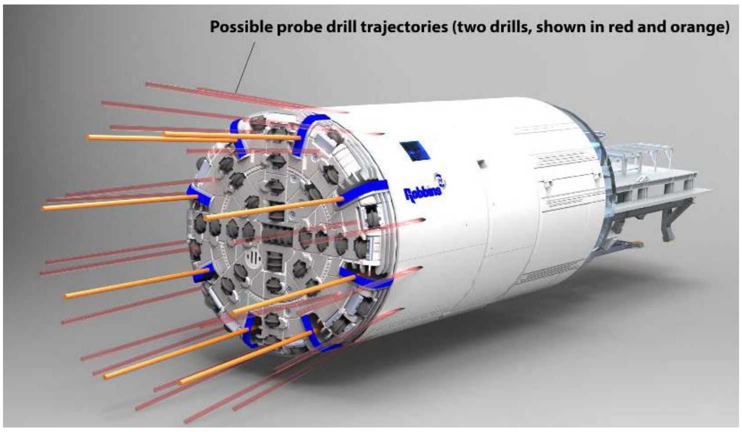


Outer Row

Inner Row

Figure 10. Outer and inner rows of seals to protect the main bearing from inrushes of water and muck.

The machine is equipped with multi-speed gearboxes to get through challenging ground and sophisticated drilling and pre-grouting equipment for detection. Water-powered, high-pressure down-the-hole hammers are capable of accurate drilling 60 to 100 m ahead of the TBM, while blow-out preventers enable drilling at high pressures up to 20 bar (see Figures 11 and 12).



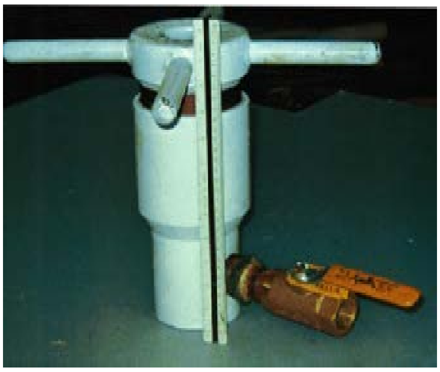


Figure 11. Enhanced probe drilling on the Rondout TBM.

Figure 12. Blowout preventers for drilling under pressure up to 20 bar.

Stepped shields will provide 50 mm overcut capabilities to prevent the machine shield from becoming stuck, while peripheral shield lubrication and six grouting ports can be employed to keep the shield moving forward in a difficult situation. This is an example of a customized system for expected geological difficulties. Tunneling is scheduled to begin in spring 2017.

4. APPLICATIONS FOR TURKEY: GEREDE WATER TUNNEL

Turkey's tough geology makes it a proving ground for TBMs, and the Gerede Water Transmission Tunnel is no exception. The tunnel, located near Ankara, Turkey, has a variety of ground conditions that make it widely considered one of the most challenging ongoing projects in the country. The 31.6 km project was launched in 2010 using several standard Double Shield tunnel boring machines. While mostly a hard rock environment, at around seven kilometers into the drive, two of the double shield TBMs encountered difficult ground conditions. One machine hit a fault zone that allowed an unexpected onslaught of around 1,500 liters per second of water and loose material to rush into the TBM. This inflow resulted in enough pressure to crush the inadequately designed TBM shields and send cylinders catapulting into the backup. With the catastrophic failure of one machine, it was decided to abandon the TBM and look at a new type of TBM.

The geology for this tunnel consists of Sandstone, Limestone and Tuff with a maximum UCS in the range of 100 MPa. Throughout the tunnel alignment there are numerous fault zones with potential for blocky rock and unstable ground water inflows. A 5.56 m Robbins Crossover TBM, a cross between a Rock and EPB TBM, was chosen for the ground conditions. The unique machine will bore through 30 fault zones requiring the TBM to be sealable to up to 20 bar so pre-consolidation grouting can be done. EPB mode will only be used in poor ground—in this mode, the TBM will bore sequentially using the screw conveyor fore and aft gates. The TBM was launched in spring 2016 from a chamber inside the tunnel to bore the remaining 9 km (see Figures 13 and 14).

Figure 13. Assembly of the Gerede TBM in an underground launch chamber.

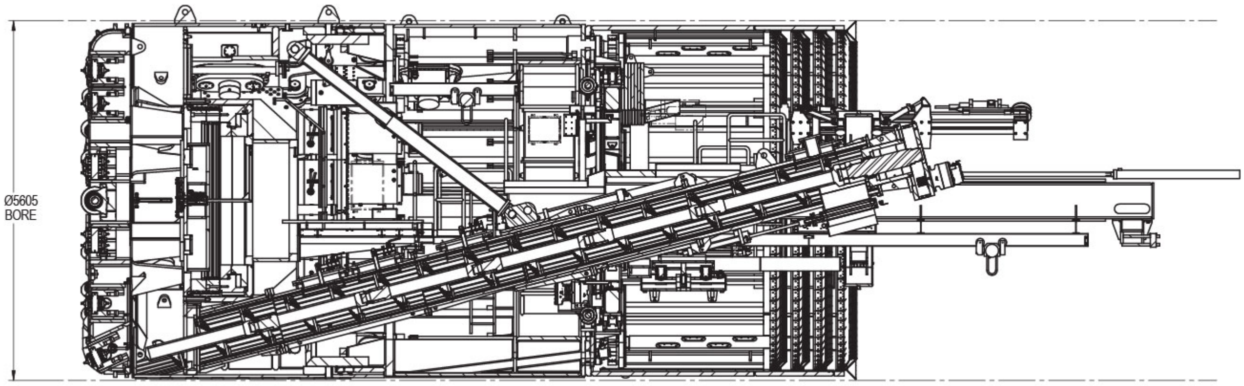


Figure 14. Cross-sectional drawing of the Gerede TBM.

4.1 Difficult Ground Solutions at Gerede

Similar to the Rondout machine, the Gerede TBM was supplied with a two-speed gearbox. With the ability to shift into two speeds, the machine can easily bore through different types of ground. For hard rock, the machine can run in a high rpm/low torque and for EPB mode, it can shift into a low rpm/high torque. The low rpm/high torque allows the machine to bore through fault zones and soft ground, reducing the risk of becoming stuck.

Also similar to Rondout and as a result of the previous experiences at Gerede, extensive measures have been taken to protect against massive inrushes of water. Around the main bearing, there is an outer row of six seals and an inner row of three seals. The articulation joint, gripper and stabilizer shoes are sealed off in the same manner. All of these locations have two rows of seals with a grease-filled, pressure-controlled cavity between to hold constant pressure. The tail seals are also sealed off in the same manner with four rows of seals.

Because of the potential for inflows, the machine's screw conveyor has also been designed to be completely sealable. If a fault zone is encountered with large amounts of water, the machine will still be able to continue excavation. In this case, the screw can be used in a sequential operation. First, the rear discharge gate is closed, sealing off the interior of the machine from the incoming water. The screw extension cylinders will then push the rear of the screw back, thus pulling the screw out of the cutting chamber and inside of the screw casings. Next, the bulkhead gate is closed and the screw conveyor is dewatered. The rear discharge gate can be reopened and the screw conveyor can run, emptying the casings of muck. A catchment basin, under the hopper of the bridge conveyor, can be filled with leftover water coming from the screw. The water is then pumped out of the back-up system. Once the screw has been emptied, the rear discharge gate can be sealed. The bulkhead gates can be reopened and the screw extended into the cutting chamber. Boring can then commence until the screw conveyor is once again full. Once the screw is refilled, it can again be retracted and sealed, starting the process over again. This process can be slow, but it can get the machine through a fault zone and into better ground.

Lastly, due to the unpredictable ground conditions probe drilling is of prime importance. It is necessary to detect and grout off zones of concern wherever possible in order to protect the machine from flowing ground and water pressure. The Gerede machine achieves this using a standard array of twelve Ø100 mm ports angled at 7° that are equally spaced around the rear shield. Each port is sealed by a ball valve until it is needed for probing. There are also ten of the same sized ports straight through the forward shield for probing and grouting. Six additional hatches are built into the pedestal at the front of the machine. The hatches are equipped to mount an optional pneumatic percussive drill that can be used in the center section of the cutterhead (see Figure 15).

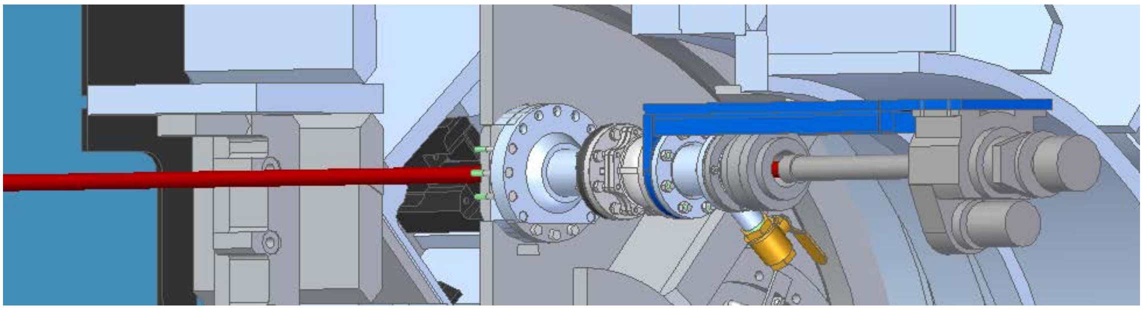


Figure 15. Probe drilling through a port in the machine shield**.**

The probe drill on the Gerede machine also has an extra feature. The drill is designed to pull back behind the tail shield and at an angle of 16°, so it can drill behind the shields and into the segment lining. This procedure is for emergency cases. If water has filled the cutting chamber and the pressure is great, drilling a hole in the roof of the tunnel will allow the water to spill out, thus relieving the buildup of pressure on the machine and the segment ring (see Figure 16).

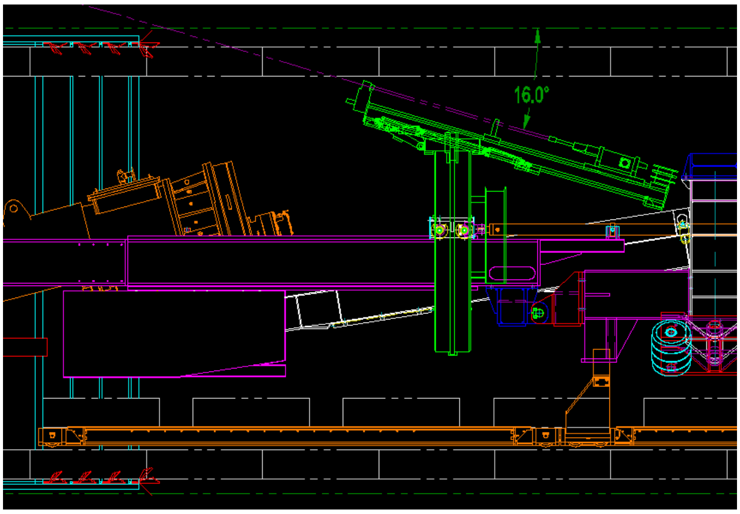


Figure 16. Probe drilling behind the tail shield to control severe water inflows

5. CONCLUSIONS

While the Gerede project is ongoing, the ground investigation and water control systems installed on the TBM can help to mitigate the risks of known difficult geology. The system could be widely useful as Turkey has some of the most difficult geology in the world. The overall goal of the machine features is to avoid making modifications in the tunnel as was done at Kargi—a process that can cause significant downtime. The system is an assurance that the machine will be able to handle expected and unexpected conditions, and if conditions are known the system can be made all the more accurate.

In general, contractors and owners must strive to provide geological reports that are as accurate as feasible so that TBM designers can built appropriate TBMs. In-tunnel excavation continues this geological exploration. Owners and contractors should give full consideration to building in ground investigation and treatment features when difficult conditions are a possibility. With these features, it is possible for a shielded machine to keep advancing, whether the concern is high cover mountainous tunneling with squeezing and rock bursting, water inflows, fault zones, or all of the above.