Tunneling through 48 Fault Zones and High Water Pressures on Turkey's Gerede Water Transmission Tunnel

D. Harding[1] and Y. Alpagut[2]
[1]*The Robbins Company, Solon, Ohio, USA*
[2]*ATES Engineering Construction Ltd., Istanbul, Turkey*
E-mail: hardingd@robbinstbm.com

ABSTRACT: The December 2018 breakthrough of a 5.5 m diameter hybrid-type Single Shield/EPB TBM at the Gerede Water Transmission Tunnel in Central Turkey was a feat of modern construction. The 9 km leg was the final section of the 31.6 km long water supply line bored through what is widely considered to be Turkey's most challenging geology. The project was originally started with the contractor selecting three Double Shield machines, which were procured and supplied without Robbins involvement. When two of the machines became stuck and were unable to continue, the solution of the hybrid-type TBM was developed to complete the rest of the tunnel. The TBM was assembled and launched more than 7 km from the tunnel portal and successfully navigated 48 fault zones as well as hydrostatic pressures up to 26 bar. The machine also bypassed areas where the Double Shield TBMs had become stuck. The paper describes the machine and the unique design for the geological conditions, including the requirement to be sealable up to 20 bar hydrostatic pressure. When boring and during large water inflows, the TBM held back the water/muck and allowed time for pre-consolidation grouting. Despite the challenges, crews were able to achieve a best month of 484 m with a 285 m monthly average throughout tunneling. This paper will also discuss the performance of the machine in conditions above and beyond the TBM design pressure, and analyze the difficult geological sections and how the crew responded to the more severe fault zones. It will seek to make recommendations as to other projects in difficult and faulted mountainous rock conditions with high water pressures.

KEYWORDS: Fault zones, TBM, Crossover, Water Inflows

1. INTRODUCTION

On December 18, 2018, a Robbins Crossover XRE TBM—a hybrid between a Single Shield Hard Rock Machine and an EPB—completed what would once have seemed far-fetched. In the mountains outside of Ankara in Central Turkey, the TBM had bored the final 9 km leg of the 31.6 km long Gerede Water Transmission Tunnel by navigating 48 fault zones and hydrostatic pressures up to 26 bar. The notoriously difficult conditions had previously caused two non-Robbins Double Shield TBMs to become stuck in massive inrushes of mud and water. The tunneling success story highlights what today's equipment is capable of, and how far the Turkish tunneling industry has come in tackling its own incredibly difficult geology.

The Gerede Water Transmission Tunnel near Ankara, Turkey was always expected to be a challenge. Preliminary geologic testing and borehole samples showed a mix of volcanic rock including tuff, basalt, and breccia, giving way to sedimentary formations like sandstone, shale, and limestone, all punctuated by fault zones. But the project was deemed a national priority by the Turkish State Water Department (DSI) due to a severe drought in the area lasting years. The 31.6 km long tunnel would pull water from the Gerede River to a water storage system near Ankara, making it the longest such water tunnel in Turkey (see Figure 1). What the contractor and owner could not know were the distinct challenges they would encounter, making it one of the most difficult projects attempted in the world of tunneling.

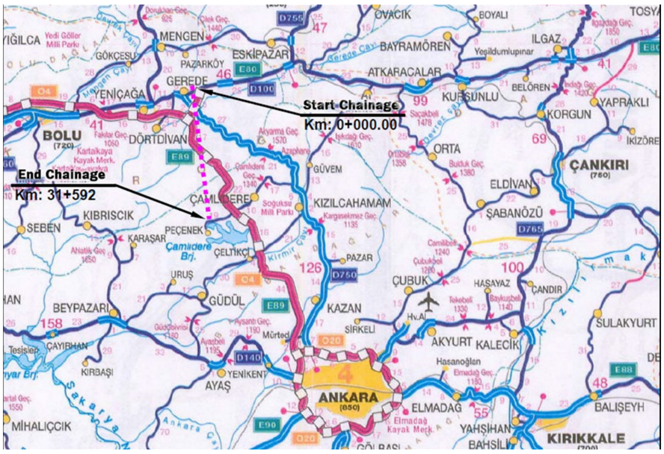

Figure 1 Tunnel route of the 31.6 km long Gerede Water Transmission

1.1 Original TBM Supply

During the original excavation, the joint venture of Kolin and Limak purchased three 5.56 m diameter Double Shield TBMs from a European manufacturer to deal with the challenging geology. Each machine was to bore a roughly 10 km section of tunnel. The TBMs arrived at the site in 2011—the first machine (TBM-1) was launched from the north portal in a relatively homogenous section of rock with low cover of 13 m. The TBM completed its 9,588 m of tunnel while achieving good average advance rates. The machine encountered some ground water inflows and squeezing that caused delays but it was still able to complete its tunnel.

TBM-2 was launched from an intermediate shaft under higher cover, starting at 60 m and reaching over 400 m as it bored toward the south. The rock was more transitional in this section, and the TBM had bored a significant section of its 10,339 m tunnel when it encountered a massive inrush of water that flooded the TBM and tunnel. The TBM was boring downhill and the water had to be pumped out, which took some time. The TBM was deemed a loss, and removed from the tunnel.

TBM-3 began boring from the south portal under increasingly high cover that would reach a maximum of over 500 m. The TBM was several kilometers into its 11,653 m downhill drive, struggling in karstic aquifer conditions that required polyurethane injection and slowed tunneling, when its problem became worse. A high water inrush of 1,500 liters/second flowed into the tunnel, causing the machine to become stuck. This inflow resulted in enough pressure to crush the TBM shields and send cylinders catapulting into the back-up. Dye tests showed that the water had come from a river flowing overhead and entered into the tunnel through a cave system. As quickly as it had started, the Gerede Water Transmission Tunnel ground to a halt with two TBMs stuck 9 km apart (see Figure 2).

Figure 2 Of the three standard Double Shield TBMs used to originally bore sections of the tunnel, two became irretrievably stuck or damaged amid massive mud and water inflows

1.2 Lessons Learned in Challenging Geology

The Gerede Water Tunnel is just one tunnel of many in Turkey but, like so much of what is considered difficult in tunneling, the story of why Gerede is so challenging begins and ends with geology. Turkey is in a tectonically active region controlled on a grand scale by the collision of the Arabian Plate and the Eurasian Plate. At a more detailed level, a large piece of continental crust almost the size of Turkey, called the Anatolian block, is being squeezed to the west. The block is bounded to the north by the North Anatolian Fault and to the south-east by the East Anatolian fault. Geology in the fault zones tends to be highly variable and unstable. Several current and recent projects have been affected by these faults, including the Kargi HEPP, the Bahce-Nurdag High Speed Rail Tunnels, and the Gerede water tunnel. At Gerede for example, geologic testing and borehole samples showed a mix of volcanic rock including tuff, basalt, and breccia, giving way to sedimentary formations like sandstone, shale, and limestone, all punctuated by fault zones that contained clay and alluvium.

Experiences at other projects including the Kargi HEPP have shown that a shielded hard rock machine with specific capabilities can traverse significant fault zones. Crews at Kargi bored into the North Anatolian fault zone, where the squeezing of the TBM was a big problem. The TBM's emergency thrust system, shield lubrication facilities and multi-speed gearboxes played a big role in the success of the project. The 10 m Double Shield machine was modified in the tunnel, effectively allowing it to operate like an EPB in fault zones, with high torque and low RPM. These changes were made with great success and significantly increased advance rates. These are the same principles used in Crossover, or dual-mode type, machine designs.

Also on the Kargi project, the machine utilized a canopy drill and umbrella arch to consolidate ground directly above and in front of the machine, and operated with continuous probe drilling. When probe drilling and umbrella arches are used together in a tunneling project, machine utilization time and mean daily advance rates may decrease considerably. However, the contractor should be aware of the fact that if these techniques are not used in such challenging ground, the machine will most likely become jammed, necessitating a bypass tunnel that will require much more downtime. As far as the selection of TBM type, a Crossover/Dual Mode type TBM has multiple advantages: while it may require a larger initial investment than a classical Single Shield TBM, this type of TBM is more likely to overcome the many difficulties arising from such complex geology.

2. A NEW STRATEGY: THE CROSSOVER TBM

The Kolin/Limak JV had to develop a new strategy given the incredibly difficult ground conditions. They contacted The Robbins Company, who suggested a Crossover (Dual-Mode Type) TBM for the remaining 9 km section of tunnel. The 5.56 m diameter XRE (standing for a Crossover between Rock and EPB) could effectively bore conditions in both rock and mixed ground under water pressure by converting between modes.

The revised geology was now understood to contain more significant fault zones and an aquifer system that could cause high-pressure water inrushes of up to 20 bar. However the ground was expected to improve as the TBM advanced and consist mostly of sandstone, limestone and tuff with a maximum UCS in the range of 100 MPa.

Kolin/Limak needed a machine that could effectively bore in those wide-ranging conditions, but also statically hold water pressure up to 20 bar in the event of an emergency flow—a failsafe that none of the standard Double Shield TBMs were equipped with. In order to successfully design a machine for these conditions, the following list of specifications in Table 1 were used.

Table 1 Gerede XRE TBM Specifications

Gerede XRE TBM Specifications		
Design Parameters	Curve radius (vert. and horiz.)	500 m
	Gradient	± 0.5°
	UCS	Average 100 MPa
	Hydrostatic Pressure	20 bar
Segmental lining	Number of segments	5+1 key
	Segment width	1,400 mm
	Segment thickness	350 mm
	Segment Backfill	Single Component Grout
Diameter	Bore Diameter	5.605 m
Cutterhead Style	Cutterhead	Mixed ground, convertible
	Cutters	17" disc cutters, back-loading
Cutterhead Drive	Cutterhead Power	8 x 210 kW = 1,680 kW
	Cutterhead Speed (Low Gear)	0-1.73 rpm (constant torque range)

		1.73-3.54 rpm (constant power range)
	Cutterhead Speed (High Gear)	0-4.22 rpm (constant torque range) 4.22-8.61 rpm (constant power range) 8.61-10.0 rpm (reduced power range)
	Breakout Torque	13,896 kNm
	Maximum Thrust	42,000 kN
TBM Conveyor	Screw Conveyor Type	Shafted, hydraulic drive
Exploration/Ground support	Probe Drill/Grout	12 peripheral ports, 10 bulkhead ports; 2 drills
Protection	Methane Monitors	6 locations
	Explosion-Proof EPB Sensors	6 locations
Weights and Dimensions	Total length	221 m
	TBM weight	470 tonne

2.1 Cutterhead

Due to the geology, the Gerede machine required a unique Crossover cutterhead. The cutterhead has the face and internal structure of a hard rock machine with the open rear structure of an EPB. On a standard hard rock machine, rock is scooped up in the buckets and as the head rotates, rock slides from the bucket onto a belt conveyor in the center of the machine which minimizes wear. Instead, this machine has a screw conveyor at the bottom of the chamber to aid in cutterhead cleaning in the event of a fault zone. Thus, rocks entering the cutterhead now have the entire height of the machine to fall. In order to reduce damage from large falling rocks, the pedestal was specially designed with multiple deflector plates to slow the fall (see Figure 3). The cutterhead buckets were also designed to direct the muck from the face by push it backward into the cutting chamber. Because of the open back design, this cutterhead can also be converted to an EPB head if conditions require it.

In addition, the cutterhead is designed to operate in a single direction. The setup allows for greater efficiency while excavating, with lower power requirements and less chance of regrind. The problem of regrind occurs in bidirectional heads when already-excavated muck enters through the cutterhead and back out of the next opening, wearing the back portion of the cutterhead. The phenomenon can be very severe in bi-directional cutterheads depending on the ground conditions and cutterhead design.

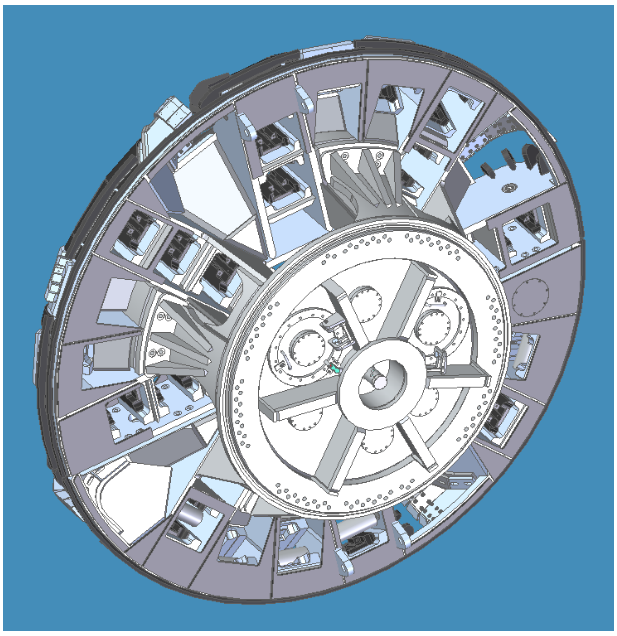

Figure 3 Crossover Cutterhead for Gerede

2.2 Main Drives

A new feature on the Gerede machine, which will also be supplied on all subsequent Crossover machines, is the 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 without becoming stuck like an EPB TBM (see Figure 4).

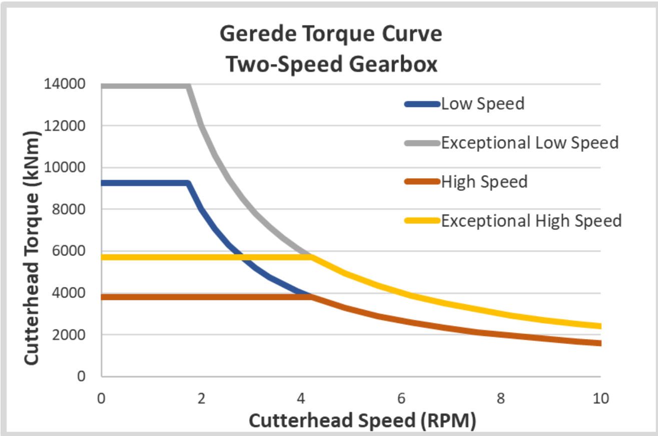

Figure 4 VFD Torque Curve for the Gerede TBM

2.3 Seals

Due to previous experiences at Gerede, the new TBM is designed to statically hold up to 20 bar pressure in the event of a massive water inflow. In order to protect the machine from such high water pressure, an extensive sealing system has been put into place. Around the main bearing, there is an outer row of six (6) seals and an inner row of three (3) seals. Between each seal, the cavity is filled with pressurized grease to ensure a constant pressure in each of the cavities (see Figure 5). 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 from the pace pressure. The articulation joint, gripper and stabilizer shoes are sealed off in the same manner. All of these locations have two (2) 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, but this location has four (4) rows of seals.

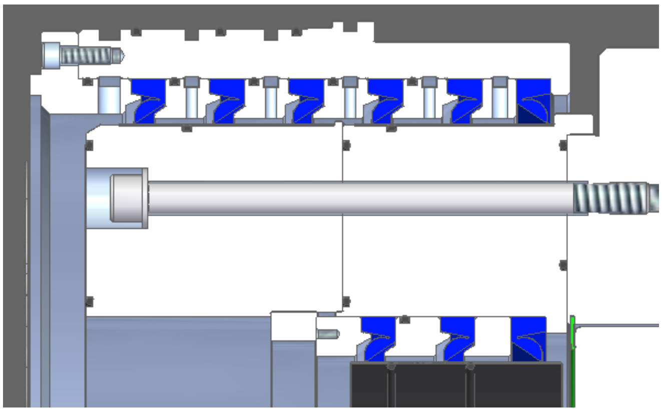

Figure 5 Extensive Main Bearing Seals (dark blue)

2.4 Screw Conveyor

Perhaps one of the most important parts of the Gerede TBM design is the screw conveyor. On a standard hard rock machine, the muck would be transported out of the cutterhead by a belt conveyor. Because of the potential for massive amounts of water, the machine must have a sealed screw conveyor. Unfortunately, running rock through a screw conveyor can be highly abrasive and high wear is expected. In order to account for the wear, the screw has been designed with replaceable wear plates along its entire length of the casing and screw. The screw itself is also made up of short sections that can be removed and replaced if needed. Multiple access hatches were included for maintenance of the wear plates, while two large, removable outer casings can accommodate the change-out of entire screw sections (see Figure 6).

A special feature of the conveyor is the ability to seal itself off so the TBM can continue boring. 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.

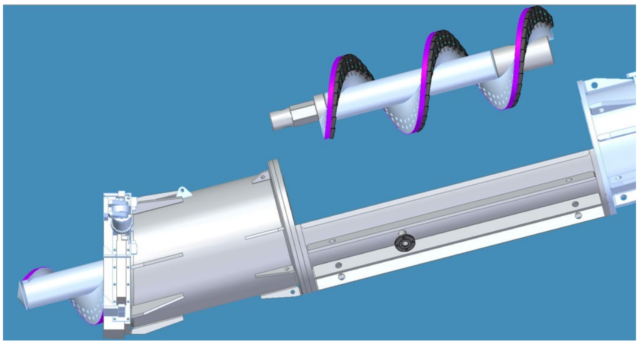

Figure 6 Screw conveyor designed in removable and replaceable sections, with wear plating for use in abrasive ground

2.5. Probe Drilling

Due to the unpredictable ground conditions, probe drilling is very important to this tunnel. 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 will achieve this using a standard array of twelve (12) 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 (10) of the same sized ports straight through the forward shield for probing and grouting. Six (6) 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 7).

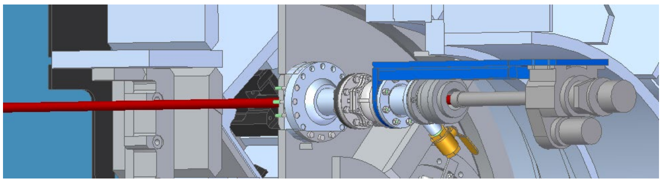

Figure 7 Probe drilling through a port in the machine shield

The probe drills on the Gerede machine also has an extra feature. The drills are designed to pull back behind the tail shield and at an angle of 16°, so they 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 8).

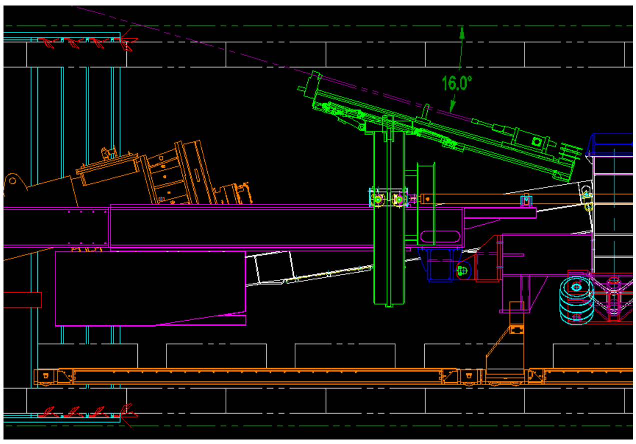

Figure 8 Probe drilling behind the tail shield to control severe water inflows

3. ASSEMBLY & EXCAVATION

3.1 TBM Assembly

The Robbins XRE TBM was launched in summer 2016, using some components from the original Double Shield TBM back-up, as well as the remaining segments being stored for the project. Crews excavated a bypass tunnel to one side of the stuck Double Shield (TBM-3), and the Robbins TBM components were walked in through the south portal. The machine was assembled using Onsite First Time Assembly (OFTA) in an underground launch chamber. The logistics of getting components through the existing tunnel were very challenging, as the assembly chamber was 7 km from the portal. The water inflow made it difficult to get the materials to the machine. To overcome this, custom flat cars equipped with hydraulic lifts were used to transport the bigger sections of the TBM through the tunnel to the build chamber. Large sections of the TBM shield were positioned high enough to pass through the segment lining using the hydraulic lift and side shift adjustments as the cars passed through the tunnel (see Figures 9-12).

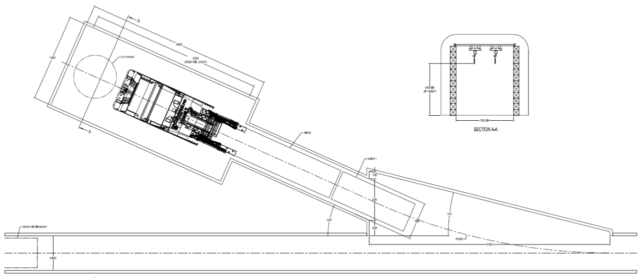

Figure 9 Bypass Tunnel Configuration

Figure 10 TBM assembly in the chamber

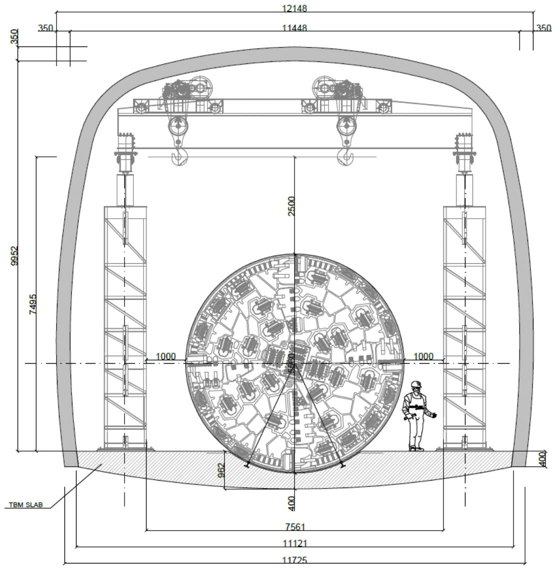

Figure 11 Assembly chamber configuration

Figure 12 Custom Flat Cars

3.2 Excavation

The Robbins machine began boring at a slight angle to the rest of the tunnel and in a fault zone, bypassing the stuck machine before gradually meeting up with the original tunnel alignment. The section of tunnel from the launch chamber up to the point adjacent to the buried Double Shield was reasonably known due to the existing bored tunnel info—crews knew to expect large water inflows with flowing materials at any point over the initial 300 meters of tunnel.

In fact, the machine was required to be used in EPB mode as it encountered water pressures up to 23 bars, alluvium, flowing materials, and clay. Water pressure was lowered by draining the ground water through the rear shield probe drill ports, which were equipped with normally-closed ball valves. Probe drilling became routine after advancing 50 meters past the section that buried the original Double Shield TBM. The Crossover machine bored at approximately 30mm/min through the first bad section of ground, with any limitations in speed the result of the existing tunnel belt conveyor, which tended to have spillage issues resulting in significant clean-up. Despite the challenges, crews were able to cross through material that caused the Double Shield machine to become stuck. They were able to bore 80 meters to the side of where the original machine is currently buried and pass it.

As the machine continued excavating, it encountered a mixture of volcanic rock including tuff, agglomerate, and basalt while using systematic probe drilling. Due to the seismically active region, these formations were punctuated by a series of fault zones containing squeezing clay and water. By the end of tunnelling, the TBM had crossed 48 such fault zones and statically held back 26 bar water pressure. Each time a zone was encountered, exceptional thrust was used to keep the machine from becoming stuck combined with dewatering to lower the water pressure. The rear discharge gate was sealed at these times and the machine was operated in a sequential fashion as described in section 2.4.

By keeping the TBM advance rate, RPM, and screw conveyor at an optimal level, the machine was able to navigate the squeezing conditions in clay. TBM advance rates are shown in Table 2.

Table 2 Best & Average TBM Advance Rates

Best Day	29.4 m	Average Day	9.49 m
Best Week	134.6 m	Average Week	71.14 m
Best Month	484.0 m	Average Month	284.54 m

4. CONCLUSION

With careful design and planning, Crossover machines can be a viable alternative for tunneling in very challenging conditions that would be difficult for conventional machine configurations. In opting for a Crossover machine, factors must be seriously considered by consultants or contractors at the time of machine selection. These factors include cost, time, logistics, maintenance, risk, and tunnel design. Benefits can often outweigh negative factors, and result in significant cost benefits. In the case of the Gerede project the decrease in machine advance rate and higher wear of the screw conveyor has been balanced out by the decreased risk of getting the machine stuck in fault zones as compared with a standard Double Shield TBM.

Gerede is certainly not the first tunnel in difficult ground, nor is it the last, with projects such as the Bahçe Nurdağı High Speed Railway ongoing in extremely hard and abrasive rock elsewhere in Turkey. As for the Gerede project, past TBM projects have shown that in order to achieve success in difficult ground or in very hard and abrasive rock formations, robust machines equipped with the latest technology must be coupled with the experience of the machine manufacturer. These things are a necessity for rapid and efficient tunnel excavation.