Use of Two Novel Hybrid-Type "Crossover" TBMs for Hard Rock Conditions with Water Inflows

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ABSTRACT

Mixed ground tunnels come in all kinds. In rock tunnels with possible faults and high pressure water, the challenges are many. With the advent of Crossover TBMs, contractors can minimize risk in such conditions while maximizing efficiency. The newest generation of Crossover is exemplified by two projects in Albania and Turkey.

A 5.56 m Crossover TBM destined for Turkey's Gerede Water Transmission will be assembled using Onsite First Time Assembly (OFTA) from within an existing tunnel. 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.

Skewing further towards hard rock, a unique 6.2 m diameter Double Shield TBM with Crossover features was designed for Albania's Moglicë Headrace Tunnel. The machine features closure doors and a sealing system to contain inrushes of water until they can be grouted off.

This paper will discuss the unique aspects of the Crossover designs and their utilization at the two projects.

INTRODUCTION

Specialized tunnel boring machines have been made for years to tackle specific types of ground conditions. Traditional types of TBMs bore within a specific set of ground conditions. If a project is located in a competent granite face, then a Main Beam machine is a good solution. In soft ground, Earth Pressure Balance (EPB) machines are the method of choice. Years of experience and engineering advancements have made both types of machines fast and economical solutions for tunneling. Unfortunately not all ground conditions are a perfect mix of one material, and the need for a more diverse machine is apparent.

In years past, the industry has developed various types of Dual Mode machines that can handle a mixed variety of materials. The outcome has typically resulted in a compromised design biased towards hard rock or EPB tunneling. This type of design results in a machine that can adequately bore in one type of ground, but advance rates suffer when ground conditions change to less than optimal. To that end, a new iteration of Dual Mode machines, termed Crossover TBMs, has been designed for optimal excavation in a wider range of ground conditions. The most common form of Crossover TBM, termed the XRE, for a Crossover (X) between Rock (R) and EPB (E), is detailed in this paper. These machines can bore in tunnels with sections of both hard rock and soft ground.

GEREDE WATER TRANSMISSION TUNNEL—AN XRE FOR EXTREME CONDITIONS

The Gerede Water Transmission tunnel, located near Ankara, Turkey, has a variety of tough ground conditions to consider (see Figure 1). The 31.6 km project was launched in 2010 using several 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 800 gallons per minute of water and loose material to rush into the TBM. This inflow resulted in enough pressure to crush the 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 design.

The expected 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. 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

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. Instead, this machine has a screw conveyor at the bottom of the chamber. 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 2). 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, planned to be used on all Crossover machines, 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.

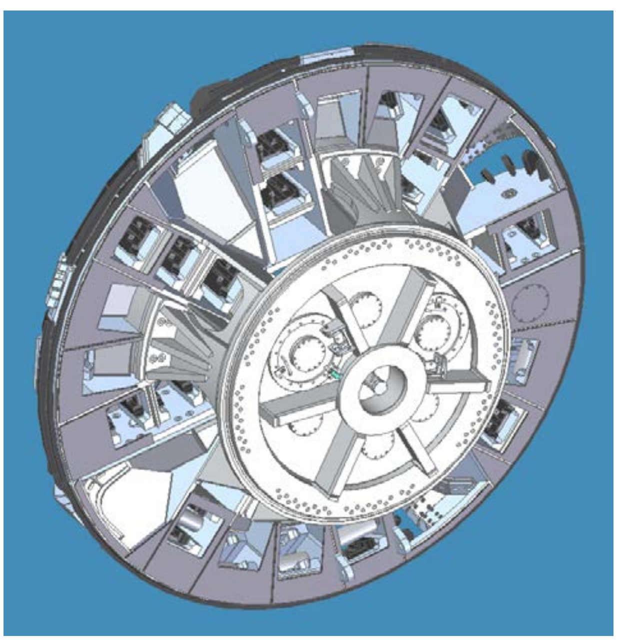


Figure 2. Crossover cutterhead for Gerede

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 3).

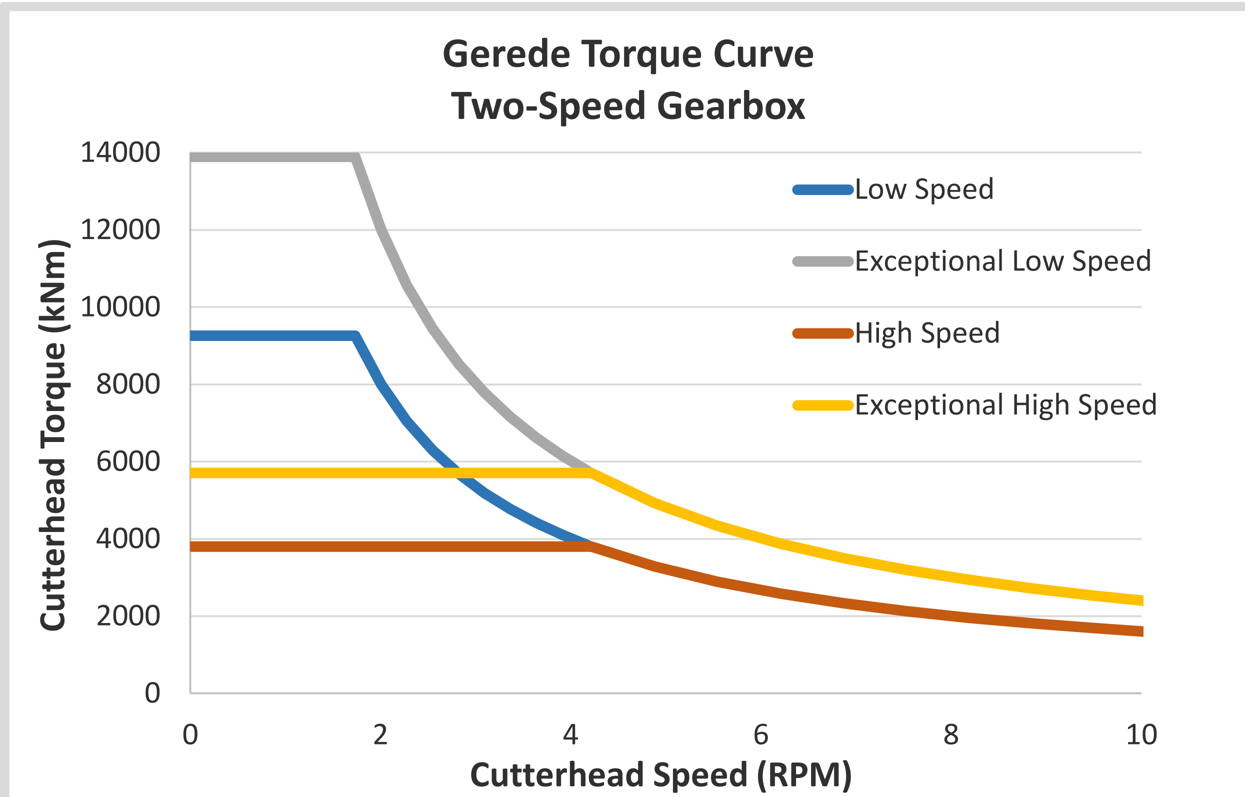


Figure 3. VFD Torque Curve for the Gerede Machine

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 4). 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.

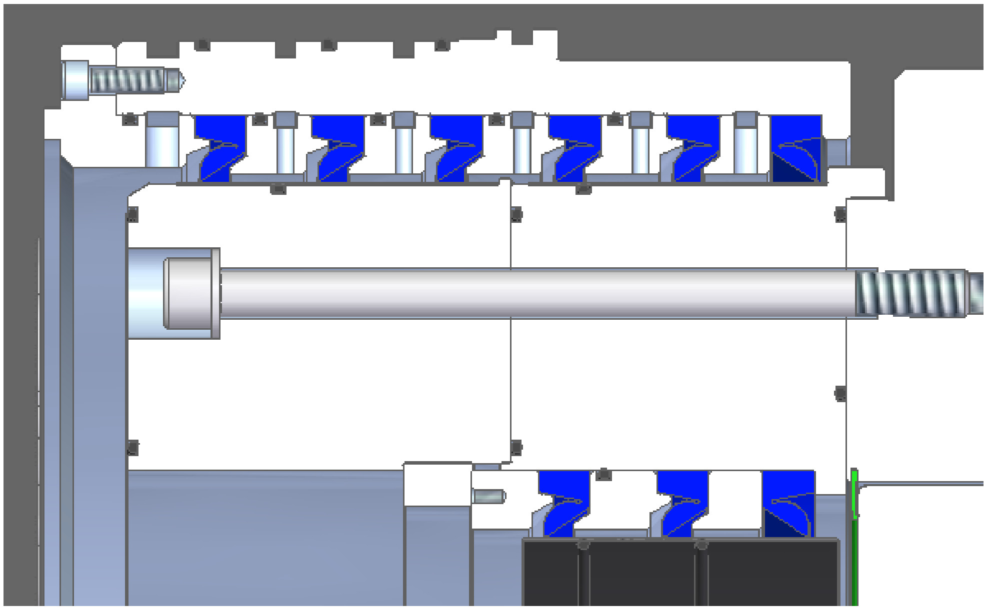


Figure 4. Extensive main bearing seals (dark blue)

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 include for maintenance of the wear plates, while two large, removable outer casings can accommodate the change-out of entire screw sections (see Figure 5).

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.

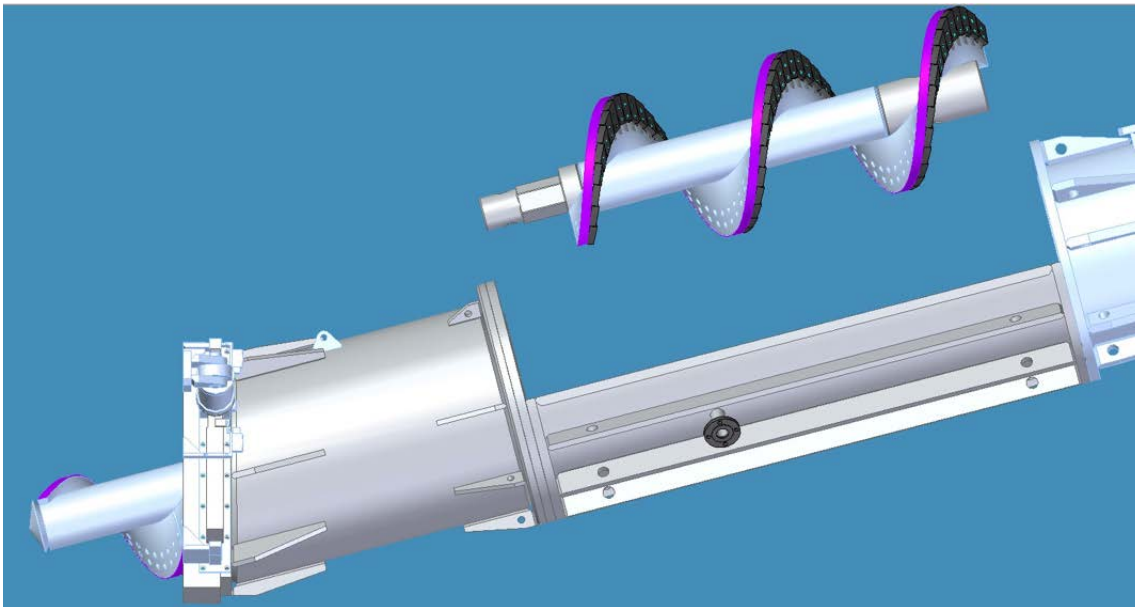


Figure 5. Screw conveyor designed in removable and replaceable sections, with wear plating for use in abrasive ground

Probe Drilling

Due to the unpredictable ground conditions, probe drilling will be 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 6).

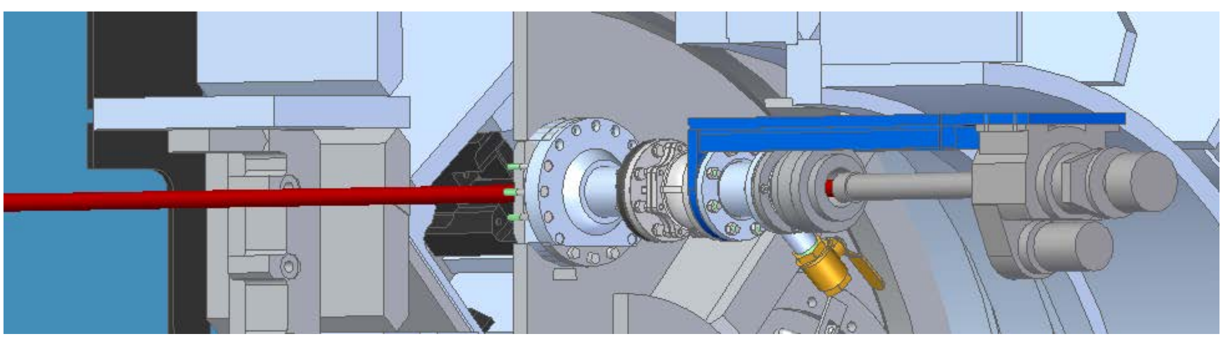


Figure 6. Probe drilling through a port in the machine shield

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 7).

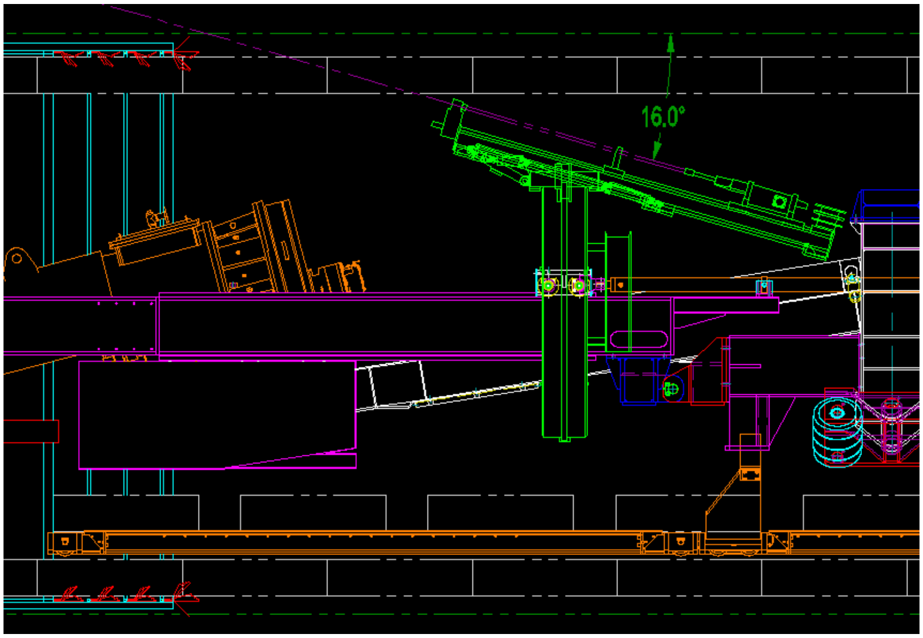


Figure 7. Probe drilling behind the tail shield to control severe water inflows

DEVOLL HEPP, MOGLICE HEADRACE TUNNEL

The Devoll HEPP, located in Albania, is a 6.7 km tunnel in ophiolite, flysch, mélange, and breccia. The tunnel has many of the same geologic problems as the Gerede Water Transmission tunnel. The 6.2 m diameter machine will also be boring through hard rock with several fault zones that could result in variations in ground type and a possible inrush of water. To best bore through this ground a Double Shield-type machine with special Crossover features was selected. The following specifications, listed in Table 2, were taken into account in the design of this machine:

Table 2. Devoll TBM Specifications

	Devoll XRE TBM Specifications	
Design Parameters	Curve radius (vert. and horiz.)	300 m
	Gradient	± 0.5°
	UCS	Average 100 MPa
	Hydrostatic Pressure	20 bar
Segmental lining	Number of segments	5+1 key
	Segment width	1,500 mm
	Segment thickness	250 mm
	Segment Backfill	Single Component Grout
Diameter	Bore Diameter	6.215 m
Cutterhead Style	Cutterhead	hard rock with optional soft ground tools
	Cutters	17” disc cutters, back-loading

Cutterhead Drive	Cutterhead Power	10 x 210 kW = 2,100 kW
	Cutterhead Speed (Low Gear)	0-1.73 rpm (constant torque range) 1.73-4.18 rpm (constant power range)
	Cutterhead Speed (High Gear)	0-4.22 rpm (constant torque range) 4.22-8.19 rpm (constant power range) 8.19-10.18 rpm (reduced power range)
	Breakout Torque	17,370 kNm
	Maximum Thrust	26,068 kN
TBM Conveyor	Belt Conveyor	variable speed, hydraulic drive
Exploration/Ground support	Probe Drill/Grout	11 peripheral ports; 1 drill
Protection	Methane Monitors	4 locations
	Explosion-Proof EPB Sensors	2 locations
Weights and Dimensions	Total length	140 m
	TBM weight	492 tonne

Since this machine may encounter unstable ground and large amounts of water, there are a few features that set the TBM apart from a standard double shield.

Seals

In order to seal off the machine from an inrush of water, measures were taken similar to those for the Gerede machine. The main bearing seals consist of a row of four (4) outer seals and a row of four (4) inner seals (see Figure 8). Between all seal cavities, grease is pumped in to ensure a constant grease cavity pressure is achieved. The stabilizer and gripper shoes are also sealed with a double row of seals and with constant grease cavity pressure in-between. The gripper shoes and inner telescopic shield are sealed with inflatable seals. These are inflated to seal off the gripper shoes and inner telescopic shield areas from the water inrush.

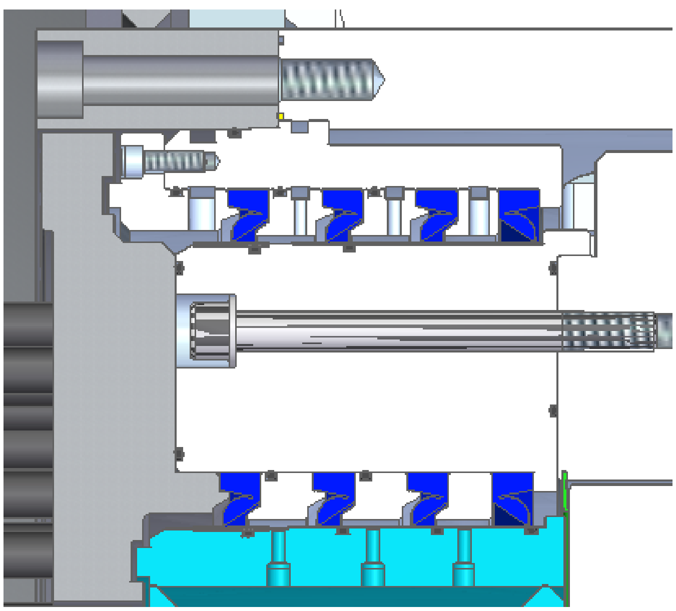
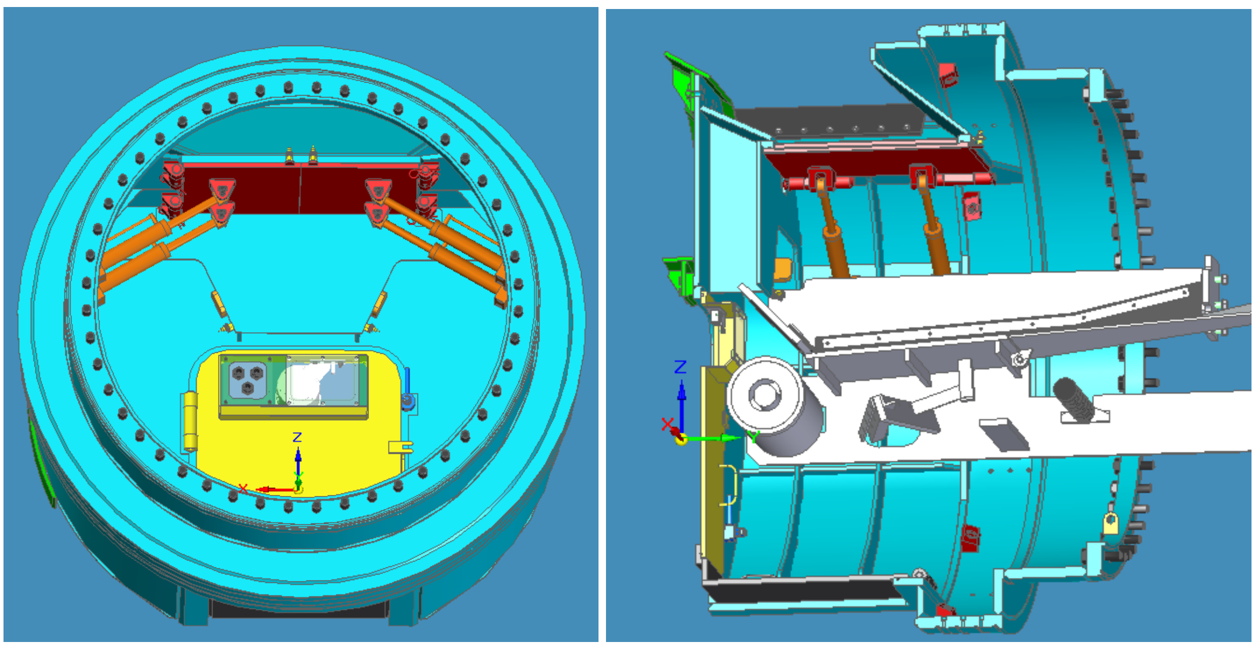


Figure 8. Main bearing seals (dark blue)

Muck Chute

Arguably the most important feature on the Devoll TBM is the muck chute. Since the conveyor is a belt conveyor and is not enclosed like a screw conveyor, it must be sealed off in the event of an inrush of water. The bulkhead has a large sealing gate just above the belt conveyor. These are pressure relieving gates. These gates can also be used in a semi-EPB mode: As the pressure builds in the cutting chamber, the gate is opened by the pressure, and material spills onto the belt. As the pressure is relieved, the gates then automatically close, again sealing off the chamber (see Figures 9-10).

In extreme cases, the gates can be sealed and the probe/grout drills can be used to forward drill and grout for ground consolidation and to seal off the water.



Figures 9-10. Views of the muck chute and pressure relieving gate system.

Main Drives

The Devoll machine will also utilize new two-speed gearboxes similar to the Gerede TBM. The gearboxes allow for ease of shifting between two speeds in differing ground conditions. High rpm/low torque can be used for hard rock and low rpm/high torque can be used for soft and/or blocky ground (see Figure 11).

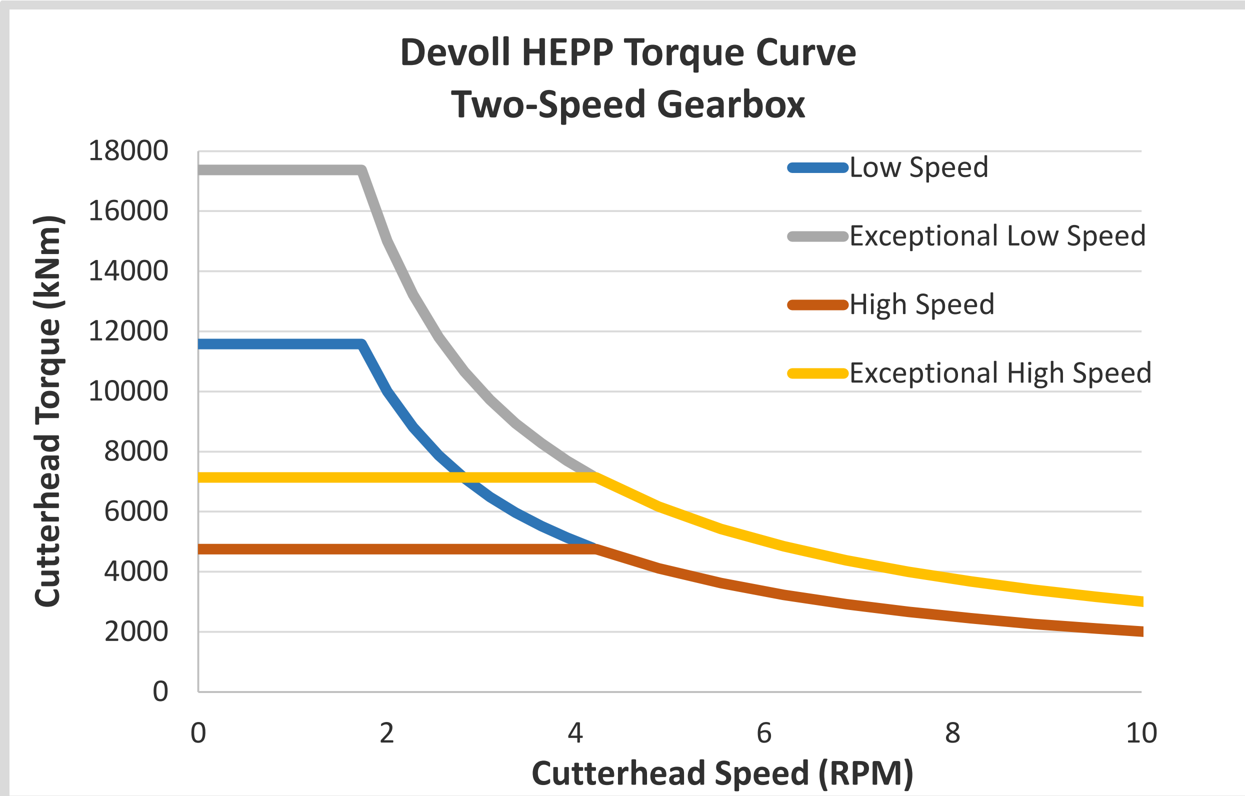


Figure 11. Torque curve for the Devoll TBM

CONCLUSION

Crossover machines are the new way of the future. As more and more tunnels are specified in mixed ground, their use is projected to keep increasing. A multi-functional machine that can fit a variety of circumstances greatly helps in the efficiency of tunnel boring. These two machines are solutions for moving through a dangerous and difficult environment in a safer and more efficient manner. Their designs offer intriguing possibilities for TBM excavation in conditions that can only be described as extremely difficult. While this paper focuses on the design of the machines, the performance of these TBMs will be provided during the conference.