Dual Mode, “Crossover” Type Tunnel Boring Machines: A Unique Solution for Mixed Ground in the Middle East

Tyler D. Sandell
The Robbins Company, USA, sandellt@robbinstbm.com

Jacek Stypulkowski
CDM Smith, Doha, Qatar, stypulkowskijb@cdmsmith.com

ABSTRACT:

While both Hard Rock Tunnel Boring Machines (TBMs) and Earth Pressure Balance (EPB) machines have been in existence for 50 years or more, the prevalence of mixed ground tunnels can make their use problematic. In many tunnels with both sections of hard rock and softer EPB type ground, the only historical solution was to use multiple machines or sacrifice efficiency by using just one machine type. Today, Dual Mode, “Crossover” type machines are edging TBMs into new territory by employing design elements from both EPB and Hard Rock Single Shield Machines. Where multiple machine types might have once been used, a Crossover Rock/EPB machine can excavate an entire tunnel in vastly different conditions. The machine type is particularly useful in fractured and faulted weak rock where clay inseams and sections of soft ground may be present. New designs are making this versatile take on tunnelling more efficient, even at larger diameters of 12 meters or more. This paper will explore modern trends in mixed ground TBM tunnelling, including Crossover EPB/Rock Designs that could be applied to the weak/soft rock so often encountered in Middle East tunnelling. It will also look at other Crossover machines being introduced into the industry, including Crossover EPB/Slurry TBMs for tunnelling in high pressure conditions.

1 INTRODUCTION

As cities and the infrastructure needed to power and run them continue to grow and evolve, so does the demand to excavate increasingly difficult and varied ground. In the broadest of terms, cities are generally built on (or near) rivers or coasts. As such the underground construction industry has become quite expert at excavating the soft clays, sands, gravels and alluvial soils that dominate the places where we build our lives. However, as our cities expand in all directions (especially downwards) including sea reclamation, the landscape above and below the surface changes; therefore, the tools needed to cope with it safely must change too.

For soft ground tunneling in the aforementioned geology, the sophisticated designs of modern Earth Pressure Balance (EPB) TBMs have enabled ever-increasing advance rates. The story of the Earth Pressure Balance machine’s development, however, is a long one. More than 50 years ago, Richard Robbins developed one of the first compressed air, full face tunnelling machines for the Paris RER metro (see Images 1 and 2).

The successful design became the blueprint for future EPB and Slurry shields, which would be further developed by Japanese engineers to rapidly build rail and road tunnels as their cities experienced massive growth during the post-war economic boom that lasted into the 1990s. Before the Japanese economy started to wane, European manufacturers began to develop their own EPB technology and dominate the market as Japanese manufacturers scaled back EPB production and, for the most part, quit pursuing international projects.

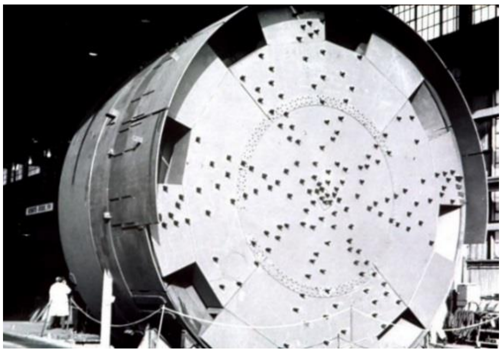


Image 1: Launch of the Robbins Paris RER Metro machine.

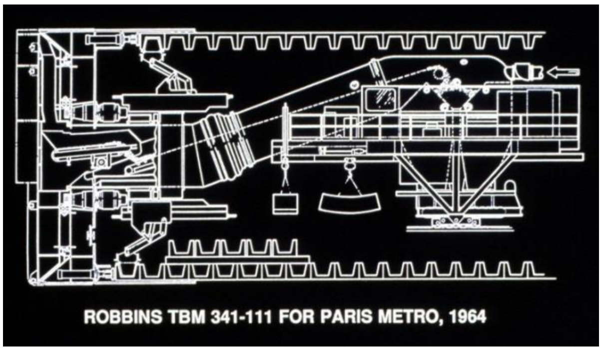


Image 2: Design of the Paris RER Metro TBM.

In most parts of the world, non-pressurized face, hard rock tunneling is generally associated with more rural projects. More than a decade prior to the Paris Metro EPB, James S. Robbins engineered and manufactured the first modern hard rock TBM for the Oahe Dam project in remote South Dakota, USA. By 1956, the rolling disc cutter was born and spurred the growth of hard rock TBM technology. As hard rock TBMs gained acceptance as the fastest and least expensive way to make long tunnels, new projects were now technologically and economically possible.

Unfortunately hard rock TBMs and EPB shields evolved as mostly separate technologies and most of the early efforts to combine them resulted in compromised designs biased toward either hard rock or soft ground. Machines of this nature could perform acceptably in one type of ground, but advance rates suffered dramatically when conditions changed.

Today, a new generation of tunneling equipment has blurred the lines between traditional hard rock and soft ground TBMs. These machines are better able to tackle changing ground conditions and excavate more efficiently in a variety of geologies. These hybrid tunnelling machines “crossed over” boundaries set by traditional TBMs and offer creative engineers around the world new opportunities to grow.

2 CROSSOVER TYPE (DUAL MODE) TBMS

Hybrid or crossover TBMs provide the flexibility to switch from one mode to another based on the ground conditions to be encountered. While a small subset of this category operates primarily in closed mode, the fundamental design feature of most crossover machines is their ability to operate in either open or closed mode. Open mode applies to hard rock or low permeability soils (clay and silt); closed mode applies to high permeability soft ground conditions generally with hydrostatic pressure.

There are many types of crossover TBMs but most fall into one of several categories. The first is a Hard Rock/EPB designed to excavate in open or closed mode, in hard rock or soft ground. This type of machine has a screw conveyor for closed mode operation. Hereinafter we will refer to these machines using the initials XRE.

Another example of a crossover tunneling machine is the Slurry/EPB. This type of TBM has a screw conveyor but is also equipped with a slurry system for operation when it's not possible or cost effective to create a "plug" in the screw. For ease of reference in this paper, we'll call these machines XSE.

Other types of Crossover machines are in development, and would involve hard rock designs with slurry systems, known as XRS (Crossover between Rock and Slurry) machines.

3 CROSSOVER TBM – XRE

The XRE machines are typically proposed for mixed face conditions that include sections of soft ground and hard rock, such that neither a standard hard rock nor EPBM could efficiently excavate the entire tunnel length (see Image 3).

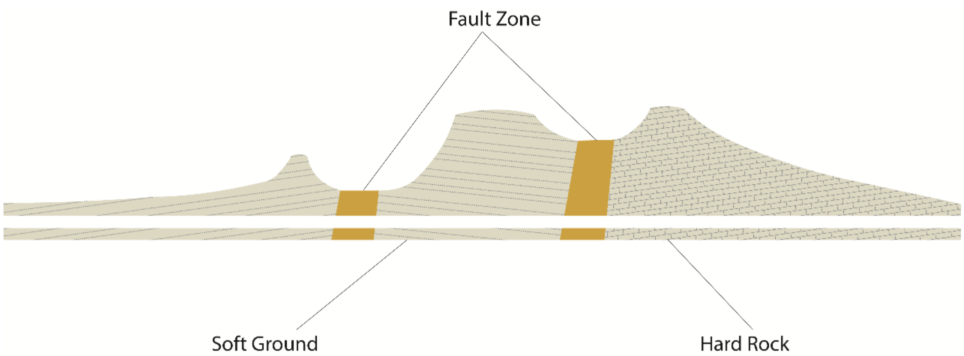


Image 3 Example of Typical Mixed Ground Ideal for XRE TBMs

3.1.1 XRE Muck removal and Control

An XRE will be optimized towards the geology anticipated for the majority of the drive. For example, if the tunnel is 20% soft ground and 80% hard rock, the overall machine design will be optimized towards hard rock. When ground types are not divided into long sections, or when the geology is 50% rock and 50% soft ground, the TBM design becomes more complex. Machines in these conditions might be optimized towards faster conversions between modes. Either way, all machines in this class have a screw conveyor for operation in closed mode. Some machines in this category will also be fitted with a belt conveyor for better open mode performance in hard rock. In larger diameter machines both conveyor types can be installed concurrently; in smaller sizes the conveyors usually need to be exchanged. This conversion process of course requires some amount of downtime but it can be justified if there are long stretches of a particular geology that are more suited to that mode (see Images 4 and 5).

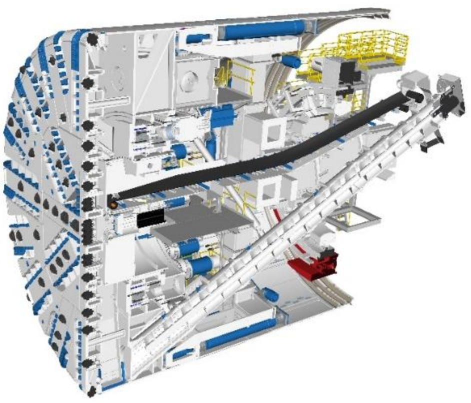


Image 4: 13.77m XRE - Hard Rock Mode

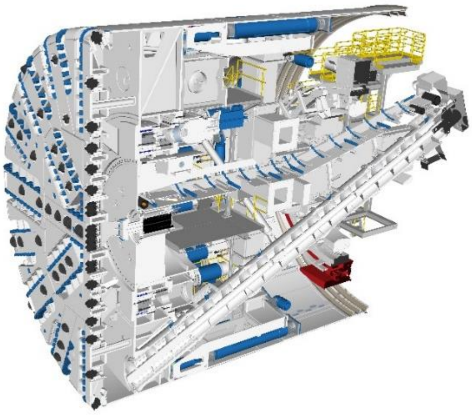
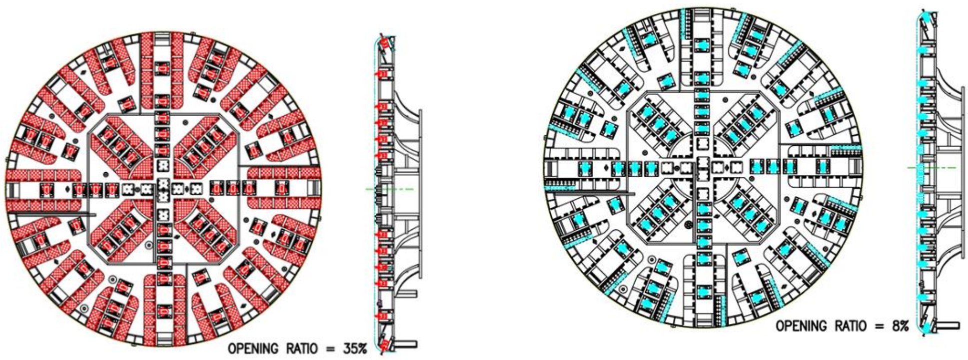


Image 5: 13.77m XRE - Soft Ground Mode

3.1.2 XRE Cutterhead

Regardless of the way muck is handled, cutterhead design is key to a successful TBM project. XREs generally have mixed ground cutterheads with the ability to install a full dress of either disc cutters, soft ground tools or a combination thereof (see Image 6). Another feature that can greatly improve performance is the use of a variable speed cutterhead drive in concert with multi-speed gearboxes that can provide high torque at slow speeds for soft ground, as well as high RPM for better performance in hard rock. If there are long stretches of hard rock great gains in efficiency can be made by utilizing a cutterhead that can be converted to/from bidirectional to single direction mucking. The conversion would generally be done while the belt conveyor is being installed in lieu of the screw. The Sleemanabad Carrier Tunnel in India and the Grosvenor Coal Mine Decline in Australia are both good examples of Hybrid TBM projects with significant hard rock stretches.



Bidirectional (Soft Ground) Single Direction (Hard Rock)

Image 6: Convertible Cutterhead for Hard Rock or Soft Ground

3.1.3 XRE Case Study – Grosvenor Coal Mine Decline

The unique XRE TBM used in Anglo American's Grosvenor coal decline was designed to bore in conditions including sand, sandy clay, clay and conglomerate, as well as mixed face/rock portions consisting of siltstone, coal, sandstone and basalt with little groundwater expected. Rock hardness was determined to range from 20 to 120 MPa with an average of 90 MPa UCS in hard rock. Methane gas was considered a risk throughout both 1,000 m long decline tunnel drives. To tackle the challenges, the XRE machine was optimized towards hard rock (Single Shield) excavation, as much of the mixed ground was determined to be rock (see Image 7).

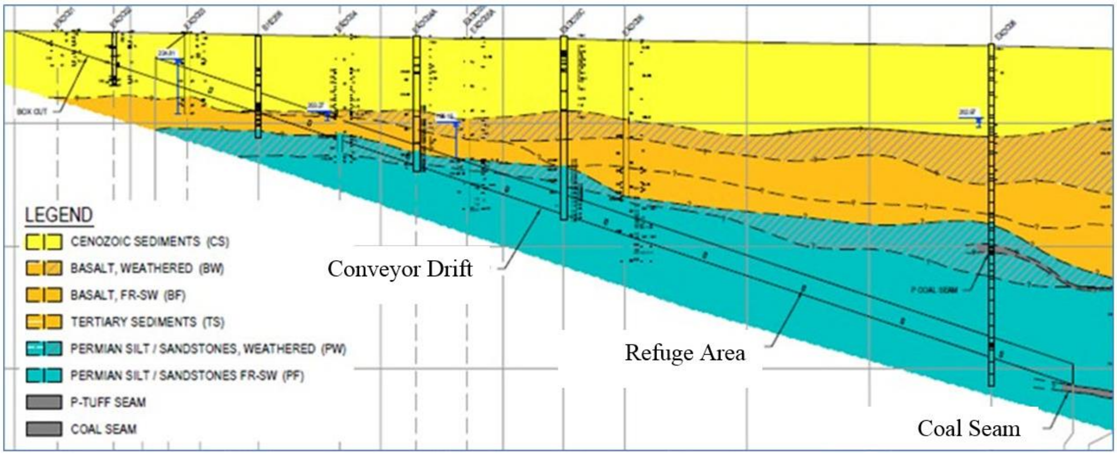


Image 7: Grosvenor Coal Decline – Geotechnical Long Section

A two-stage, center mounted screw conveyor worked for both hard and mixed ground conditions, and the adaptable cutterhead could be outfitted with back-loading cutters in hard rock mode, or with knife bits and scrapers in EPB mode (see Image 7, Table 1, and placement of screw conveyor and cutterhead setup in Image 8). Another unique design feature of this particular XRE was based on the requirement to swiftly build two blind tunnels while maintaining full ground support (a regulation in Australia). Thus, the machine was engineered for quick assembly and disassembly within the 7 m i.d. tunnels so that it could be re-launched on a second tunnel. The XRE TBM was picked over the traditionally-used roadheader method for several reasons, including excavation speed and tunnel maintenance. The choice proved prescient with the machine excavating at a rate approximately ten to fourteen times faster than a roadheader—about 70 m per week for the TBM vs. 5 m per week for a road header. A prime example of crossover technology creating new opportunities for TBMs, this was the first time a TBM had been used in an Australian coal mine. It completed its second tunnel in February 2015.

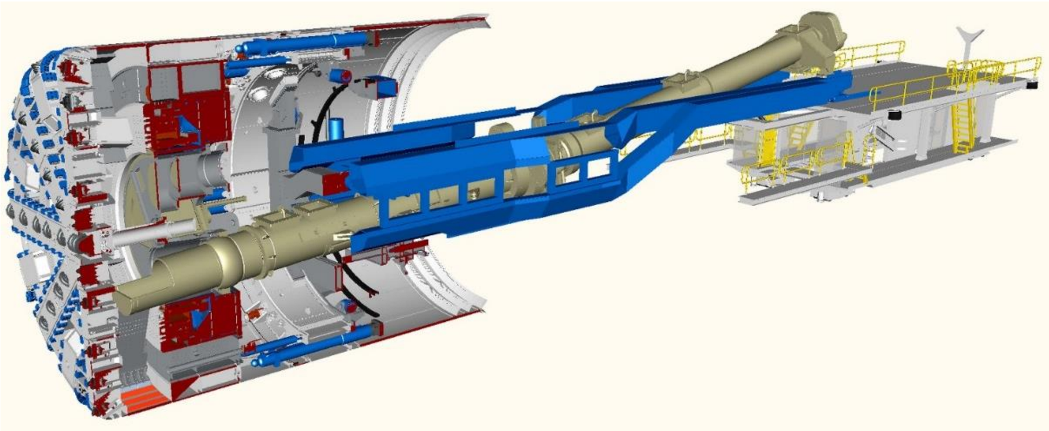


Image 7: Cutaway of Grosvenor Coal Decline XRE

Table 1: Grosvenor XRE Specifications

	Grosvenor XRE TBM Specifications	
Design Parameters	Curve radius (vert. and horiz.)	400 m
	Gradient	1:6 and 1:8
	UCS	Average 90 MPa
	Hydrostatic Pressure	3 bar
Segmental lining	Number of segments	5+1 key +1 flat invert
	Segment width	1,400 mm
	Segment thickness	350 mm
	Segment Backfill	Bi-component grout
Diameter	Bore Diameter	8.0 m
Cutterhead Style	Cutterhead	Mixed ground, convertible
	Cutters	17” disc cutters, back-loading
Cutterhead Drive	Cutterhead Power	12 x 330 kW = 3,960 kW
	Cutterhead Speed	0-6.4 RPM
	Breakout Torque	17,344 kNm
	Maximum Thrust	22,619 kN
TBM Conveyor	Screw Conveyor Type	Double, shafted, hydraulic drive
Exploration / Ground support	Probe Drill/Grout	18 peripheral ports; 1 drill
Protection	Methane Monitors	6 locations
	Explosion-Proof EPB Sensors	10 locations
Weights and Dimensions	Total length	135 m
	TBM weight	994 tonne
	TBM core weight	399 tonne
	Back-up system weight	552 tonne

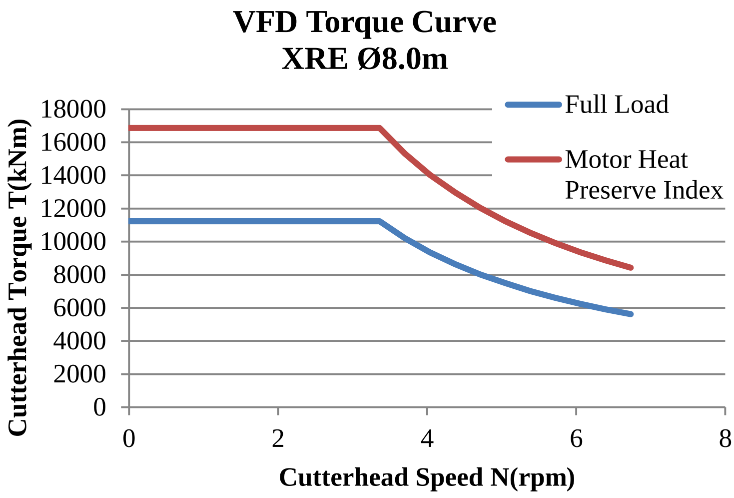


Image 8: Grosvenor XRE Torque Curve

3.1.4 XRE Case Study – Sleemanabad Carrier Tunnel

The Sleemanabad Carrier Canal, located in Madhya Pradesh, India, is part of the Bargi Diversion Project, which consists of almost 200 km of canal networks. The subsurface section is a 12 km long, 9.2m internal diameter segmental lined tunnel. The geology consists of mixed conditions ranging from fresh marble - dolomite limestone to sand and soils with approximately 50% rock and 50% sand/soil. The UCS of the rock is up to 180 MPa.

The challenging conditions of this project play to the advantages of an XRE's ability to bore efficiently in open or closed mode and in hard rock. This machine can operate as a traditional EPB or single shield hard rock TBM. When boring through soils the machine is operated in closed (pressurized) EPB mode using a screw conveyor. When short sections of rock are encountered the machine can be operated in open (non-pressurized) EPB mode. However, in long sections of rock the screw conveyor can be removed and replaced with a traditional hard rock TBM belt conveyor.

The configuration of the cutterhead can be optimized in a number of ways to suit the ground conditions. In the sand and soil section a full dress of soft ground tools can be installed. In the mixed ground sections it can be fitted with a combination of soft ground tools and disc cutters. The biggest efficiency gains come when the cutterhead is configured for hard rock with a full complement of 20-inch Heavy Duty (HD) disc cutters and it is converted from bidirectional to single direction mucking (see Table 2). The machine is also capable of excavating with high torque at low RPM to get through difficult ground (see Image 9).

Table 2: Sleemanabad XRE Specifications

General TBM Specifications		
Excavation Diameter	With Disc Cutters	10,000 mm
	With Soft Ground Tools	9,980 mm
Cutterhead	Type	Bidirectional, Mixed Face
	Opening Ratio	25%
	Cutterhead Drive	Electric motors with VFD
	Cutterhead Power	3960 kW (12 X 330 kW)
	Cutterhead Speed	0 ~ 5.4 rpm
Torque	Cutterhead Working Torque	17,615 kNm
	Maximum Starting Torque	21,700 kNm
Thrust	Trust Jack Stroke	2,302.4 mm
	Maximum Thrust	23731 kN
Electrical	Primary Voltage	33,000 V, 50 Hz
	Protection	IP55
Conveyors	Screw Conveyor Diameter	1200 mm
	Screw Conveyor Type	Shaft style with replaceable wear protection
	Speed	1.0 ~ 18 rpm
	Torque	300 kNm
	Back-Up Conveyor Belt Width	1372 mm
Weights	TBM Weight (Approx.)	1,250 tonnes
	Back-Up Weight (Approx.)	490 tonnes

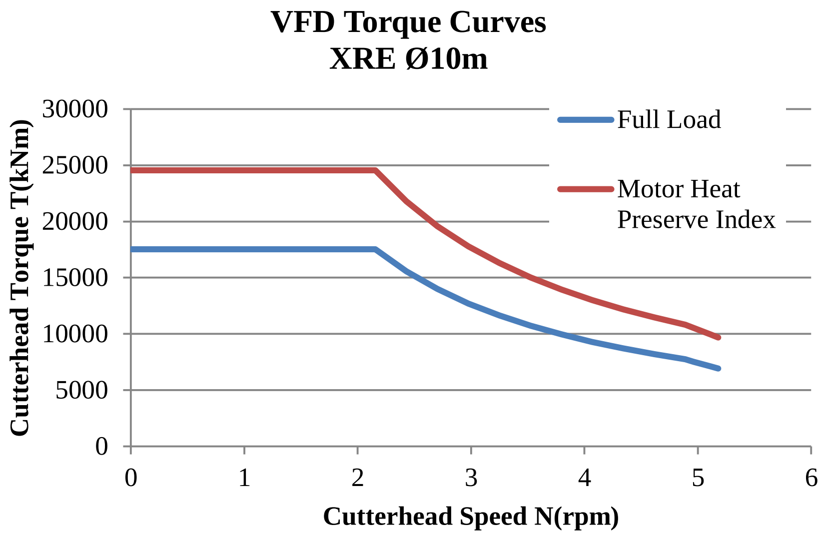


Image 9: Sleemanabad XRE Torque Curve

4 CROSSOVER TBM – XSE

The second type of crossover we will discuss is the hybrid EPB/Slurry or XSE. These TBMs almost always operate in closed mode and can cope with a wide variety of high and low permeability soils, sands, clays, gravels and rock. They are especially useful in urban environments and other places where settlement must be controlled. They have the capability to successfully excavate difficult mixed ground by accurately controlling high or low hydrostatic pressures. This minimizes risks of blowouts from high face pressure or surface subsidence due to face pressure loss.

4.1.1 XSE Muck removal and Control

In low permeability soils without high hydrostatic pressures, the XSE can advance quickly and efficiently in EPB mode without the expense and complication of slurry-based muck handling. In high permeability soils and areas with high hydrostatic pressures, the XRE can run in slurry mode thereby eliminating the problems of inaccurate volume monitoring and pressure control that EPBs can encounter in these conditions. A key benefit of the ability to run in EPB mode is that the slurry treatment plant (STP) can be simplified and more economical since it doesn't need to process soils in EPB conditions (see Image 10).

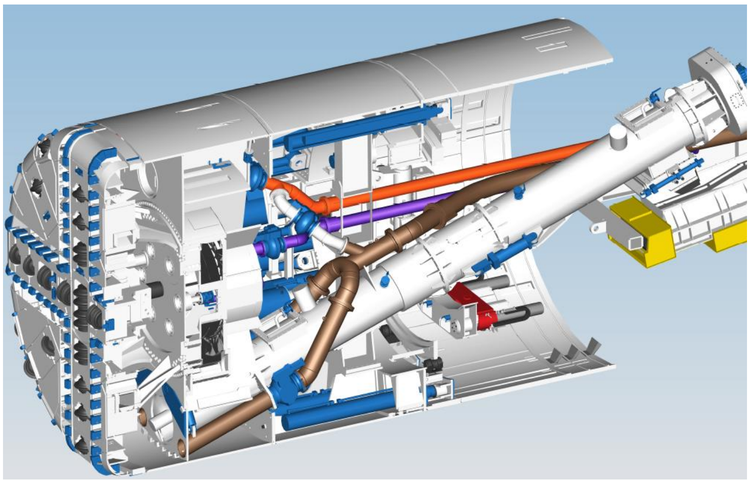


Image 10: XSE Baku Metro Cutaway

4.1.2 XSE Cutterhead

The XSE is usually equipped with a standard bidirectional EPB-type mixed ground cutterhead with the ability to install disc cutters and/or soft ground tools for maximum versatility. Large openings allow significant cobbles and boulders into the mixing chamber. In EPB mode boulders that can fit through the cutterhead openings are passed through the screw conveyor. In slurry mode, boulders not capable of passing through the slurry pipes are broken up using a crushing mechanism. This can be either a jaw type crusher in the mixing chamber and/or a rotary style crusher mounted on the free-air side of the bulkhead.

4.1.3 XSE Case Study - Baku Metro

Contractor Evrascon Joint Stock Company has chosen a crossover machine to tackle the difficult ground conditions they will encounter while excavating an extension of the metro system in Azerbaijan's capital city, Baku. A new 6.26 m diameter XSE TBM will excavate through 5.7 km of mixed ground including silt, clay, sandstone, and limestone with hydrostatic pressures up to 5 bar. This crossover TBM will break through and cross into three stations along the alignment. The new tunnel is part of a metro expansion which will connect older lines built during the Soviet era (see Table 3). Similar to other Crossover machines, the XSE is also capable of excavating at high torque and low RPM (see Image 11).

Table 3: Baku Meto XSE Specifications

General TBM Specifications		
Excavation Diameter	With Disc Cutters	6,260 mm
	With Soft Ground Tools	6,260 mm
Cutterhead	Type	Bidirectional, Hybrid Slurry/EPB
	Opening Ratio EPB Mode	33%
	Opening Ratio Slurry Mode	23%
	Cutterhead Drive	Electric motors with VFD
	Cutterhead Power	8000 kW (5 X 160 kW)
	Cutterhead Speed	0 ~ 13.5 rpm
Torque	Cutterhead Working Torque	5,830 kNm
	Maximum Starting Torque	8,162 kNm
Thrust	Trust Jack Stroke	1,450 mm
	Maximum Thrust	9,806 kN
Electrical	Primary Voltage	11,000 V, 50 Hz
	Protection	IP55
Conveyors	Screw Conveyor Diameter	900 mm
	Screw Conveyor Type	Shaft style with replaceable wear protection
	Speed	0 ~ 25 rpm
	Torque	100 kNm
	Back-Up Conveyor Belt Width	914 mm
Slurry System	Feed Pipe Diameter	200mm TBM, 250mm Tunnel
	Return Pipe Diameter	300mm TBM, 200mm Tunnel
	Rated Throughput	450m^3/hr
	Crusher Type	Rotary
	Max Face Pressure	6 bar
Weights	TBM Weight (Approx.)	382 tonnes
	Back-Up Weight (Approx.)	480 tonnes

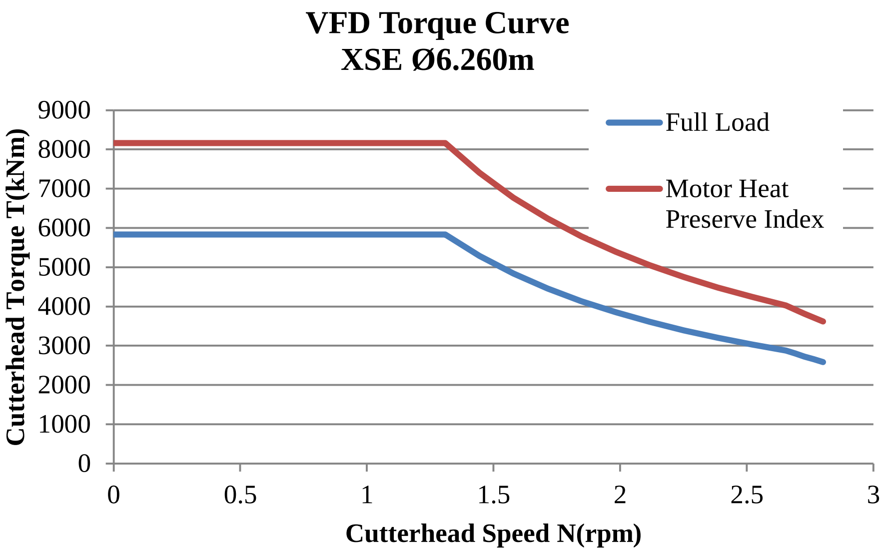


Image 11: Baku Metro XSE Torque Curve

5 APPLICABILITY OF CROSSOVER TECHNOLOGY TO MIDDLE EASTERN CONDITIONS

Hybrid TBM technology is certainly applicable and will find its way into the Gulf Region. Geologically, the Middle East is a part of the Arabian Gulf Basin. It forms a part of the Arabian shelf between the Arabian shield and Iranian mobile belt. Basement rocks in the area under consideration are overlain by differently aged sandstones, salts, limestones and shales. For example, cemented sand Sabkha deposits in Dubai have been is often interbedded with cemented as well as uncemented sands. Many of the areas are karstic with carbonate-based rocks susceptible of dissolution. Uniaxial Compressive Strength Test Results as reported previously in Stypulkowski, 2015 varies between 0.04 and 65.3 MPa. Brittleness (UCS/BTS) varies between 5.3 and 20.1. Shear wave velocity and associated elastic modulus measurements vary between 292 and 9667 MPa. The point load strength index, $I_S(50)$ varies between .02 and 4.91 MPa. The slake-durability test results vary between 37 and 98. Cerchar Abrasiveness Index (CAI) values vary between .01 and 0.7. According to the “Recommendations for selecting TBMs”, revised in October 2010 (in German) for the set of parameters listed above, it is clear that Crossover-type TBMs would satisfy a wider range of ground conditions than single-type machines. If tunneling risks are not acceptable, the EPB, with its much faster advance in good ground conditions, can be combined with slurry shields. The EPB/Slurry (XSE) would have finer control of the face and the ability to maintain higher ground pressures, particularly under mixed face conditions or when tunneling through weak rock.

6 CONCLUSION – THE FUTURE OF THE CROSSOVER DESIGN

TBMs that can cross over between modes will continue to gain popularity as the world's cities grow outward and downward. Crossover machine design is becoming more innovative with increasing demand, and includes a Rock/Slurry design (XRS TBM) currently in development that would optimally bore in permeable ground under water pressure as well as rock. Further refinements and innovations can be expected for all types of Crossover machine.

The subsurface landscape is getting very congested in many places so we are forced to tunnel under existing infrastructure. Of course as we dig deeper, we cross over from the surficial soils into hard rock. Since it's not always possible to keep the alignment in hard rock as we navigate to the next subway station, sanitary sewer, drinking water reservoir or highway interchange, we will be forced to switch between modes more often. The future is bright for Crossover TBMs because of these factors. Due to their ability to excavate in a wide variety of difficult conditions, contractors and project owners will be seeing the light at the end of the tunnel a lot sooner than previously possible. The versatility of these machines makes them ideal for the weak rock and mixed face conditions often found in Middle East tunneling.

REFERENCES

Harada et. al. (2015). The Evolution of Tunnel Boring Machine Requirements over the Course of a Project.
Proceedings of NASTT No Dig Conference, Boulder, Colorado, USA.

Grothen & Clark (2012). Hybrid TBM Design and Selection. Proceedings of the ITA-AITES World Tunnel
Congress, Bangkok, Thailand.

Scherwey (2011). The History of Earth Pressure Balance TBMs. Proceedings of ITA SEE, Dubrovnik, Croatia.

Jordan (2013). The Next Generation of Large Diameter, Mixed Ground Tunnel Boring Machines. Proceedings of the ITA-AITES World Tunnel Congress, Geneva, Switzerland.

Scialpi (2015). Unique Hybrid EPB Design for use in Coal Mine Drifts.
Proceedings of the ITA-AITES World Tunnel Congress, Dubrovnik, Croatia.

Stypulkowski, J.B., Bernardeau, F.G., Sandell, T.D., "Mechanized tunneling technologies for weak rocks of Middle East/Persian Gulf", in ATC2014 Arabian Tunnelling Conference and Exhibition, 9-10th December 2014, Abu Dhabi, UAE, pp 187-199

Recommendations for selecting Tunnel Boring Machines (German only), revised version as of October 2010 (Taschenbuch Tunnelbau 2011)