The Next Generation of Mixed Ground Tunnel Boring Machines

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ABSTRACT:

What is the most economical way of tunneling in mixed ground that may experience high pressures? Non-continuously pressurized, mixed ground Tunnel Boring Machines (TBMs) are being utilized to deal with a wide range of geology. Continuous improvements in these mixed ground machines allow for ever-increasing efficiency and reduction of project risk due to unexpected conditions. We will explore the performance of recent mixed ground machines throughout the world and then look at how new improvements to mixed ground machines will enable excavation of an expanded range of ground conditions. These conditions include mixed ground with low fines, mixed face rock, and fracture / fault zones with high pressures where in the past a Slurry TBM may have been utilized.

EXISTING MIXED GROUND MACHINE FEATURES AND PERFORMANCE

Mixed ground Rock-EPB TBMs are capable of operating in EPB mode, both pressurized and non-pressurized, as well as in Shielded hard rock mode. The key features of these machines, known as Crossover XRE TBMs, include mixed ground cutterheads, robust screw conveyors, a belt conveyor for hard rock, and cutterhead drives that are capable of handling both hard rock and soft ground conditions. Mode conversion between hard rock and EPB modes typically takes up to two weeks' time in the tunnel, as modifications are done to the muck discharge facilities, cutterhead, and any other critical structures.

In practice, many contractors utilizing hybrid machines avoid mode changes because of the downtime associated with it. In these cases, the machine selection is done as a project risk mitigation tool, though even if the machine does not end up changing modes of operation some of the features associated with a crossover may be utilized. This type of TBM is a substantial investment, and if not used properly in the ground type each mode was designed for, advance rates will be less than desired. The requirement for smooth and efficient mode changes is thus essential for these Dual Mode designs, leading to the next generation of mixed ground machines: those that compromise no features in hard rock or soft ground, and allow for ease of mode changes in the tunnel. The setup detailed below was designed for TBMs in the 12 to 15 m diameter range, and for tunnels in nearly equal lengths of hard rock and mixed face ground.

LARGE DIAMETER DUAL MODE SETUP AT THE ESME-SALIHLI RAILWAY

A dual mode design has been created, in which no design elements have been sacrificed in the engineering of this machine: It is capable of operating in 100% EPB mode or 100% Hard Rock Single Shield Mode. The TBM has been designed for sections of hard rock and mixed ground, in highly variable conditions including sandstone, mudstone, claystone, quartzite, schist, and mixed soil with clay.

In EPB Mode. In EPB mode, the screw conveyor operates as in any typical EPB machine. The screw features a replaceable inner liner and replaceable carbide wear bits for abrasion protection. A mixed ground cutterhead is fitted with knife bits that can be switched out with disc cutters in harder conditions. Much of the cutterhead is covered in Trimay wear plate for additional abrasion protection. A wear detection pipe on the cutterhead monitors any wear occurring to the cutterhead structure itself, while wear detection bits on the cutterhead and periphery tell the operator about tool wear, and if a gauge cutter has been lost. The machine design includes a man lock for cutterhead inspection and changes and mixing bars inside the mixing chamber (see Figures 1 and 2).

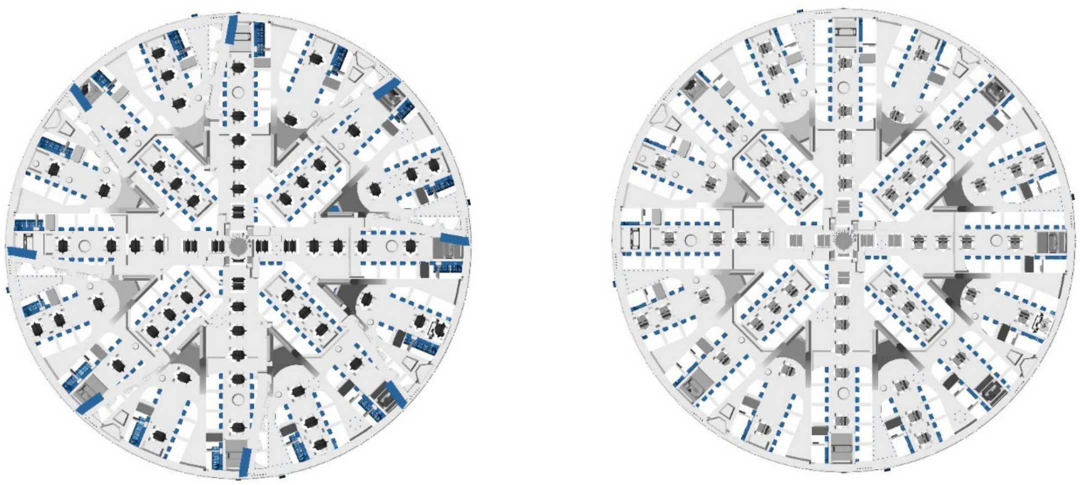

Figure 1. Left Cutterhead in Rock Configuration; Right Cutterhead in EPB Configuration

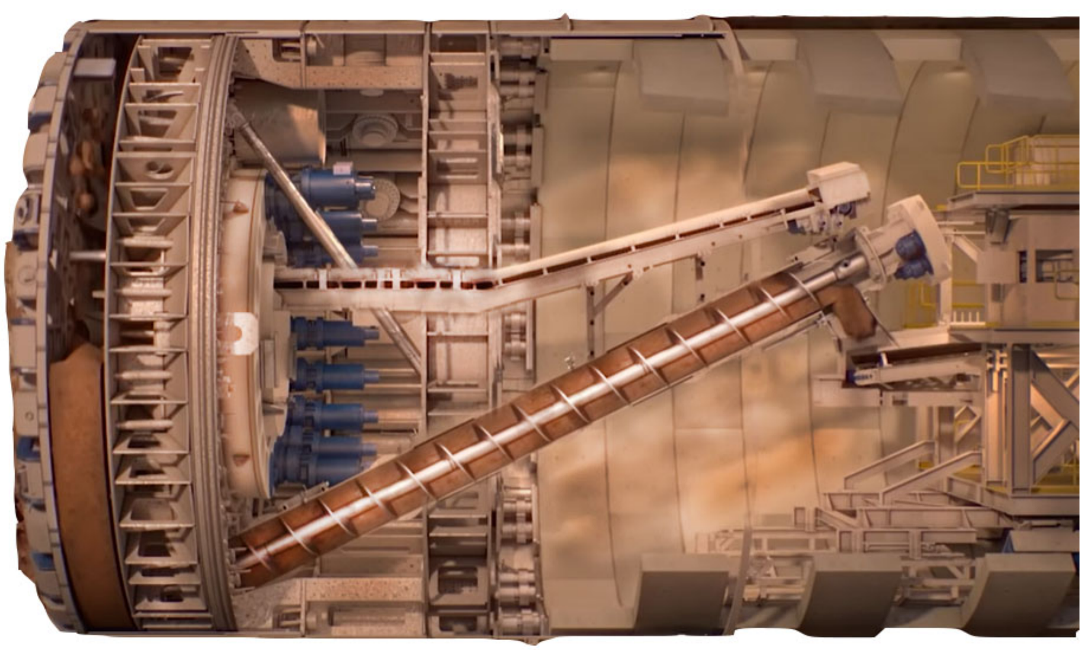

Figure 2. The Crossover TBM in Rock Mode. Belt conveyor and screw both installed

In hard rock mode. To convert to hard rock mode, the mixing bars and the first flights of the screw conveyor are hydraulically retracted from the mixing chamber. If EPB knife bits are installed these are exchanged with disc cutters on the cutterhead and the EPB scrapers on the cutterhead need to be replaced with hard rock bucket lips. Muck paddles are installed on the backside of the cutterhead to allow the muck to be scooped into the invert, lifted and deposited in the central conveyor muck chute. The conveyors muck loading chute is attached to the central bulkhead which is hydraulically extended into the mixing chamber. Once the chips are deposited in the muck chute, they are transported with the machine conveyor and discharged through the screw conveyor onto the backup belt conveyor (see Figures 3 and 4).

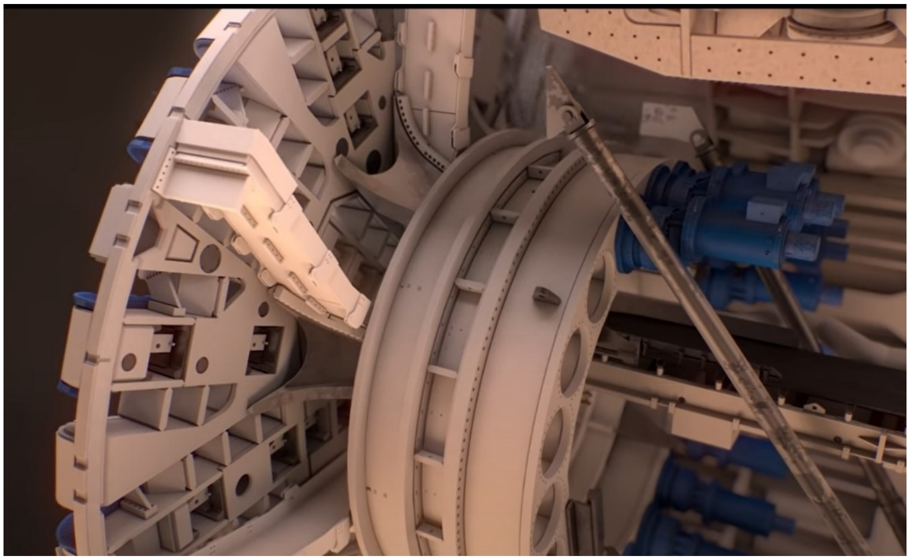

Figure 3. Cutterhead loading plates

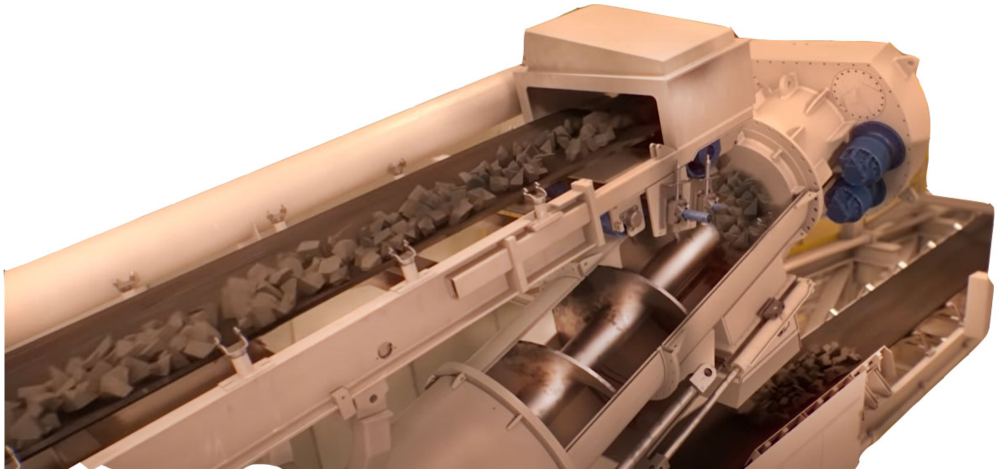

Figure 4. The belt conveyor passes through the screw conveyor to deposit muck onto the TBM belt conveyor

A skew ring offsets the torque of the machine in hard rock, allowing for more efficient single direction muck pickup. Mini grippers on the rear shield allow the machine to bore 400 to 600 mm forward, then be retracted for cutter changes.

To keep the production rate high, a two-speed gearbox with a ratio of 2:1 is hydraulically actuated to get the proper RPM for the hard rock mode. The two-speed gearbox is bypassed in EPB mode to get the proper RPM for the EPB mode.

Overall, this design is optimized for equal parts hard rock and soft ground. By contrast, if a tunnel is located in mostly hard rock or mostly soft ground, the Dual Mode machine can be customized accordingly.

Record-Setting Jobsite Performance. The 13.77 m Crossover XRE machine launched on its 3.05 km (1.90 mi) bore at the end of March 2021 as part of the Ankara-İzmir High Speed Railway Project for the Turkish State Railways (TCDD) (see Figure 5). The machine encountered a mix of mainly mudstone with gneiss. During its bore, the machine set new world records three times over for best day, week, and month in the 13 to 14 m (42.6 to 46 ft) diameter range, and finally, for all TBMs over 13 m in diameter. Its fastest rates were set in July and August 2021, with a best day of 32.4 m, best week of 178.2 m and best month of 721.8 m. While some of the crossover features proved beneficial the TBM was able to stay utilize the screw conveyor for mucking for the complete tunnel drive which was a further benefit for the projects overall schedule. The machine's final breakthrough occurred in October 2021.

Figure 5. Ankara-izmir HSR Crossover XRE TBM

LARGE DIAMETER CROSSOVER TBM DESIGN ON THE PEARL RIVER DELTA

The TBMs designed and built for the 17.6 km long Pazhou branch line of Guangzhou Dongguan Shenzhen urban rail transit in China are another good example of how these hybrid machines can be configured to efficiently excavate a project's expected geology and minimize risk.

The strata that the TBMs pass through are mainly moderately weathered migmatite, strongly weathered argillaceous sandstone, strongly weathered and moderately weathered adamellite. Due to low cover conditions, it was important that the machines have the ability to form a pressure plug in the screw. As a result, the machine has been configured as a mixed ground EPB machine, including a bottom screw and high opening ratio cutterhead for the beginning of the drive (see Figure 6).

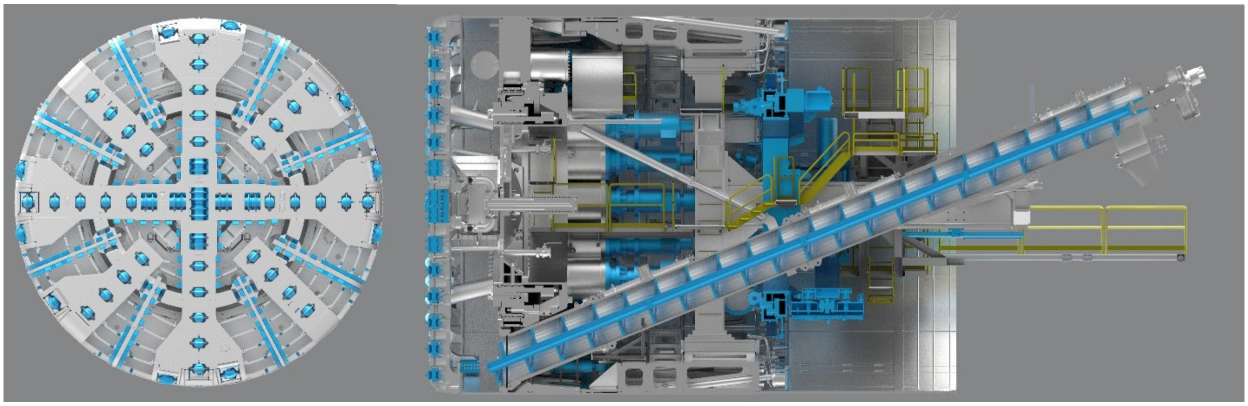

Figure 6. EPB Configuration of the Pearl River Delta TBM

As the machine moves deeper into the bedrock it will be converted to hard rock mode to increase efficiency and minimize wear. Hard rock mode utilizes a rock style cutterhead, which keeps a clean invert by constantly scooping the material and depositing it in a center conveyor. This is an important consideration due to the length and abrasive nature of the drive. Unlike some projects the geology is well known with a pre-determined changeover point planned after 1.5 km in EPB mode. The contractor wanted a higher degree of modification for more efficient rock excavation as well as the ability to use the machine for future projects. The differences between these modes can be seen between Figures 6 and 7.

While the geology to be excavated for the majority of the drive is rock, the high degree of weathering and depth create a potential risk for high pressure water and mud inrushes. For this reason, a center screw configuration was selected instead of changing over to a belt conveyor. The central location of the screw is key for reducing the cutterhead wear while its low angle and heavy wear protection allow it to negotiate the long rock sections. This is an approach that has been successfully utilized on other Crossover machines intended to excavate long sections of rock. Like other Crossover machines this one is equipped with features like two speed gearboxes on the main drive to further support rock excavation.

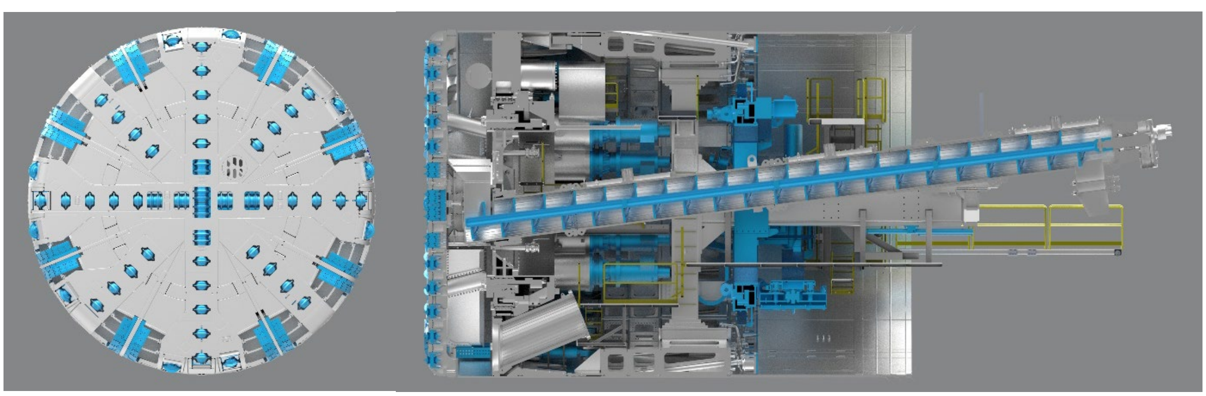

Figure7. Rock Configuration of the Pearl River Delta TBM

While these advanced Crossover TBM features have proven highly successful and flexible, as seen with the completed Esme and ongoing Pearl River Delta projects, there are many opportunities to extend mixed ground TBMs even further into ground conditions where TBMs have historically struggled.

ADVANCEMENTS IN MIXED GROUND MACHINES

As has been demonstrated, Crossover TBMs have been shown to successfully operate in a wide range of geology. Fortunately, on most projects the TBMs do not end up needing to completely change modes of excavation. The value in these types of machines is in risk reduction , ensuring that even when unexpected conditions are encountered, the machine will be able to successfully excavate. Even when the machine is not changed over it is very common to find that certain aspects or features on the Crossover machines are effectively utilized to excavate variable ground.

Pure EPB Design

One ground condition that has been particularly difficult historically for pure EPBs is rock or mixed face conditions with the presence of high pressure. Earth Pressure Balance technology is traditionally limited to about 5 bar, primarily due to the risk of pressure loss within the screw or a blow-out. This pressure limitation can be increased to about 7 bar with the introduction of a second screw conveyor, which increases the number of flights to hold pressure and gives the possibility to run the screws at different speeds to create a plug. The ability for the screw to hold pressure is further limited in rock geology due to the limited number of fines present—a key component. This lack of fines can be overcome with the use of modern chemicals, though economics limit the degree to which this can be applied.

Rock-Slurry Machines

Rock-Slurry machines, also known as Crossover XRS TBMs, are a good way of addressing rock or mixed face conditions with low fines. The XRS design allows for efficient open rock excavation when there is no pressure and the ability to use a slurry system designed to operate with rock when there is a need to hold pressure. The primary downside to this machine type is economic. To efficiently run in rock conditions, a full-sized belt conveyor system is required to transport the rock out of the tunnel, which can be a significant cost. To operate in slurry mode, a slurry system also needs to be installed, including the transportation and separation system. There are variations available that can bring down the cost slightly, like running with a smaller slurry transport system and separation plant, though even at the smaller sizes they represent significant investment. It is not recommended to run with only a slurry transport system, as many of the negative aspects of running a slurry machine in rock come into play, like increased cost, maintenance, and the size of the system—in particular the slurry system size invariably limits the much higher advance rates that could be achieved with a machine in rock mode using a belt conveyor.

Rock-EPB Machines

Rock-EPB machines, known as Crossover XRE TBMs, have been designed to keep boring under pressure in rock by implementing a center-mounted screw conveyor and sequential operation, which does not require fines or conditioning of the muck outside of what is needed for wear reduction. The sequential operation proceeds as follows: The screw conveyor discharge gate is closed, and the cutterhead chamber and screw conveyor are pressurized with water. The muck chute gates remain open so the muck can enter the cutterhead chamber and screw conveyor as the machine mines forward. As the screw conveyor fills up with muck, the water is pushed out of the screw and back into the cutting chamber. Once the screw conveyor is nearly full, the muck chute gate is closed and the water pressure inside the screw conveyor is lowered by emptying it into a holding tank on the back-up. The muck is then removed from the screw conveyor onto the back-up conveyor, the discharge gate closed again, and the screw conveyor refilled with water at pressure. Once again, the muck chute gate is opened so the machine can bore forward. See Figures 8 and 9.

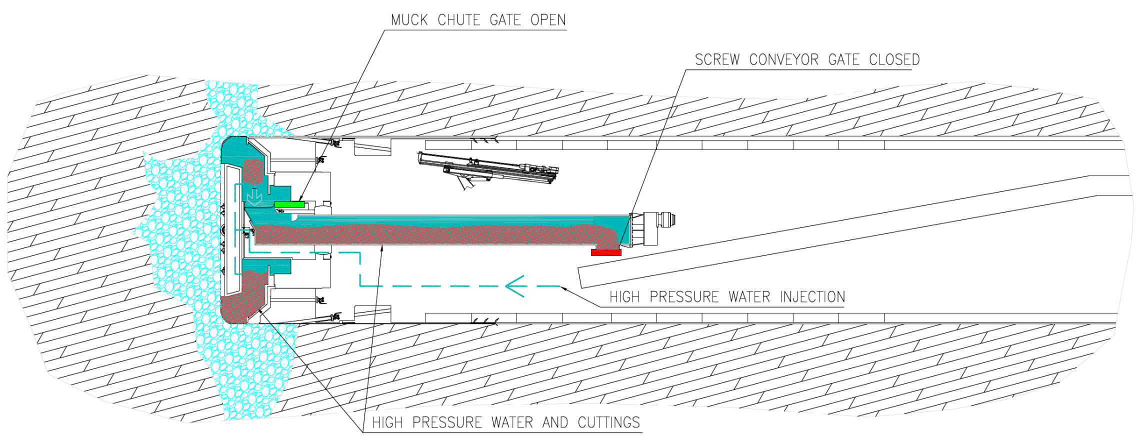

Figure 8. Muck chute gate is open with high pressure water and cuttings flowing onto the screw conveyor as machine advances forward

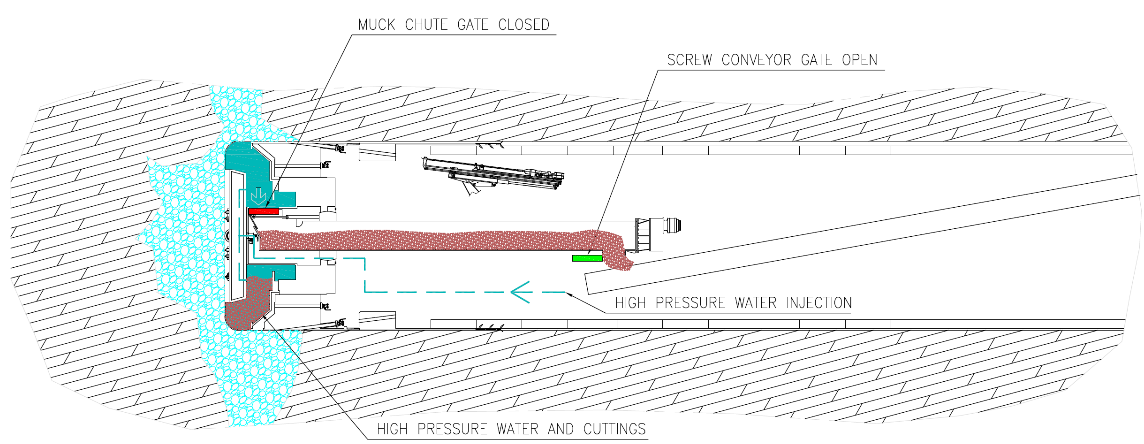

Figure 9. Muck chute gate is closed and water pressure is lowered, then muck is removed from the screw conveyor onto the back-up conveyor

While the sequential operation process allows the machines to bore under high pressures in rock if required, there are potential difficulties that may arise. The first involves the muck chute gate, which is located in the mixing chamber. Due to its problematic location, reliability of the gate can be affected and the possibility to correct any issues can be limited. When the front gate is opened the pressure will drop inside the chamber unless there is the introduction of water into the chamber to counteract this effect. Material that is brought into the screw with the cutterhead will be water-laden; this can be minimized by pumping off the free water once the forward gate is closed. Problematic aspects of this portion of the operation can be the time associated with fully dewatering the material and the difficulty of dewatering depending on its permeability. As in all EPB machines, liquid at the discharge point can be problematic, especially since this is typically over the segment build area and can create issues with segment build operations.

Rock-EPB Machines using Compressed Air

Sequential mining on a Crossover XRE TBM is a good method to be utilized if the need arises; however, if there is a high likelihood of a high-pressure water event then the machine to be considered is a Rock-EPB machine that utilizes compressed air. This type of machine, known as a Crossover XRE-Air, is configured specifically for projects where high-pressure water events are predicted. While an XRE-Air can be configured in multiple ways the preferred configuration has a center #1 screw conveyor, which can feed either a belt conveyor or a second screw conveyor (see Figure 10).

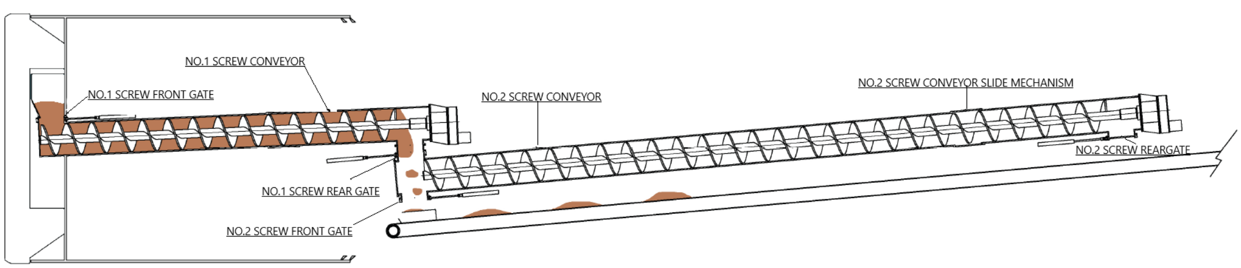

Figure 10. XRE-Air in Rock operating mode

The central screw location is preferred as it allows for an efficient rock-style cutterhead that maximizes performance and minimizes cutterhead wear. This setup also keeps the cutterhead configuration the same, which is important as any changes required to the cutterhead are the most time consuming and difficult when changing operating modes on Crossover machines. While a belt conveyor is always best for rock mining, the design of a center screw can be optimized for extended rock mining operations using a flat angle, screw pitch and wear protection. For open excavation, the muck can be deposited on a back-up conveyor for removal from the tunnel; however, when high pressure is encountered the second screw can then be utilized. The first step in the operation would be to close the gate at the discharge of the #1 screw, which will hold the pressure in the chamber. If it is not already, the second screw is connected to the #1 screw, the discharge gate on the second screw is then closed and the second screw is then pressurized with air (See Figure 11).

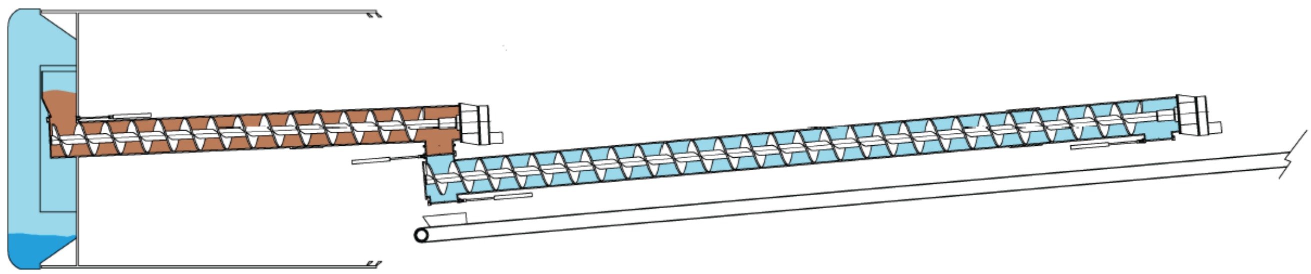

Figure 11. Pressurized Second screw

Once the desired pressure is achieved the gate between the screws is opened and the machine is able to advance with the material flowing into the previously sealed second screw until it is at capacity. As material is added, the air pressure is controlled at the back end of the screw conveyor (see Figure 12).

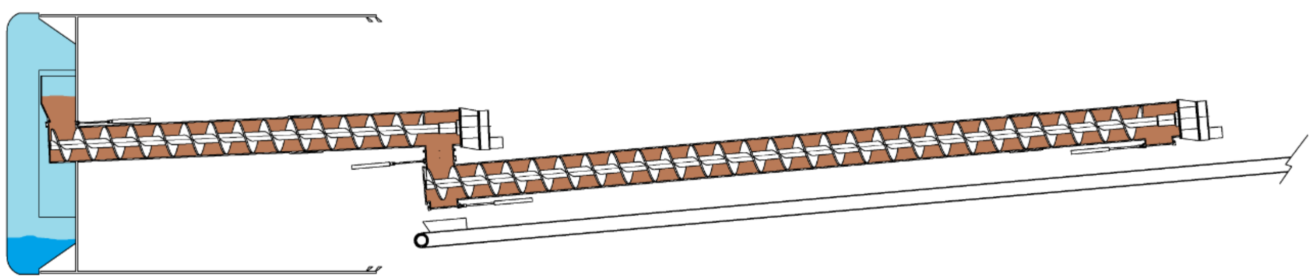

Figure 12. Mining with the XRE-Air

At this point the connecting gate between the #1 and #2 screw is closed again, thereby isolating the face pressure from the second screw, which can then be discharged at atmospheric pressure (see Figure 13). Once the second screw is empty, it is ready to be pressurized, starting the sequence again.

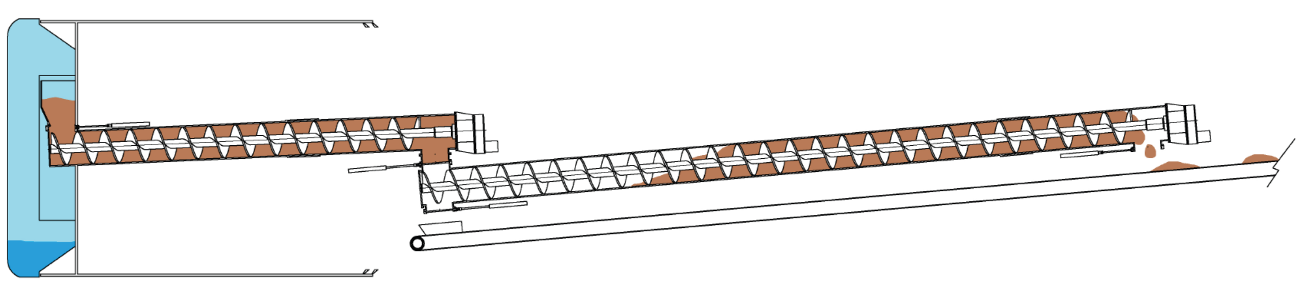

Figure 13. Material Discharge

Pressurization options on the XRE-Air. One of the big advantages to this configuration during sequential operation is that the primary sealing gate can be brought into the same reliable position that is seen on standard EPB machines. It is possible to discharge into the second screw without the use of air, and since it is sealed, some of the risks associated with a blow-out are minimized. That said, the introduction of air to the second screw adds flexibility and brings several advantages depending on the pressure used. If the air is set below the pressure, the amount of time required to pressurize the screw is minimized. This method also reduces the amount of pressure that the #1 screw needs to manage to allow for a higher pressure in the mixing chamber than a typical EPB—this would be an appropriate pressure setting when the excavated material has some level of EPB characteristics.

By setting the pressure equal to the face pressure, the #1 screw is used only for transport, and all pressure sealing is accomplished by the gates. As the gates are cycled, the face pressure is stable, and unwanted flow of water is reduced. If the geological conditions support using compressed air in the excavation chamber, it is also possible to excavate with a full chamber of compressed air for additional water and face control.

By setting the pressure above the chamber pressure, water is able to be pushed back to the chamber provided that the excavated material is porous, as in what would be found with full face rock conditions. This higher pressure further minimizes water management issues at the screw discharge. It is worth noting that another advantage of the second screw configuration is that the discharge point for the second screw is behind the segment build area so that any spillage that may occur will have less effect on TBM segment building operations. It is for this reason some contractors will request a double screw configuration even when geological conditions do not require it.

Comparisons with Slurry TBMs

The sequential nature of the operation does have an impact on possible advance rates since the machine cannot mine during material discharge of the second screw and pressurization, though the advance rate can be close to the same as most slurry machines in the same conditions. These rates are achievable because XRE-Air TBMs do not require the sizing, crushing, transport and separation processes of slurry machines and, more importantly, the XRE-Air is able to achieve high advance rates when pressure control is not required.

It is important to point out that pressurized tunneling in rock, whether using Slurry or Sequential TBM excavation, needs to be carefully considered. Cutterhead inspections in rock must be viewed with a different mindset than in soft ground tunneling, which is where most pressurized machines are used. When tunneling in rock with any type of machine, inspections should be performed regularly; once per shift can be a requirement. This is in contrast to tunneling in soft ground, where Slurry Shield machines are more commonly used as this is the type of geology they were originally designed to excavate. In soft ground conditions, cutterhead inspections are often planned and based on a set number of meters, for example every 100 m. Contractors who are used to tunneling in soft ground may not realize that when using a Slurry TBM in rock, inspections must be frequent due to increased cutter consumption.

Often, these inspections in Slurry TBMs require hyperbaric interventions--high-risk operations, particularly as water pressures go up. In water pressures over 6.5 bar, divers are often not permitted to enter the cutterhead, so grout must be used or there must be an alternate plan to bring down the high pressure. Higher pressure hyperbaric interventions up to approximately 12 bar have been successfully performed, but at what risk? Pressures in some tunnels have far exceeded 12 bar and would make hyperbaric interventions even more costly, risky and time consuming, or impossible.

CONCLUSIONS

Crossover machines have shown themselves capable of excavating in a wide range of geology, and with the configuration of a Rock-EPB type machine using compressed air (XRE-Air), the range of conditions that these machines are equipped to handle has been expanded. This is not to say that this is a one-size-fits-all machine, there are certainly times when a Slurry, EPB or Rock TBM will be best choice for the project. The strongest case for the use of the XRE-Air is in rock projects that have a risk of high-water flows and/or pressures. In these conditions managing the pressure and flow through grouting should always be the primary approach due to cutterhead maintenance requirements. This is not a perfect solution as some rock formations are very difficult or nearly impossible to grout, and therefore the success of pre-excavation grouting will not be a given, particularly if conditions unexpectedly change. In these cases, the ability to excavate under high pressure for short distances is a key feature that the XRE-Air provides.