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The 10m diameter Robbins Double Shield machine used for Turkey's Kargi Hydroelectric project.

ENSURING ADVANCE

Even in difficult ground, new TBM solutions can carve a path to success says Lok Home, Robbins President

IN MANY ROCK PROJECTS, 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 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.

Solutions informed by field experience

The project in question began its underground excavation in 2012 near Ankara, Turkey using a 10m diameter Double Shield TBM. Known as the Kargi Hydroelectric Project, the initial 11.8km long tunnel was expected to be bored in softer yet self-supporting geology for the first 2.5km, giving way to competent rock

Left: Crews at Kargi encountered everything from squeezing ground and blocky rock to running ground and cathedralling, requiring in-tunnel machine modifications.

Below: The Robbins Crossover machine for Túnel Emisor Poniente II is equipped with drills including a probe drill and forepole drill for ground consolidation.

that would not require a tunnel lining for the rest of the drive. 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 80m the TBM became stuck in a section of collapsed ground that extended more than 10m above the crown, loaded onto and around the cutterhead. 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 10m 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 2km of tunnelling.

It became apparent that much larger 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 10m ahead of the cutterhead, 90mm 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 30m 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 or collapses, 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 thrust jacks were installed between the normal auxiliary thrust to double total thrust capabilities.

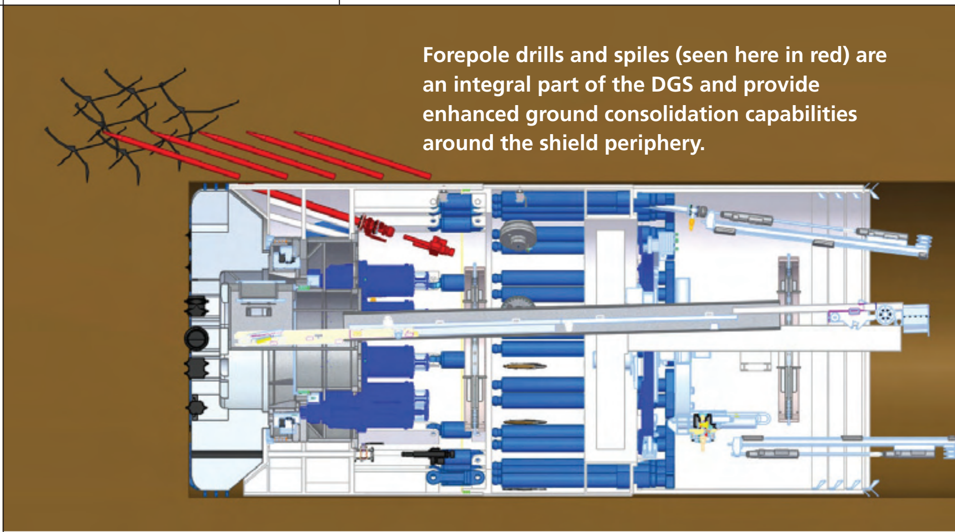
Ultimately, after in-tunnel modifications, the machine at Kargi was able to excavate the ground very efficiently, even boring 723m in one month - more than twice the rate of a drill and blast heading proceeding from the opposite end of the tunnel. The TBM broke through in July 2014 after boring 7.8km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

The lessons learned at Kargi are now being applied in multiple ways. Robbins' latest generation of Crossover machines has been improved by the experiences in Turkey - for instance, the successful canopy drill design from Kargi was pre-installed on the TBM for Mexico's Túnel Emisor Poniente II (TEP II), providing another ring for grout drilling or forepoling close to the cutterhead. As used at Kargi, the canopy drill operates in the top 120 degrees of the tunnel, while a second probe/grout drill is located further back on the machine, allowing two different patterns of holes.

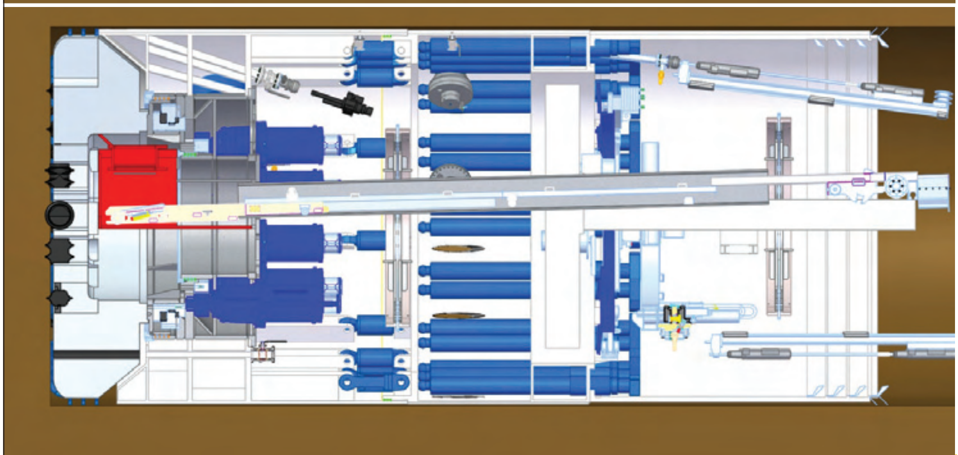
High torque/breakout torque is another feature added to the TEP II machine, so that two-speed gear boxes can be activated to achieve high torque at a low speed, similar to how an EPB operates. With two-speed gear boxes, the cutterhead can be freed in bad ground where it might otherwise become stuck. The TEP II operating crew have been obliged to use this feature on several occasions; as at Kargi the first few 100m of tunnelling contained collapsing ground.

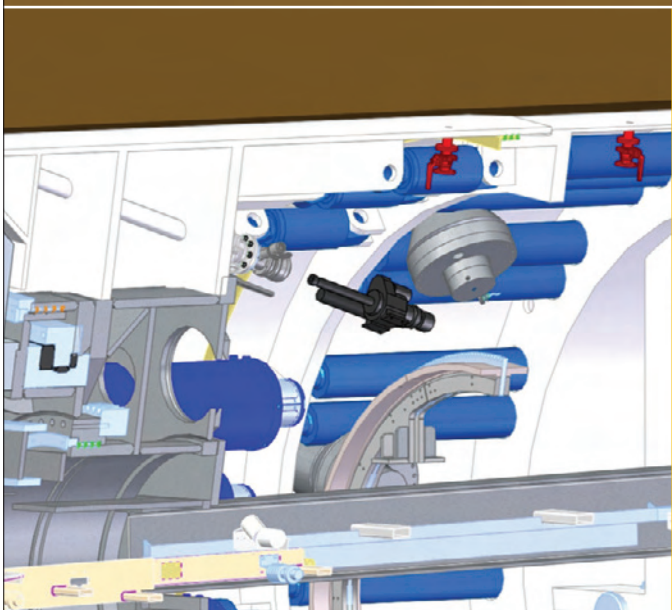
Pathway to success in difficult ground

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. Known as Difficult Ground Solutions (DGS), the system consists of a set of integrated features tailored to a specific project's geology. The main components of DGS 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.



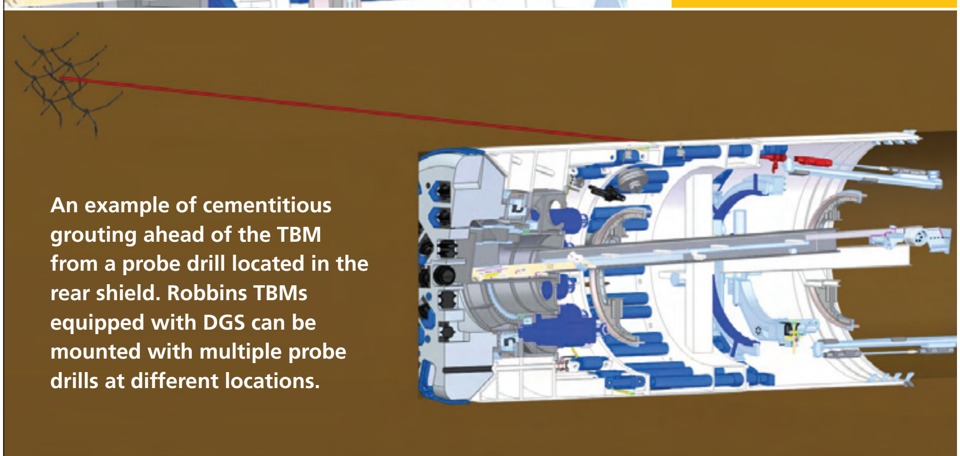
Forepole drills and spiles (seen here in red) are an integral part of the DGS and provide enhanced ground consolidation capabilities around the shield periphery.





Above: A sealable muck chute with closure doors (seen here in red) can effectively seal off a machine from severe water inflows.

Left: Peripheral ports located 360 degrees around the machine shield (seen in red) can be used to inject bentonite and prevent a shielded TBM from becoming stuck in squeezing ground conditions.



An example of cementitious grouting ahead of the TBM from a probe drill located in the rear shield. Robbins TBMs equipped with DGS can be mounted with multiple probe drills at different locations.

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.

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. Continuous Advance Shields involve designing 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 over-break conditions. The radial ports can be made to inject pressurized hydraulic lubricants to free a shield that has already become stuck. Lastly, additional thrust jacks between the normal thrust cylinders can supply added thrust in a short stroke to break loose a stuck shield.

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 measures to limit it. 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.

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. With DGS, the probe and injections holes in the cutterhead and front shield are specifically designed to accept these cameras.

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.

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 tunnelling 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 40m 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.

Applications & The Future

The DGS system will be used on several TBM projects, including New York City's Rondout West Bypass Tunnel. Scheduled to begin in 2017, that project will use a 6.6m diameter Single Shield TBM to excavate a 4km long tunnel below the Hudson River. Ground conditions are expected to consist of shale with possible zones of intense water inflow up to 30bar. The machine will be designed to passively hold the potentially high water pressure using a cutterhead drive sealing system and backfill grouting through the tailskin. The machine is equipped with high thrust 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 100m ahead of the TBM, while blow-out preventers enable drilling at high pressures up to 20 bar. This is an example of a customized DGS system for expected geological difficulties.

Of course the overall goal of DGS is to avoid making these modifications in the tunnel - 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. Contractors and owners must strive to provide accurate geological reports so that DGS can be at its most effective. Owners and contractors should give full consideration to building in these features when difficult conditions are a possibility. With these features, we are confident that a shielded machine can keep advancing, whether the concern is high cover mountainous tunneling with squeezing and rock bursting, water inflows, fault zones, or all of the above.