Rock Tunnels at High Water Pressure: Non-Continuous Pressurized TBMs vs. Slurry

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ABSTRACT

The choice of TBM type is never easy, but it becomes especially challenging when faced with a hard rock tunnel with expected high water flows and pressure. Slurry Shield tunneling has a long history of being used in these conditions to minimize the risk, though this method has brought with it other risks along with cost considerations. At recent projects around the world, another method has been proven to effectively manage these project risks without utilizing Slurry Shield tunneling: Shielded, Non-Continuous Pressurized (NCP)-TBM tunneling in rock with a comprehensive grouting program. In this paper, the authors will analyze the use of Shielded NCP TBMs at projects around the world as compared with slurry shield tunneling in rock under water pressure. Recommendations will be given in order to establish a clear picture of the optimal tunneling method.

COMPARING SLURRY TUNNELING TO NCP-TBM SHIELDED TUNNELING IN ROCK

There are certain inherent traits to a Slurry tunneling operation that appear to give a lower level of risk: the entire operation is sealed; the slurry itself is conveyed to the surface through a system of pipes. But is this truly the case? We will outline key risk factors of Slurry tunneling as compared to NCP-TBMs below.

For purposes of this paper, an NCP-TBM is defined as a Non-Continuous Pressurized Tunnel Boring Machine that may be of Single Shield Hard Rock or Crossover (Hybrid Rock/EPB) type. NCP-TBMs are capable of sealing themselves off to water pressures above 20 bar using a pressure bulkhead when needed. Whether the machine is designed to statically hold water pressure using a sealable muck chute, or to bore under pressure using a screw conveyor, is up to the requirements of the project.

Cutterhead Inspections

Cutterhead inspections in rock must be viewed with a different mindset than in soft ground tunneling. 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 bars have been successfully performed, but at what risk? Pressures in some tunnels have far exceeded 12 bars and would make hyperbaric interventions even more costly, risky and time consuming or impossible.

We have seen this borne out on recent projects such as the Hiroshima Expressway Line 5 in Japan. On that project, a 13.7 m diameter Robbins Slurry TBM is boring in granitic rock. The contractor opted for a Slurry machine because that was their historic experience, and they were expecting up to 13 bar water pressure (Greger & Konda, 2019). This high pressure water zone was only in a small section of the overall tunnel length, about 5 percent (see Figure 1).

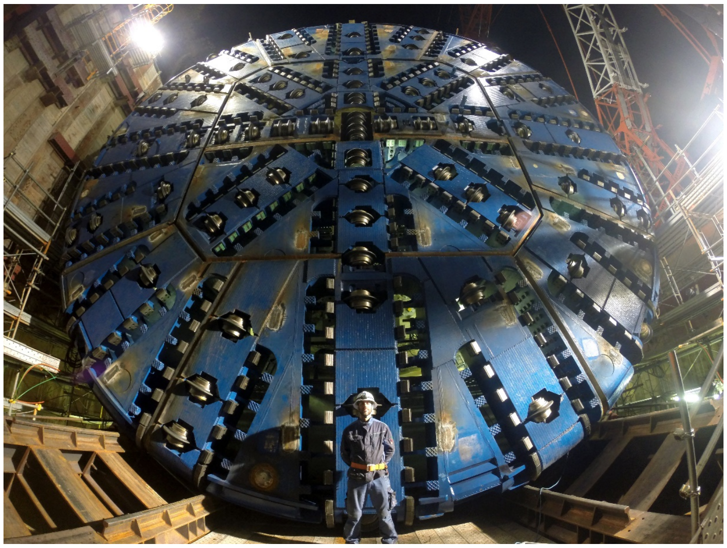

Figure 1. Cutterhead view of the 13.67 m (44.8 ft) Robbins Slurry TBM for the Hiroshima Expressway Line 5

The contractor in Hiroshima had grouted off from the surface a planned safe zone in which to inspect the cutterhead without requiring a hyperbaric intervention, but this strategy did not go according to plan. The abrasive rock damaged the cutters and cutterhead before they could reach the safe zone, resulting in unplanned delays.

By far the biggest benefit of using a shielded NCP-TBM in rock, rather than Slurry, is the ease of cutter and cutterhead inspections. In areas with no pressure and with frequent or continuous grouting, the cutterhead can be inspected regularly and without the requirement of expensive, time consuming, and often risky pressurized interventions or complicated procedures to remove slurry from the cutterhead. Frequent inspections mean that cutter and cutterhead damage can be caught early before they cause significant downtime (see Figure 2).

Figure 2. The 6.58 m (21.6 ft) diameter Delaware Aqueduct Repair TBM, a Single Shield machine used in hard rock and designed to statically hold high water pressure, is a good example of an NCP-TBM

Abrasive Wear

To go along with the above point, abrasive wear in any type of TBM can be high depending on the abrasiveness of the material—whether rock, sand, or otherwise. However, in Slurry machines, which crush the rock and send the rock chips through a system of pipes, abrasive wear is of even greater concern than in hard rock machines. The material being excavated by a Slurry TBM is constantly in contact with the cutterhead and cutting tools, increasing the amount of time that abrasive wear can occur. Even with use of durable slurry piping, transfer points and pipe elbows will require higher rates of replacement, causing more delays associated with muck removal than a typical NCP-TBM operation using a conveyor belt.

Dealing with Water Inrushes

If sudden water inrushes at high water pressure are a known risk, NCP-TBMs can effectively be designed to statically hold the pressure using sealable muck chutes in the bulkhead. This type of design can be used as a pressure-relieving gate in semi-EPB mode, opening by pressure and allowing muck to be metered out onto the belt. Or in extreme cases, the sealed gates can be activated and probe/grout drills can be used to forward drill and grout for ground consolidation and to seal off the water. Extra seals around the main bearing can be filled with pressurized grease and other vulnerable points can be sealed off in the same manner.

A Crossover TBM can also be designed to keep boring under pressure by implementing a center-mounted screw conveyor. A long screw conveyor can be used to draw down high water pressures and abrasion resistant hard facing can be added to the screw conveyor flights for abrasive wear. Under such conditions, a machine could operate continuously with, say, 3 bar pressure and sequentially in high pressure of 15-20 bar. An example of this is the Mumbai Metro, an ongoing project using two Robbins Crossover TBMs. In these machines, the center screw conveyor is able to seal itself off/hold pressure so the TBM can continuously bore or operate using the screw conveyor in a sequential fashion. Boring is done when there are not enough fines to form a plug.

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. The entire process can be automated to simplify TBM operation in water-bearing ground (See Figures 3-4).

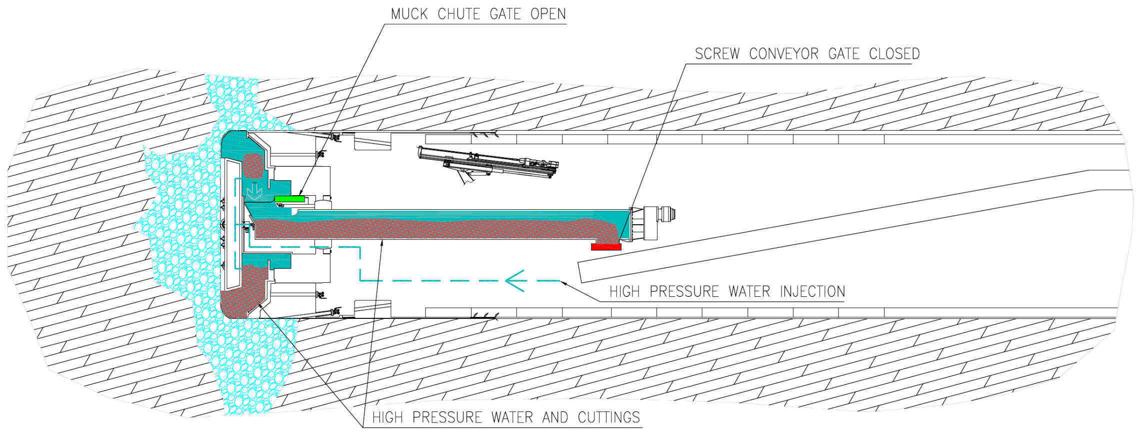

Figure 3. Muck chute gate is open with high pressure water and cuttings flowing onto the screw conveyor as machine advances forward

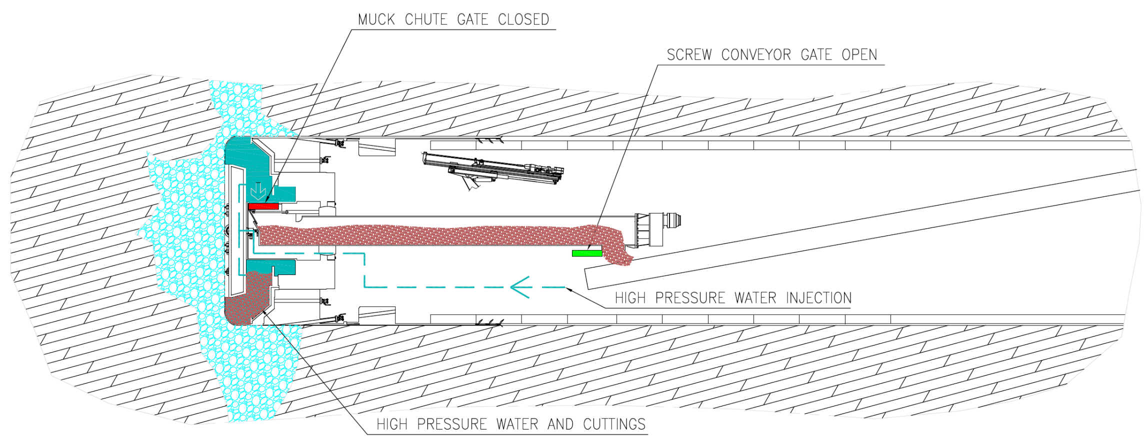

Figure 4. Muck chute gate is closed and water pressure is lowered, then muck is removed from the screw conveyor onto the back-up conveyor

Dealing with Gasses and Contaminated Ground

In Slurry tunneling, dealing with gasses in the tunnel is relatively easy because the gasses are contained in the slurry pipes. Gasses can also effectively be contained and safely dispersed on non-pressurized TBMs using scrubbers and high volumes of air. On a recent Robbins TBM in Australia the machine was capable of operating in open mode with gasses using a bulkhead fitted with suction ports to draw any gas from the top of the cutterhead chamber and directly into a sealed ventilation system.

Contaminants such as asbestos may be better contained in slurry pipes, but many other types of contaminants may not be easily separated from the slurry and therefore easier to deal with using NCP-TBMs. In Slurry operation the quality of Bentonite itself can vary widely, with some lower cost material containing heavy metals, which has the potential to be detrimental to the environment. The slurry solution itself also tends to bind well with heavy metals, contaminating the slurry and making separation difficult.

THE COST OF GROUT VS. SLURRY

In ground with fines, slurry separation can be costly and difficult. Slurry tunneling is also not immune to problems such as blowouts/loss of face pressure when a fault zone or low cover zone is encountered, as is well-known in our industry from projects such as Hallandsås in Sweden and the SMART Tunnel in Malaysia.

The increased power requirements due to the slurry separation and transport system need to be considered in any evaluation of cost. In order to make the excavated material pumpable by centrifugal pumps and prevent settling, high levels of flow are required over the length of the tunnel with substantial losses due to friction—this leads to both wear and increased power requirements. Since the pumps in the transport system are carrying the excavated material, high clearance pumps are used which further lowers the efficiency of the systems. Once on the surface the added fluid must then be separated, which requires additional power. Increased power is further required when fine particles like silt and clay are present.

In general, Slurry TBMs need a level of expertise in operation that NCP-TBMs simply don't require. The operation of most NCP-TBMs is both simple and straightforward, which in turn saves on personnel costs. In an NCP-TBM operation, crew members may be more exposed to the tunneling environment but risks are not increased. With a good geotechnical baseline report and ground investigation tools, contractors can determine the zones requiring grouting ahead of the machine. It is now common to drill probe holes accurately of plus 100 meters with Down-The-Hole (DTH) drills.

While grouting does take time and cost money, this cost has to be balanced against the cost and time to do hyperbaric intervention during slurry tunneling. Even 100% grouting in a rock tunnel could require less time than high-pressure hyperbaric interventions. The practice of pre-grouting has been done for years in drill & blast rock tunnels in Scandinavia and worldwide.

Grouting can also be done from a Slurry TBM of course, and is normally done to set up safe zones. However, it is worth noting that based on having a pressurized face filled with slurry, drilling through the head is very difficult. Sealed pipes/ports need to be installed in advance, eating up space and compromising the working conditions during hyperbaric interventions.

There has been a recent development to enact cutter changes by accessing the cutters through the cutterhead under atmospheric pressure. However, this system requires a large diameter machine as well as a deep cutterhead structure. The deep structure severely affects muck flow and substantially increases the need for more frequent inspection and cutterhead repairs. These atmospherically accessed cutterheads do not address the problems of cutterhead repair, changing center cutters, or replacing scrapers, all of which are high wear items in rock tunneling at large diameters.

Lining requirements are another potential reason not to go with Slurry: The operation of a slurry TBM goes hand-in-hand with the use of an (often expensive) segmental lining. Pre-excavation grouting using an NCP-TBM offers tremendous cost savings when done in a non-lined tunnel or when the liner can be installed independently after excavation. In cases where a final liner has to be installed with tunnel boring, and often in cases where excessive water inflows are predicted, a slurry TBM may make more sense. Under excessive water inflows a grouting operation may still experience leakage after the initial tunnel construction, making installation of a final liner afterwards potentially costly and time consuming.

RECENT INDUSTRY EXAMPLES

Delaware Aqueduct Repair

One of the best recent examples of a correctly applied NCP-TBM can be seen at the Delaware Aqueduct Repair tunnel in New York, USA. On that project the contractor won as the lowest cost bid using an NCP-TBM and grouting because they understood the risks and the geology of the project. They anticipated significantly less water impacts than the maximum indicated in the bid documents, as well as less grouting efforts after careful analysis of all available geotechnical data. However, Robbins and the contractor included redundant pre-excavation grouting plants on the TBM in the event of possible high water flows. These redundant plants were ultimately seldom used during tunneling.

The 6.8 m diameter Robbins Single Shield TBM featured a unique setup to deal with water pressure. The tunnel was bored from 270 m to 180 m below the Hudson River and the machine featured a bulkhead for sealing in case of high water inflows at the tunnel face. The closeable bulkhead allowed the excavation chamber to be sealed off in the event that groundwater inflows (shunt flows) from the excavated portion of the tunnel caused washout of the annulus grout. If the bulkhead was closed the groundwater flows could be stopped and secondary grouting of the precast liner could be performed, effectively cutting off the flow path (Terbovic et al, 2017).

When water inflows exceeded contract-allowable values, grouting was required to reduce water inflows to acceptable levels. The TBM could then advance inside the grouted area of the alignment.
To accomplish this feat, the TBM was equipped with two types of grouting systems. The pre-excavation grouting system was a mono-component grout system used to grout ahead of the TBM. The two-component (A+B) grout system was used to backfill the annular gap between the segmental lining and the bored tunnel. The machine was equipped with two drills in the shields for drilling through the cutterhead in 16 different positions and a third drill on the erector to drill through the shields in an additional 14 positions. To add to that, water-powered, high pressure down-the-hole (DTH) hammers allowed for drilling 120 m ahead of the machine at pressures up to 20 bar if necessary.

The setup was a novel use of DTH hammers in a North American TBM tunnel (the drills have been used on other projects internationally). The contractor needed to be able to bore two to four probe drills up to 120 m ahead of the machine, then mine 115 m, then drill out 120 m again. The straightness of the DTH drill holes is a huge advantage, as DTH hammers can be maintained within the tunnel alignment even at this distance. More typically when top hammer drills are used, meaning that the hammer action is on top of the drilling rod, the hammer action only allows the drill string to accurately reach 45 to 60 m ahead of the TBM.

Interestingly, the contractor was able to utilize data from the probe drills and DTH hammers to detect patterns and identify discreet features along the tunnel alignment by looking at drill depth, water ingress, and type of grout injected. These recordings were taken using data loggers on the drills and underground batching unit for the grout. Much of the analysis was done post-operation, but in the future data processing like this could be used during tunneling to make changes based on upcoming geology (see Figure 5).

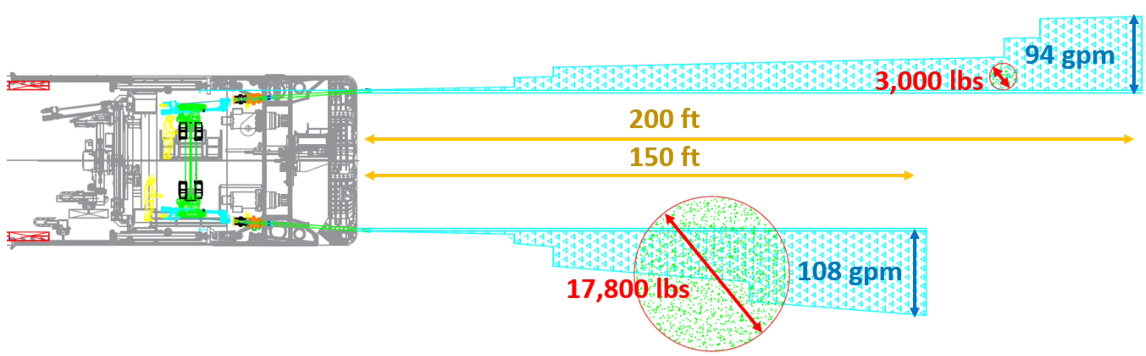

Figure 5. An example of post-operation analysis. The spheres in the images were scaled relative to a 2:1 grout mix with its test bleed and the center of the sphere was placed in a location that represented the average of where water was picked up along the drill length

Ultimately, the project was highly successful, with the TBM achieving instantaneous penetration rates of 6 m per hour, and boring safely through zones of fractured rock with high pressure groundwater.

Mumbai Metro

Direct comparisons of NCP TBMs and Slurry machines are not common, but one recent such example is at India's Mumbai Metro. Two 6.65 m diameter Slurry TBMs were launched in 2018 to bore 3.5 km long tunnels in basalt and breccia with water pressures up to 3 bar. Meanwhile two more 6.65 m diameter Robbins Crossover XRE TBMs were launched to bore parallel 2.8 km long tunnels in shale, tuff and breccia with possible water pressures up to 2 bar (Bayart et al, 2020). The ground conditions are not identical, but similar enough to make some comparisons. The Crossover TBMs, operating in open mode for most of the project, have bored 2,351 m as of December 2020. The TBMs have each passed through multiple station sites where they were stopped for around four months each time to complete station construction and have just 592 m each left to bore. The Slurry TBMs, by contrast, have bored 2,260 m and 2,196 m respectively, with the net result that the Crossover machines will finish their operation first.

CONCLUSIONS

Are there times when a Slurry TBM has an advantage over an NCP-TBM in rock? Yes. Rock properties can drive the decision: Some rock formations are very difficult or nearly impossible to grout, and therefore the success of pre-excavation grouting will not be a given. If significant water inflows are predicted and the rock will not readily take common grouting material, or chemical grouting is not an approved option, a slurry machine is the logical TBM selection.

The conclusions to draw from this discussion are straightforward. Slurry tunneling is a valid option in rock with potential of high water pressure. However, is Slurry tunneling the most cost-effective option? Is it safer than any other option? In many circumstances the answer is no.

It is the authors' hope that consultants and owners realize that Slurry TBMs are not the only option when high water pressure is expected. Slurry TBMs are not in most cases the lowest cost, and other methods can be just as safe while being simpler to operate. While grouting takes time, so does slurry tunneling with its typically lower advance rates and possible need for expensive, high risk hyperbaric interventions. When Slurry machines operate in rock, the need for frequent cutterhead inspections ultimately makes their use questionable. In most cases NCP-TBMs are the better option.

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