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Extreme ingress: Managing high water inflows in hard rock TBM tunneling

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ABSTRACT: Managing water inflows is not new to TBM tunneling, but today there are an increasing number of methods and best practices to handle potentially high water inflows efficiently and safely. High volumes of water can be safely contained or managed in hard rock TBM tunneling, but this requires the proper foreknowledge and planning. This paper will outline how machines can be designed ahead of time for expected high water, and how risk can be mitigated during tunneling. We will also cover the importance of pre-planning and include a look into the future of water control methods. Case studies of hard rock tunneling with heavy water inflows will be examined, with a focus on New York, USA's Delaware Aqueduct Repair. The 3.8 km long bypass tunnel below the Hudson River requires excavation through limestone rock at water pressures of up to 20 bar. A unique 6.5 m diameter Single Shield TBM, sealable for high pressure excavation, is boring and lining the tunnel.

1 INTRODUCTION

Probe drilling and pre-grouting is an essential part of drill and blast tunneling and the most important defense against weak rock mass and water leakages in D&B tunneling. The first use of pre-grouting in a TBM application was on the Oslo sewer tunnels from 1977–1981 in Norway. Due to the risk of ground settlement the project owner required a system on the TBM capable of extensive pre-grouting in order to qualify any bids. The solutions chosen by the contractors and machine manufacturers were mainly to place a drill jumbo behind the TBM, guide the drill string through the TBM and bore through the cutterhead. This proved to be a bad solution and eventually the chosen contractor decided to force the drilling rod into the tunnel wall behind the grippers. The project was successful at limiting the water ingress, but the extensive pre-grouting limited the advance rate.

Since this time many machines and projects have faced similar circumstances, where the systems or procedures that were in place were less than optimal for advancing in the difficult conditions. In some particularly difficult projects heavy modifications or changes needed to be put into place to help the projects advance. During the process a better understanding of what was needed and the tools to complete the job were developed that would make for more effective mechanized tunneling. Some projects of particular note and in no special order are:

- Arrowhead Project, California USA
- Kargi HEPP, Turkey
- Hallandsas, Sweden
- Gerede, Turkey

A machine feature proven particularly valuable by these projects is the ability to seal the machine from water flows, both at the heading and behind the machine using sealed segments.

Drilling and grouting is made more effective by monitoring the drilling parameters, monitoring while drilling (MWD), probing longer distances, and supporting an increased grout pattern. These methods, along with new kinds of grout and improved machine systems like auxiliary thrust, variable speed cutterhead torque, and dewatering systems are integrated together so that machines can more effectively manage the potential for high water inflows.

An ongoing project in the US, the Delaware Aqueduct Repair, is a prime example of the use of a machine that has brought these features together, and some new ones, to address the geology.

2 CASE STUDY: DELAWARE AQUEDUCT REPAIR

In 1990 a utility worker at a power plant along the Hudson River found water shooting up from the ground in an area where a large water line ran. At that time, the New York City Department of Environmental Protection (NYCDEP) was treating the water in the Delaware Aqueduct with copper sulfate, which was used to prevent algal growth at some of the city's reservoirs. The water samples tested positive for copper sulfate, and as the NYCDEP were the only ones using copper sulfate in the area there was good reason to believe it was coming from the Delaware Aqueduct.

At 137 km long, the Delaware Aqueduct is cited in the Guinness Book of World Records as the world's longest continuous tunnel. Since 1944 the Delaware Aqueduct has supplied water to New York City and today it accounts for more than 50% of the water supplied. The Delaware Aqueduct is a gravity-fed water supply line of 4.1 m diameter that conveys water from several reservoirs in the Delaware System and across the Hudson River. The tunnel was constructed using drill and blast methods and most of the rock was competent ground made up of schist and shale, but as the teams approached the Hudson River, the ground gave way to faulted limestone. Work crews documented groundwater inflows of 7.5 to 15 million liters day into the tunnel, and they invented some creative solutions to deal with it. The ground was lined with concrete, and then a steel interliner was placed in the tunnel before a final concrete lining was set on top, effectively creating a sandwich of concrete with steel inside. While the method was groundbreaking for the time, the steel liner ultimately did not extend far enough through the troublesome rock formation to prevent leaks.

For more the 25 years leakage has been monitored in the section that connects the West Branch Reservoir to the West Branch Tunnel. It was determined that approximately 132 million liters per day was lost with approximately 95% coming from two sections of this tunnel, the Roseton and Wawarsing areas, which are just outside of the lined section. Compared to the overall flow this was not a critical amount, but the location and nature of the leaks was a cause of concern. The repair would be anything but simple. To address the issue it was decided to bypass the Roseton and Wawarsing areas with a newly constructed tunnel, the Rondout West Branch Bypass Tunnel (RWBT).

The project was separated into two distinct phases and two separate contracts were tendered, BT-1 and BT-2. The first phase, contract BT-1, consists of completing the shaft sinking to a depth of approximately 275 m at shaft 5B, near the town of Newburgh and 213 m at shaft 6B near the town of Wappinger. The excavation connecting the shafts is approximately 3,810 m of tunnel at a diameter of 6.58 m. This phase also includes the installation of 2,800 m of 4.87 m diameter steel interliner pipe through the new bypass tunnel with cast-in-place concrete liner for a finished diameter of 4.27 m. Access chambers at the top of shafts 5B and 6B will be constructed for access and housing of the mechanical and electrical equipment for supporting pumps and valves. Figure 1 shows the location and layout of the project.

The second phase, BT-2, includes an additional 30 m of excavation from shafts 5B and 6B to the existing tunnel and will be completed during a scheduled shutdown of the main tunnel. Additionally, construction of the permanent plugs within the RWBT will be undertaken. Figure 2 shows the layout of the work. Access to the work is through the deep shafts.

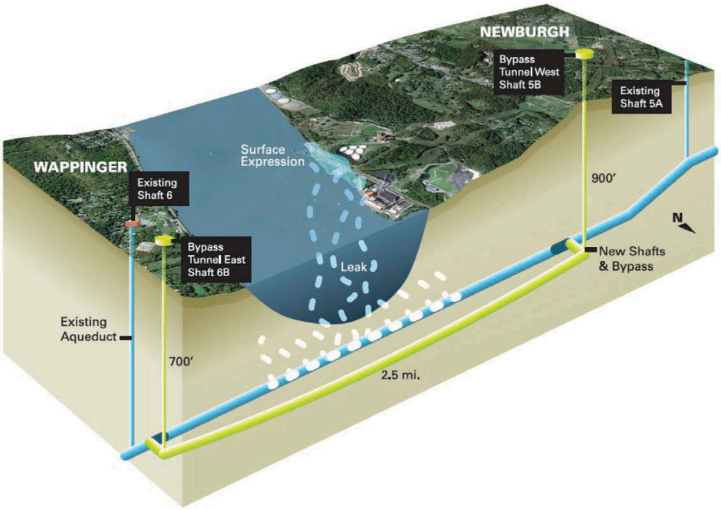

Figure 1. Project location and layout.

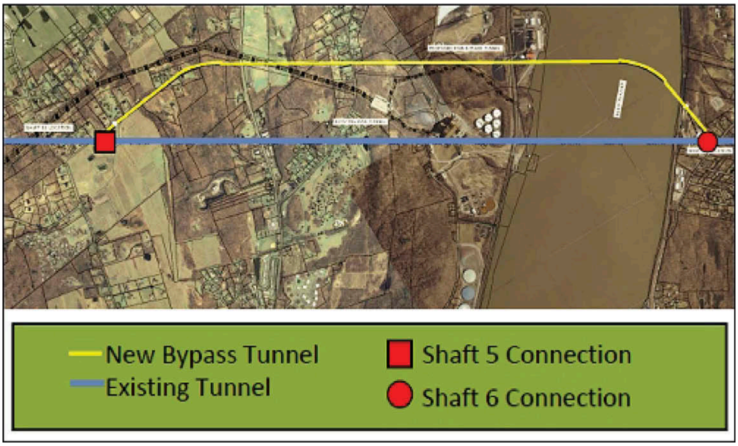

Figure 2. Shaft and connecting tunnel locations.

3 SIGNIFICANT PROJECT ASPECTS

The geologic formations encountered on the project mainly consist of the Wappinger group (dolomite, dolomitic limestone and limestone). At the beginning and the end the tunnel excavation will be in the Normanskill and Mount Merino Formations, respectively, which are made of slatey shale, argillite and sandstone. The GBR states that there will be some areas of extremely hard rock with UCS values as high as 372 MPa, but averages in the Wappinger formation are a more reasonable 241 MPa with low to medium boreability ratings.

From Figures 1 and 2 it can clearly be seen that the tunnel alignment passes under the Hudson River at a depth of 183 m, having a width of 1,052 m at that location. The groundwater head along the rest of the tunnel ranges from 267m on the west to 213 m on the east side. The most challenging tunneling conditions are anticipated to be the high conductivity of the Wappinger formation with the fault zones in the Normanskill Formation. Per the owner's tender documents, the selected contractor had the option to excavate the tunnel between the shafts with either a TBM or drill and blast (D&B). The protentional for high water inflows combined with high head conditions, due to the depth and large source, made water control a driving factor. To handle these potential inflows the owner prescribed probing ahead and intensive pre-excavation grouting. These methods were introduced as requirements and were intended to lower the groundwater inflow potential of the rock mass, not necessarily to increase its strength or improve stability. The difficulties of water control are compounded by the fact that the tunnel is being bored downgrade and ground water will need to be pumped to shaft 5B and on up to the surface more than 267 m above.

While still significant the TBM method of excavation had lower dewatering requirements of 9500 l/min. The contractor, a Joint Venture between Kiewit and J.F. Shea Construction, determined that mechanized excavation would be the most economical and safest solution to control ground water when compared to D&B multi-stage excavation methodology.

The gasketed segmental lining installed behind the TBM would help to minimize the water inflow, however these geological challenges at the face in concert with high water pressures (over 20 bar), required the TBM to be designed with many special features for drilling, pre-excavation grouting and dewatering.

4 TBM DESIGN

To ensure the best chance of project success the NYCDEP and Kiewit/Shea were heavily involved in the specification and design elements of the TBM. The basic Robbins Single Shield TBM specifications and features are listed below with the TBM general layout shown in Figure 3.

- Bore Diameter 6,583 mm
- Cutterhead Speed 0–8.8 rpm
- 9 x 330 kW Drive Motors
- Pressure compensated 19-inch disc cutters
- Sealable TBM design – 30 bar
- Large dewatering system capacity
- Mucking via muck train
- Forward and aft drill positions
- Drill-in ports in cutterhead and forward shield
- Dedicated dewatering ports to dewater from the heading
- Water handling at conveyor discharge

4.1 *Special TBM Features*

The owner's specifications concerning water drove much of the TBM design in water pressure and flow as well as degree of grouting that needed to be planned for on the project. The

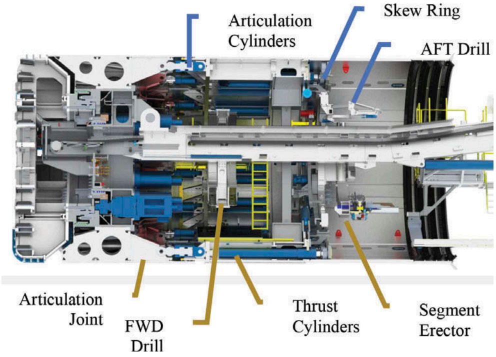

Figure 3. General TBM arrangement.

priority was placed on sealing the TBM from the high pressure/high flow water at the face, but the presence of water was also taken into account for the design of the dewatering system. This was because efficiency in managing the muck-laden water inflows from the heading was also important. KSJV worked closely with Robbins to develop and install these systems and optimize the planned operations as well as others on the machine not closely related to the expected water. Some examples of this include the cutterhead, which was designed to prevent clogging in shale, and the design around segment handling that included a decked back-up and rapid segment unloading system.

4.2 *Design Considerations for High Water Pressure*

The owner also required that the TBM be capable of withstanding 30 bar of hydrostatic pressure (20 bar with a 1.5 safety factor). Due to the 20 bar static water pressure expected on the project, a new main bearing sealing system was engineered for the project and is comprised of multiple rows of traditional lip type seals and emergency inflatable seals. The inflatable seals are not in running contact with moving parts of the sealing system during boring but can be activated like a "parking brake" when needed for additional protection of the TBM's main bearing. The seals are flushed and lubricated with grease for protection when exposed to the fines-laden water expected on the project. As such, the use of pressure compensated disc cutters became a necessity. Their unique design incorporates a pressure equalization system to keep water out and protect the bearings when the pressure is high.

4.3 *Design Considerations for High Water Inflow*

The TBM was designed to be quickly sealed to protect the TBM and personnel from sudden inrushes of water. The steps listed below are required to seal the TBM during high inflows and are shown in Figure 4:

1. Close knife gates over muck chute
2. Retract conveyor frame
3. Retract belting out of cutting chamber
4. Retract bulkhead sealing plate
5. Close stabilizer doors

Due to the water inflows measured during the geotechnical investigation, the contract specifies a very high dewatering capability. To achieve this, dewatering is controlled by two separate systems that can work independently or in concert:

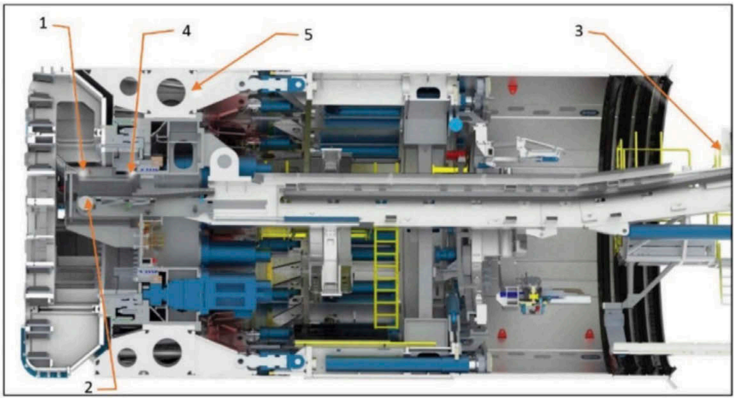

Figure 4. TBM sealing sequence.

- Primary Dewatering – 0–3,000 l/min during boring without impact on boring or ring building
- Emergency Dewatering – 9,500 l/min emergency capacity for water from heading and construction water

The primary dewatering system can collect water from the cutterhead chamber, shields/ring build area and the transfer point between machine conveyor and transfer conveyors. The system is designed to transfer fines up to 7 mm in diameter through the piping, tanks and on to the tunnel dewatering system. The TBM is equipped with 20 m^3 of dewatering storage capacity through the combination of two, 10 m^3 tanks. Each tank is fitted with mixing pumps to prevent settlement of fines and reduce shutdowns for maintenance and cleaning. Since the inflow of water is variable and the required size of the pump is quite large the primary dewatering pump is controlled with a VFD to effectively manage lower water flow events.

The emergency dewatering system bypasses the dewatering tanks and transfers water directly to the tunnel dewatering system. A telescoping pipe extender on the back-up allows the TBM to advance 6m before adding another 305 mm tunnel line. Figure 5 shows a general system schematic of the dewatering system.

4.4 *Drilling and Grouting Methodology*

The project specification requires a mandatory probe drilling program for the entire tunnel alignment that includes water inflow measurements at the probe hole locations. The TBM is required to drill four probe holes every 60 m to measure water inflows. When water inflows exceed contract-allowable values, grouting will be required to reduce water inflows to acceptable levels. The TBM can then advance inside the grouted area of the alignment. The TBM is equipped with two types of grouting systems. The pre-excavation grouting (PEG) system is a mono-component grout system used to grout ahead of the TBM. The two-component (A+B) grout system is used to backfill the annular gap between the segmental lining and the bored tunnel. A detailed drill scheme to allow drilling under pressure was developed during the TBM design phase and has been further refined during boring operations.

The first step in the probe cycle is to rotate the cutterhead into either the A or the B positions to align the eight associated ports in the forward shield and locations in the cutterhead. A 127 mm diameter casing is then installed through the shield up to the face. The casing is in 1.22 m long sections. A blow-out preventer (BOP) installed on the forward shield port is inflated to lock the casing in place.

The drill—a down-the-hole hammer, the W70 manufactured by Wassara, with a bit diameter of 104 mm—is then used to collar the hole and drill 2.74 m deep. The 127 mm casing is then removed and a drill-through inflatable packer is installed. The packer is made up of five sections, which are screwed together. Once installed the packer is inflated with water to 20 bars. The BOPs are also inflated again around the packer. At the end of the packer there is

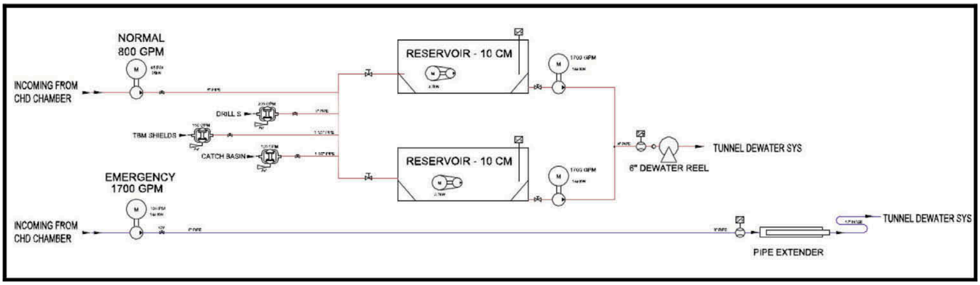

Figure 5. Dewatering schematic.

a 3-inch ball valve, a T with a hose for cuttings, and then an additional BOP, which is installed after the hammer and centralizers. Once the hammer is to the face drilling can commence. Drilling out with the probe drill requires 130 sections of 1.5 m long drill steel, hoses to bring cuttings out of the shield and filter bags for drill cuttings. Drilling out ahead of the machine is done using Wassara W50 DTH hammers. The contractor has been drilling around 91 m with the cuttings coming back and being diverted through the T in front of the BOP and back to filter bags in the bridge area. Each probe hole produces around 0.75 m^3 of cuttings and requires 5 to 6 hours to complete (see Figure 6).

4.5 *Drilling Systems*

The TBM is equipped with two drill systems for probing and grouting operations. The forward drill system is used for drilling operations through the tunnel heading at angles of 0 degrees and up to 5 degrees measured relative to the tunnel alignment. The drill system consists of two independent drill positioners mounted on a fixed ring that can position each drill 360 degrees radially to drill and grout through 16 cutterhead drill ports. This system is the primary drilling and grouting system used on the TBM and will be used to probe and grout along the tunnel alignment.

The aft drill system is a single drill permanently mounted to the segment erector. The segment erector is used to position the drill for drilling and grouting operations through 14 peripheral shield ports. The ports are at seven degrees to the tunnel alignment and are used for umbrella drilling and grouting to form a grout curtain, thus cutting off water inflows surrounding the tunnel alignment.

The down-the-hole water hammer is ideally suited to this project for the following reasons:

- Down-the-hole drilling reduces size of drill equipment inside TBM
- Water used to power drill also provides flushing of cuttings
- Drills longer, straighter holes compared to top hammer type drills
- Water used to power the drill will not erode borehole
- Core drill units are relatively short and compact, making them better suited to fit inside TBM
- API drill rods are used in drill string to power drill with high pressure water

Drill testing completed with water hammer drills near the jobsite area verified the drill performance and suitability for the project.

The bridge area of the TBM was also designed to allow for radial drilling with a portable drilling platform in order to verify backfill grouting. Forward shield drilling/grouting and dewatering ports are shown in Figure 7.

Figure 6. Drilling with pressure.

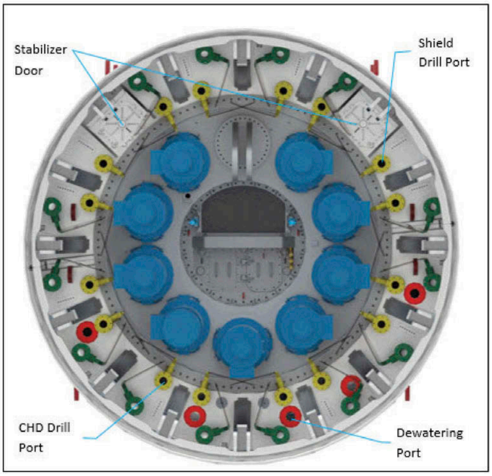

Figure 9. Forward shield drilling and dewatering ports.

4.6 *Grouting Systems*

The TBM is equipped with two PEG mixing and grouting plants for grouting ahead of the TBM. In addition, the PEG system can be used for proof grouting the segmental lining to counteract high water pressure and to mix and inject bentonite around the TBM shields to reduce friction in squeezing ground conditions.

The A+B grout system is supplied from a batch mixing plant at the surface and pumped directly to the TBM to help simplify the already-complicated shaft logistics. A+B storage tanks on the TBM back-up are equipped with level sensors that start and stop pumps at the contractor-supplied surface grout batch plant. This ensures grout is available when required for grouting operations on the TBM.

Due to high static water pressure the contractor required the TBM to have the ability to backfill grout through the TBM tail skin, which is more common on machines that excavate in soft ground to prevent subsidence. Although not an issue on this project this was done due to the concerns with the grout penetration plugs becoming dislodged at high velocities, which could endanger worker safety.

5 TUNNEL EXCAVATION

The TBM is currently in 1,219 m with a best month of production being 228 m. Reach 1 is composed of Normanskill Group shale and is around 762 m in length; the GBR in this section indicated max heading inflows of 946 l/min. During excavation two 91 m long probe holes with a 6 m overlap were drilled and no water was encountered.

Reach 2 is composed of a dolomitic limestone and is part of the Wappinger Group and is 1189 m long with anticipated steady inflows of 6.21 l/min/meter and up to 3,785 l/min during probing. This reach requires four probe holes per cycle and with half of the reach completed no water has been encountered.

There have been challenges on the project, including the extensive probe drilling and the number of required cutter changes. As expected, mucking out the TBM from the bottom of a 274 m deep shaft while delivering segments and supplies slows down the mining process. Each TBM stroke is around 100 m^3 of muck, which fills seven muck boxes. Currently the project is running two trains with a service loci to assist in loading segments and material. The probe drilling has been a challenge due to the setup required to handle potential high water/pressure inflows. The tight space also allows only 1.5 m drill steels to be used, which means 60 steels per hole. Mining advance rates went as expected during the softer shale of Reach 1 with limited cutter wear/changes. During reach 2 there has been much greater than expected cutter wear and advance rates have been cut in half.

6 CONCLUSION

All tunneling projects come with challenges that need to be overcome with water inflows being one of the primary concerns that needs to be considered. Three key areas in managing this risk are isolating the tunnel from the water with the use of grouting, preventing the water from entering the tunnel with the use of a sealed machine and lining, and finally managing the water once it has entered the tunnel with a dewatering scheme. How these different elements are brought together with the rest of the machine features can make a successful project even in difficult conditions. The Delaware Aqueduct Repair is no exception, requiring several innovative solutions with water driving much of the design. This includes drilling and grouting systems that are able to support an extensive ground improvement scheme. The machine's ability to handle high-water pressures is equally important and requires the TBM to have many features typically associated with pressurized face TBMs. Muck removal is, however, still done using a belt conveyor to minimize wear and maintenance due to the hard rock. Finally, the planning and integration of a dewatering system helps manage the water if it does make it to the tunnel heading. Few projects have all the same constrains, but these features along with others reviewed in the paper are valuable tools that with the right collaboration and planning can be applied to make for more successful future projects.

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