

Rondout West Branch Bypass Tunnel—TBM Boring in Hard Rock Against High Water Pressure and High Water Inflows Beneath the Hudson River in New York

David Terbovic ▪ The Robbins Company
Martino Scialpi ▪ The Robbins Company

ABSTRACT

A single shield hard rock tunnel boring machine is set to bore in hard rock, high water inflows and high water pressure in New York State. To overcome the difficult conditions the TBM is designed to handle 2500 gpm water inflows and seal against 30 bar of pressure. The TBM will bore a tunnel to replace a damaged portion of the Delaware Aqueduct that supplies half the raw water to New York City. The 2.5 mile bypass tunnel passes beneath the Hudson River with geology consisting of shale and limestone. Due to the high water pressure and inflows the TBM was designed with new sealing systems for the main bearing and to close the TBM off if high water inflows are encountered. The TBM is to be equipped with two dewatering systems and multiple drilling and grouting systems for pre excavation grouting and segmental lining backfill. Systematic drilling and grouting procedures specific to the project were developed and incorporated into the TBM and backup design to ensure that the TBM can handle the extremely difficult ground conditions of the project.

INTRODUCTION

The construction of the 85 mile long Delaware Aqueduct commenced in 1939 and operations began in 1944. It conveys about 500 million gallons per day of water to the city of New York, about 50% of the city's drinking water supply.

Since the 1990s the New York City Department of Environmental Protection (DEP) has been monitoring leaks in a portion of the aqueduct that connects the Rondout Reservoir to the West Branch Reservoir, finding specific areas of the Rondout West Branch Tunnel (RWBT) leaking approximately 35 million gallons of water per day into the Hudson River. As a percentage of the capacity of the tunnel, the leaks are not excessive, but the location and nature of the leaks, together with the fact that they are concentrated in one location, is a cause for substantial concern. In 2009 the DEP (which owns and operates the tunnel) determined that a repair was needed and the investigation and design process was initiated.

In addition to historical construction records and pictures of the interior of the tunnel taken by an autonomous underwater vehicle in 2003 and 2009, in 2014 a remotely operated vehicle was put into the RWBT. Cracks in the lining were observed and mapped. The conclusion was that leaks could not be repaired from within the tunnel. Thus, it was decided to proceed with the construction of a by-pass tunnel right under the river and build two shafts at each end between the towns of Wappinger and Newburgh, New York.

Construction of each shaft provides access points for construction of the by-pass tunnel and enables the by-pass to connect with the existing tunnel. The tunnel will be bored by a single shield TBM.

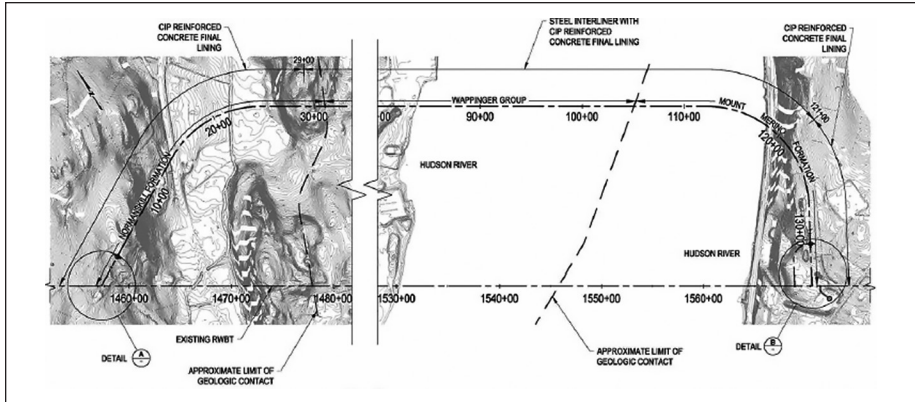


Figure 3. Bypass tunnel details

The shielded TBM, assembled at the Robbins facility in Solon, Ohio, will be delivered in pieces to site in the spring of 2017. The machine components will be lowered down the 28ft diameter shaft and assembled at depth.

The 21.4ft (6.5m) diameter TBM will operate on the 12,500ft (3,800m) drive by installing pre-cast reinforced concrete segments as tunnel lining concurrently with the excavation. Such supports will be the by-pass tunnel interior walls. The voids between the lining and the rock will be sealed by injecting cement grout, creating an effective barrier against the seepage of water into the by-pass tunnel.

The by-pass tunnel will be constructed in a constant minor downhill slope, with a total elevation change of 5ft (1.5m) over its length.

At completion of the by-pass tunnel excavation, the TBM will be disassembled and removed through the 700ft (213m) deep shaft 6B, at the east connection site.

After TBM removal, an additional steel liner (made up of steel segments) will then be installed to reinforce the tunnel in certain sections surrounded by weaker rock, for a total length of 9,200ft (2,800m).

Following the installation of the interliner pipe, a cast-in-place concrete liner will be installed throughout the full length of the by-pass tunnel, as well as the starter tunnel and connection tunnels. The locations of the CIP concrete and steel interliner pipes are shown in Figure 3.

PROJECT CHALLENGES: GEOLOGY, WATER PRESSURE, AND WATER INFLOW

The Rondout by-pass tunnel crosses through various geologic formations. The Wappinger Group consists of dolomite, dolomitic limestone and limestone rock types. The Normanskill and Mount Merino Formations consist of slaty shale, argillite and sandstone rock types. Figure 4 shows the tunnel alignment overlaid onto the geologic formations below. Very high UCS values up to 372MPa with an average of 241MPa and low to medium boreability are anticipated for the Wappinger Formation. The expected strong and tight dolomitic limestone have influenced the TBM selection and its design along with other anticipated ground conditions such as spalling behavior, raveling blocky ground, squeezing ground conditions.

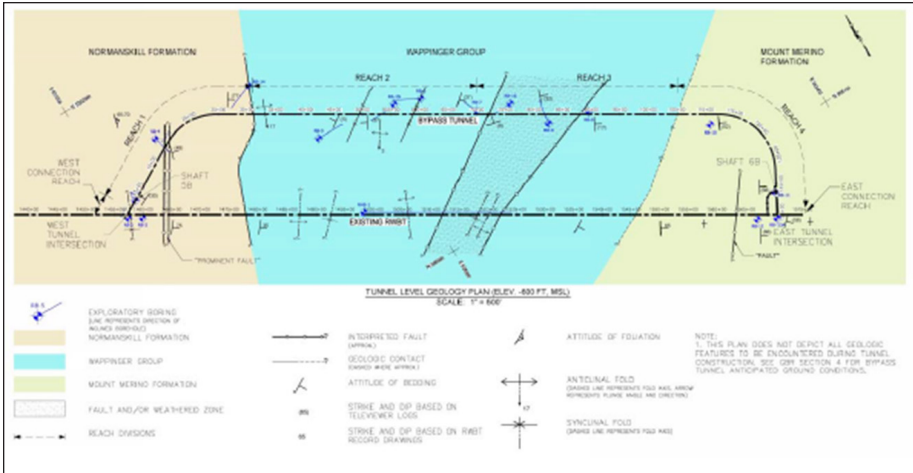


Figure 4. Tunnel level geology plan

The bypass tunnel alignment crosses under the Hudson River for 3,451ft (1,052m). The groundwater head along the tunnel ranges from a minimum of 600ft (183m) under the river to a maximum of 875ft (267m) and 700ft (213m) respectively on the west and the east side. The anticipated high conductivity of the Wappinger formation with the fault zones in the Normanskill Formation represent the most challenging tunneling conditions, especially if and when combined with high head conditions.

A groundwater model was developed to predict water inflows along the alignment and determine the excavation methodology (drill and blast vs TBM).

In favor of the TBM option, the gasketed segmental lining installed behind the machine would be able to minimize the water inflow. However in the Wappinger formation higher inflows up to 1,300gpm (4,920 l/min) were predicted from the full face TBM heading, compared to D&B multi-stage excavation methodology. In order to handle these potential inflows, mandatory probing ahead and intensive pre-excavation grouting were introduced into the requirements (where the pre-excavation grouting is intended to lower the groundwater inflow potential of the rock mass, not to increase its strength or improve its stability).

With the tunnel designed to be bored downhill, another challenge is represented by the water accumulating at the heading. This will need to be pumped to Shaft 5B for discharge to the ground surface.

To manage geological adversities in conjunction with exceptionally high water pressure (over 20bar) and water inflow (over 1300gpm), unique features have had to be implemented in the design of the machine, together with ad hoc procedures for pre-grouting and dewatering.

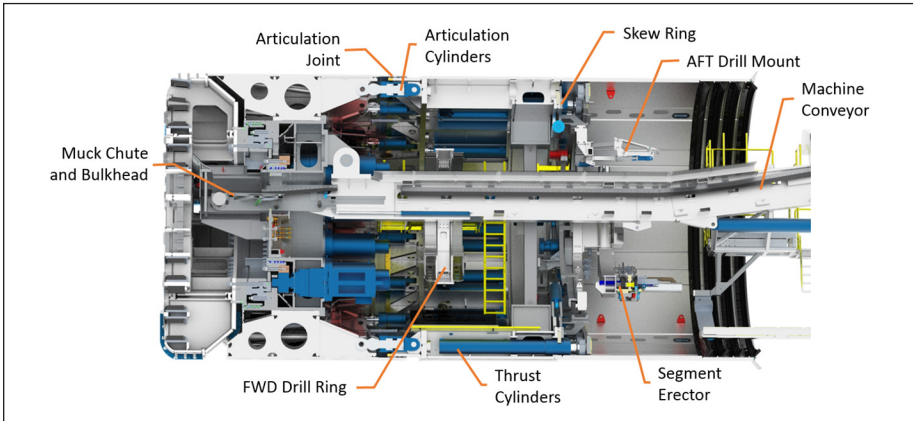
TBM DESIGN

TBM General Specifications

The NYDEQ and Kiewit/Shea were heavily involved in the specification and design of the TBM. This approach was critical to ensure the best chance of project success.

Table 1. Robbins single shield TBM general specifications and features

<ul style="list-style-type: none"> ▪ Bore Diameter 21' 7" (6,583 mm) ▪ Cutterhead Speed 0–8.8 rpm ▪ Bolted Cutterhead Design ▪ 9 × 330 kW Variable Freq. Drive Motors ▪ Pressure Compensated 19" Disc cutters ▪ Sealable TBM design – 30 bar ▪ Stabilizers shoes on forward shield ▪ Gripper shoes on rear shield ▪ Skewing ring for roll correction ▪ Large dewatering system capacity 	<ul style="list-style-type: none"> ▪ Mucking via muck train ▪ Rapid segment unloaders ▪ Stepped Shield Design ▪ Bolted CHD design – no welding at site ▪ Drill in ports in CHD, and Forward shield ▪ Dedicated dewatering ports to dewater from the heading ▪ Water handling at conveyor discharge
---	---

**Figure 5. TBM general layout**

Specifications and features of the Robbins Single Shield TBM are listed in Table 1 and the TBM general layout is shown in Figure 5.

TBM Special Features

The contractor added additional specifications for the TBM and backup systems in order to optimize the TBM with respect to drilling and grouting operations, to handle muck-laden water and to optimize operational efficiency of the backup system. De-mucking of the cutterhead was studied with a priority placed on how to seal the TBM against water inflows.

The project specifications required that the TBM be capable of withstanding 20 bar of hydrostatic water pressure with a safety factor of 1.5. Pressure compensated disc cutters were selected for the project. The special cutters are equipped with a pressure equalization system to ensure protection of the cutter bearings at high water pressure.

High Water Pressure Design Considerations

A new main bearing and sealing system design was required for the project due to the 20 bar static water pressure expected on the project. The system is comprised of normal TBM lip seals and emergency inflatable seals. The advantage of the inflatable seals is that they are not in running contact with moving parts of the sealing system during boring and can be activated when needed for additional pressure protection of the main bearing of the TBM. The seals are flushed and lubricated with grease. Grease flushing was selected because it provides better protection of the seals when exposed to the water with fines that is expected on the Rondout project.

High Water Inflow Design Considerations

In order to protect the TBM and personnel from sudden inrushes of water the TBM was designed to be sealed quickly in the event of a sudden inrush of water. The below steps are required for sealing of the TBM against inflows and are shown in Figure 6:

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 specification required a robust dewatering system for the tunnel. Two dewatering capacities were required on the TBM.

- Continuous Pumping—800 gpm during boring with no impacts on boring or ring building
- Emergency Pumping—2500 gpm emergency capacity for water from head- and construction water

The continuous dewatering system is capable of collecting water from the CHD chamber, TBM shields/ring build area and also at the transfer point between TBM conveyor and Transfer conveyors. The dewatering system is designed to transfer fines up to a ¼ inch in size from boring through the piping and tanks to the tunnel dewatering system. The TBM is equipped with two 10 cubic meter dewatering tanks with mixing pumps inside the tanks to prevent fine settlement, thus reducing shutdowns for maintenance and cleaning.

The emergency pumping system bypasses the dewatering tanks and transfers water directly from the backup system to the tunnel dewatering system via a telescoping pipe extender on the backup. A general system schematic of the dewatering system is shown in Figure 7.

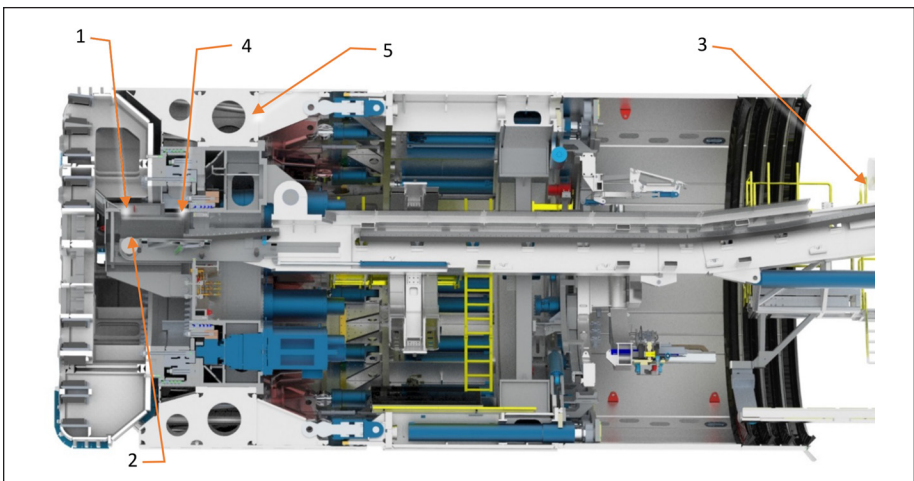


Figure 6. TBM sealing sequence

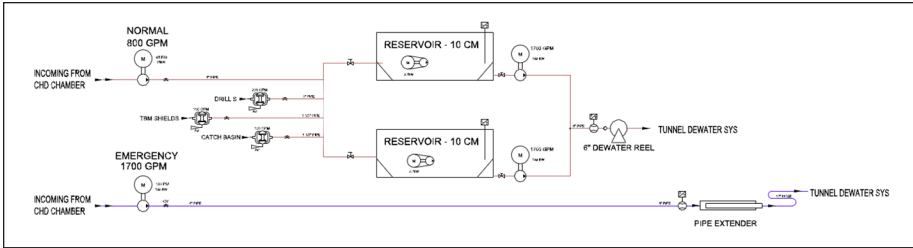


Figure 7. Dewatering system line diagram

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 4 probe holes every 200 feet and 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-excitation 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.

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 7 degrees to the tunnel alignment and are used for umbrella drilling and grouting to form a grout curtain to cut off water inflows surrounding the tunnel alignment.

The drills selected by the contractor are down-the-hole water hammers manufactured by Wassara. The 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 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.

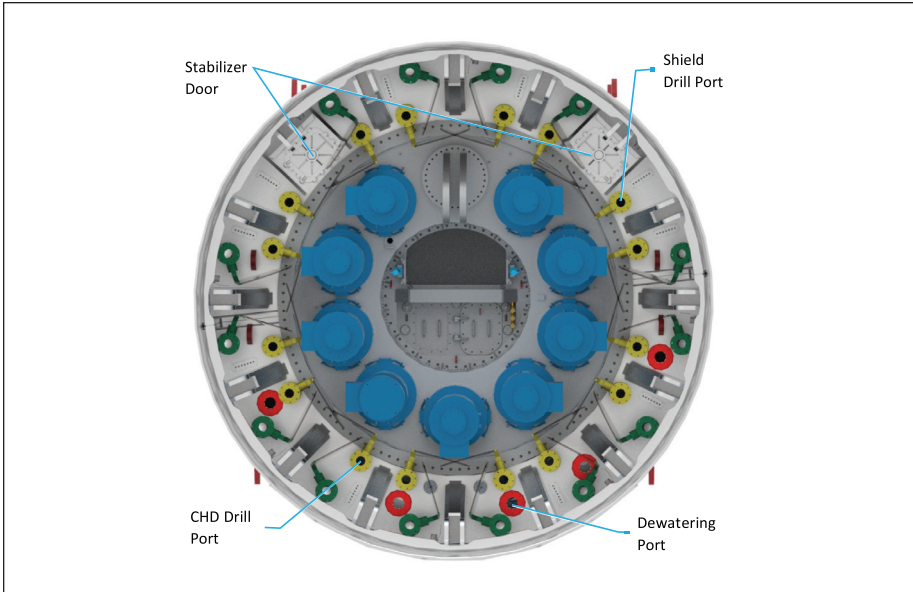


Figure 8. Forward shield drilling and dewatering ports

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 8.

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 through 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 TBM. A+B Storage tanks on the TBM backup 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 and not through the segmental lining in order to increase worker safety. On previous projects grout penetration plugs have been dislodged at high velocities that endanger worker safety. Grouting through the tail skin reduces the segmental lining penetrations and improves safety by eliminating these penetrations.

Project Update and TBM Assembly Challenges

The project site presented several challenges to the assembly and launching of the TBM. Due to limited space at the launch shaft the shipping of TBM assemblies was carefully planned to coincide with the assembly sequence. The TBM is to be assembled at the bottom of a 900 foot vertical shaft. To facilitate the assembly and launch of the TBM the weight and lifting of major parts of the TBM was carefully coordinated with the contractor to ensure the machine design worked well with the site constraints.

The contractor muck haulage crane has a maximum lifting capacity of 100 US tons. The TBM components were designed so that all lifts are less than 100 US tons and will fit down the limited shaft window designated by the contractor. The TBM is to be assembled on a moving cradle at the bottom of the shaft that can then be moved to the tunnel face.

The TBM is currently being assembled at the Robbins Facility in Solon, OH and is tentatively scheduled to begin boring in the spring of 2017.

CONCLUSIONS

The Rondout West Branch Tunnel Bypass Project presents many challenges that required innovative solutions. The difficult geology and large water inflows required the TBM to have features typical to a normal rock TBM's. The high static water pressure required the TBM to have many features that are typically associated with pressurized TBMs. The TBM is to be equipped with robust drilling, grouting and dewatering systems to overcome the expected challenges of the project. In addition, custom sealing systems have been developed so the TBM can bore at atmospheric conditions and then be sealed in a short time to withstand 30 bar water pressure. The innovations developed for the Rondout project show that TBM technology continues to improve to allow hard rock TBMs to tackle more difficult geology than ever before.

REFERENCES

Dowey, T., Sozer, Z., and Brion, P. 2015. Rapid Excavation and Tunneling Conference 2015 Proceedings. Edited by M.C. Johnson and S. Oginski: Society of Mining and Engineering

Dowey, T., Kharivala, B., and O'Connor, P. 2014. Rondout West Branch Bypass Tunnel Construction and Wawarsing Repairs, Delaware Aqueduct Bid Set. New York City Environmental Protection

Water for the Future: Delaware Aqueduct Rondout-West Branch Tunnel Repair, www.nyc.gov/html/dep/html/environmental_reviews/rwb_tunnel_repair_project.shtml