Design and Construction Considerations for the Pawtucket CSO Tunnel

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ABSTRACT

The Pawtucket Tunnel is a 2.2-mi, 30.2-ft diameter CSO storage tunnel in Rhode Island. The primary tunnel is built using a dual-mode open-EPB TBM capable of sealing the face within 120 seconds to manage poor ground and water ingress which is launched from within a SEM starter tunnel. The main tunnel connects to four adits along its alignment, three of which are SEM tunnels and one being a MTBM tunnel. This contribution describes the selection process, potential risks, and requirements for the TBM, as well as the design of the main tunnel, the adits, and the adit-bored tunnel connections.

INTRODUCTION

The Narragansett Bay Commission (NBC) owns and operates Rhode Island's two largest wastewater treatment facilities, the Field's Point Wastewater Treatment Facility (FPWWTF) and the Bucklin Point Wastewater Treatment Facility (BPWWTF). NBC also operates 112 miles of interceptors, nine outlying pump stations, 26 tide-gates, 65 combined sewer overflows (CSOs), and a septage receiving station. In addition, NBC owns and operates a 62-million-gallon-capacity CSO storage tunnel, a tunnel pump station and numerous CSO diversion facilities.

NBC embarked on a three-phase CSO control program in 1998, aimed at lowering annual CSO volumes and reducing annual shellfish bed closures in accordance with a 1992 Consent Agreement (CA) with the Rhode Island Department of Environmental Management (RIDEM). Phases I and II of the Program, which focused on the Field Point Service Area in Providence, were completed in 2008 and 2015, respectively. The program succeeded in lowering annual CSO volumes and reducing annual shellfish bed closures to levels that are in keeping with a 1992 CA between NBC and RIDEM.

The third and final phase (i.e., Phase III) is focused primarily within the communities of Pawtucket and Central Falls. The implementation strategy prioritizes water quality benefits, while also limiting the financial impact on rate payers. The primary elements include the Pawtucket Tunnel and ancillary underground components including a launching shaft, receiving shaft, drop/vent shafts, adit tunnels, and tunnel pump station. The tunnel system provides volume to store all contributing overflows during a storm event up to the three-month storm for subsequent pump out and treatment. The required minimum storage volume to achieve the defined hydraulic criteria (i.e., no overflows for the three-month design storm, and no more than four overflows per year per outfall for typical year storms) is 58.5 million gallons (MG).

The Pawtucket Tunnel is a rock tunnel, 115-ft to 155-ft below the ground surface, located adjacent to the Seekonk and Blackstone Rivers in Pawtucket, RI. The tunnel is approximately 11,600-ft in length with a 30-ft inside diameter (see Figure 1). The tunnel is mined with a Herrenknecht dual mode (open/EPB) TBM. The machine is fitted with a hard rock cutterhead and a conveyor to extract muck from the face when it is operated in open mode or a screw conveyor when operated in earth pressure balance (EPB) mode. The lining is made of universal double taper rings of seven fiber reinforced segments, thickness 14-inches and 6.6-ft in length. Each segment joint both radial and circumferential is fully gasketed to achieve the water tightness criteria.

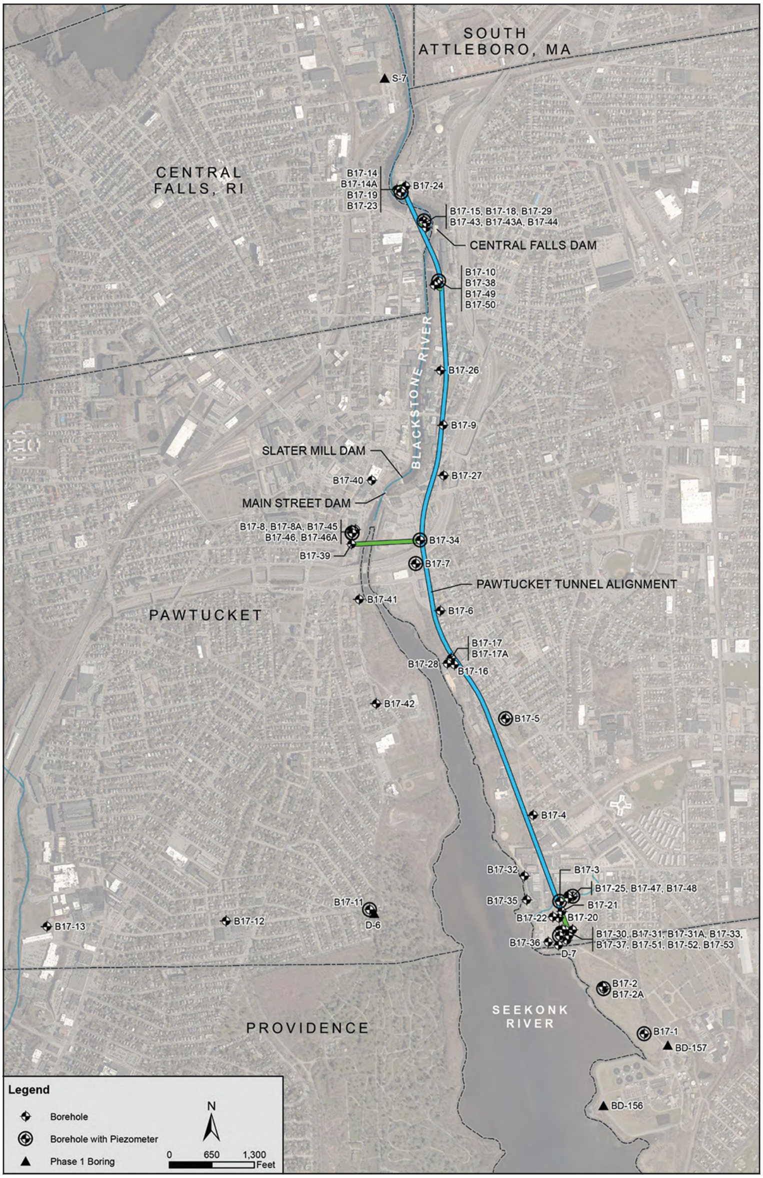


Figure 1. Pawtucket tunnel alignment

NBC is under a CA with RIDEM, which defines the implementation schedule for the Phase III CSO Program. The final construction completion date is for a fully operational tunnel system. The tunnel, tunnel pump station, and near surface projects must be completed and operational prior to the dates specified in the CA. Near surface structures planned at drop shaft sites and the mechanical fit-out of the tunnel pump station will be constructed by others under separate contracts.

NBC selected a design build delivery to meet the regulatory schedule and manage risk. The objectives included the following:

- Establish a collaborative relationship between NBC, Program Manager, and Design-Builder to deliver a quality Project on time and within the defined Project budget.
- Maintain a safe, injury-free work site(s).
- Minimize impacts to the community through close coordination with NBC and community stakeholders.
- Control costs to reduce economic burden to ratepayers.
- Manage risks to successfully deliver the Project.
- Minimize disruption to customers and NBC operations.
- No impacts to environmental water quality and/or BPWTF performance during construction.
- Maximize participation of Rhode Island based engineering firms, contractors, subcontractors, suppliers, and construction trade labor.
- Protect and enhance water quality in Narragansett Bay and its tributaries by providing safe and reliable wastewater collection and treatment services to customers at a reasonable cost.

The project team for the Pawtucket Tunnel Design Build include Stantec/Pare, Program/Construction Managers; CBNA/Barletta JV, Design Builder; and AECOM in association with Gall Zeidler Consultants, Engineer of Record.

GEOLOGY

The geologic history of the bedrock is complex. The rock originates from fluvial deposits, which characteristically are not laterally continuous. Rock types range from conglomerate to coal with sandstone and siltstone as the predominant rock types. Sequential episodes of tectonic deformation have superimposed structural features including folds, faults, and joints.

The Pawtucket Tunnel is constructed mainly in the Rhode Island Formation, a Carboniferous-age sedimentary rock comprised of sandstone and siltstone, with lesser amounts of conglomerate, shale, and coaly deposits. Bedrock is moderately folded and faulted. Bedrock is overlain by a thin layer of glacial till and thick layers of glaciofluvial deposits. Glacial deposits are comprised mainly of sand, gravel, and silt, and are overlain by granular fill.

The project area is within the Narragansett Basin, which is approximately 55 miles long, 15 to 25 miles wide, and is made up of several thousand feet of non-marine sedimentary rocks that have been folded, faulted, and slightly to moderately metamorphosed. Sedimentary rocks of the Narragansett Basin have been divided into five formations, of which the Wamsutta Formation and the Rhode Island Formation occur within the tunnel horizon. Bedrock is overlain by glacial deposits consisting of till and glaciofluvial deposits as well as man-made fill deposits near surface.

The Rhode Island Formation is widespread and consists mainly of gray sandstone and siltstone, with lesser amounts of gray to black shale, conglomerate, and coaly rock. These sediments were deposited in medial to distal alluvial fan environments, and are comprised of meandering stream deposits, bank and flood plain deposits, and swamp deposits. Sediments of the Rhode Island Formation generally are finer-grained than those of the Wamsutta Formation. Rock types are laterally and vertically discontinuous, a characteristic of the environment in which they formed.

The Wamsutta Formation occurs in the northern part of the Narragansett Basin, where it underlies and partially interfingers with the Rhode Island Formation (Skehan, Rast, and Mosher 1986). The Wamsutta Formation consists of a sequence of red conglomerates, sandstones, and shales up to 3,000 feet thick. Volcanic fragments are common. Conglomerate in the Pawtucket quadrangle contains boulders as large as 4 feet in diameter (Quinn 1971). These sediments were deposited in an alluvial fan environment, and are composed of braided stream deposits, with related crevasse splay deposits and flood plain deposits. Bedrock of the Wamsutta Formation is present along the northern 200-ft to 400-ft of the tunnel.

PROJECT CRITERIA/RISK MANAGEMENT

Project Criteria

Stantec developed Project Criteria, including Base Technical Concept (BTC) Design, to support the procurement. The BTC design included preliminary design drawings, Geological Baseline Report (GBR), Geotechnical Data Report (GDR), and Environmental Data Report (EDR). The Design Builder (DB) was responsible to developing final design documents for project elements to comply with project criteria for each of the project elements. The project elements included bored tunnel, large diameter shafts, suction header, drill and blast adit tunnel, and drop/vent shafts. The design was completed in January 2022 to comply with dates in the CA.

The primary functionality of the tunnel is to provide storage of combined sewage during wet weather events to control CSOs. The project criteria require the tunnel provide a storage capacity of 58.5 MG to store CSO generated during the 3-month design flow. The hydraulic criteria are prescriptive specifying vortex style drop shafts with hydraulic capacity to convey peak flows from the 2-year storm.

Durability criteria requires precast concrete segmental lining, internal components, permanent bolts, and associated inserts to be designed for a minimum of 100-year service life. Service life for reinforced concrete is defined as total duration to initiation of steel corrosion plus five years of propagation duration of carbon steel. Design and durability analysis considers pH level, chloride content, sulfates and other contaminants in soil, rock, ground water, and future wastewater. Analysis and testing confirmed exposure conditions for service life modeling.

Key project criteria for the Pawtucket Tunnel included the following:

- Diameter 30-ft ID
- Slope 0.001 ft/ft
- Minimum rock cover of two tunnel diameters. *Note: CBNA/Barletta raised tunnel elevation by 25-ft, during the Alternative Technical Concept process.*
- Maximum allowable groundwater infiltration 1 gpm per 1000 ft of tunnel and 0.1 gpm at any one segment

Risk Management

NBC identified the following top five (5) risks: worker and public safety; TBM mechanical failure; damage to third party building, structures, or utilities due to ground movement during excavation; delay in production or delivery impacting project schedule and milestone completion, and differing site conditions. The procurement commenced in December 2019 prior to risks/issues associated with COVID, supply chain delays, and macroeconomic inflationary pressures. The risks associated with bored tunnel focused on ground conditions, which were baselined in the GBR for Bidding (or GBR-B): methane, water inflow, low strength rock, and fault at northern alignment.

The GBR-B identified construction considerations attributed to how predominant types of ground are expected to behave in response to construction. During preliminary design, the vertical profile provided two diameters of sound rock cover over the crown in an area of low rock near tunnel station 146+00. The horizontal alignment and shaft locations accommodated property acquisition constraints and operational preferences. As previously noted, the JV submitted an alternative technical concept (ATC) to raise the tunnel elevation, thereby reducing the amount of rock cover.

Pawtucket area coal has the capacity to retain high amounts of methane, but geologic history combined with mining and drilling experience indicates that the actual methane content of coal is low. Methane can be adsorbed on organic surfaces of coal and is released by a reduction in hydrostatic pressure. The potential exists for discharge of methane from carbonaceous rock, so excavations in rock were classified as "potentially gassy."

RMR values along the tunnel range from about 30 (poor) to 70 (good). Rock mass quality generally improves from south to north. For an excavated diameter of 33.5-ft, immediate collapse in the crown is indicated for most of the alignment. To mitigate the risk of roof fallout, the project criteria require tunnel excavation with a shielded TBM and concurrent installation of a permanent lining of gasketed precast concrete segments. The single-pass lining approach minimizes groundwater discharge volumes. This approach mitigates problems associated with localized deposits of weak mudstones and coal, such as loss of bearing on gripper pads, and a soft invert.

A potential fault crosses the tunnel alignment under the river at the northern end of the alignment (see Figure 2). The GBR-B baselined the fault to be vertical, composed of a major slip zone 3-ft wide, surrounded on each side by a damage zone comprising a network of low-throw faults trending subparallel to the major fault. Each damage zone is estimated to be 60-ft in width, for a total width of the fault zone of 123-ft. To mitigate the risk of excessive inflows while tunneling under the river, it is expected that probing and grouting ahead would be needed. The baseline conditions were conservative based on the inability to locate the contact between the two formations during the preliminary geotechnical investigation.

The JV successfully located the contact, which indicated a contact zone (i.e., no fault) and no fractured water bearing features. The JV conducted additional investigations from the surface to revise the baseline within the reach in the GBR-C. In addition, a probe at the base of the receiving shaft was drilled in December 2022 with two horizontal probes confirming the contact between the Rhode Island and Wamsutta formations. At the time of this article, one of the two probes was completed, confirming the following: no apparent faulting along the contact between the two formations, two formations appear to be interfingered, and no significant groundwater inflows. The JV

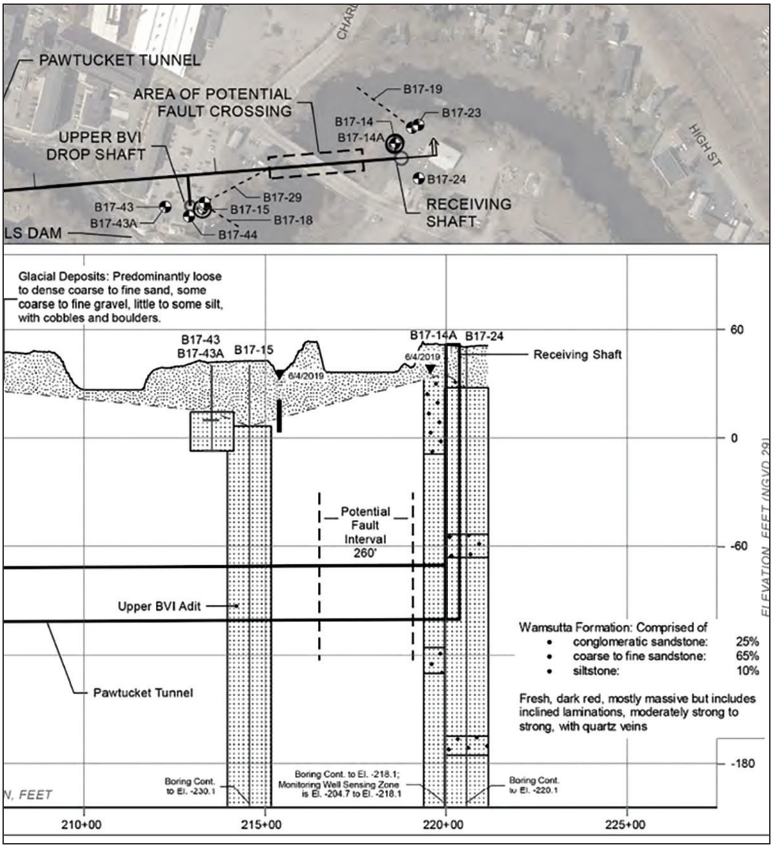


Figure 2. Pawtucket Tunnel ground conditions at receiving shaft

updated the GBR-C accordingly, identifying TBM operation through this zone to be in open mode.

Groundwater inflow was an identified risk due to flow rates encountered during construction of the Providence tunnel. A secondary risk was impact to NBC wastewater treatment facility from elevated loadings of total suspended solids, pH, and impact to sludge production. Efforts to reduce tunnel dewatering flows became important for both points.

Estimated flush flows from the heading of Providence Tunnel were typically 100 gpm with brief intervals ranging up to 200 gpm (Kaplin, Peterson, and Albert 2009). These heading inflows ranged from about ½ to 1 times the steady state inflow.

The GBR-B baselined the main tunnel drive to cross one or more shear zones. Such locations of high fracture density would produce high inflow rates over a short distance of up to 100-ft. The baseline for localized heavy inflows is set at a sustained inflow rate of up to 130 gpm per 100-ft of tunnel, to occur at one interval up to 100-ft long, at an unidentified location south of station 208+00. It also baselined the tunnel drive to cross a fault zone under the river. As a baseline, sustained inflows of up to 400 gpm per 100-ft of tunnel may occur within the fault zone. The fracture network related to the fault zone is expected to be directly connected to the river.

BORED TUNNEL CONSTRUCTION AND TBM DESIGN

The JV selected Herrenknecht from Germany as the TBM supplier. Through negotiation and risk allocation, the Project Team agreed on the use of a TBM with open mode/EPB capabilities which presents the advantage of controlling muck management, minimized maintenance and optimized production time. The TBM contract was secured during the tender time and triggered when the Notice to Proceed was provided on December 18th, 2020. The TBM was manufactured in the Herrencknecht factory in Germany and despite the disturbance due to the COVID pandemic, the Factory Acceptance Test was completed ahead of schedule in January 2022. The TBM delivery time frame went from end of April to end of June 2022.

The 33.8-ft diameter TBM has a 46-ft long shield and a 300-ft long trailing gear, comprised of four gantries to supply power to the shield, and connect the utilities and logistics. The shield is composed of three main sections with one active articulation. This enables operators to achieve the minimum required curvature of 1,000-ft. The structure and seals are designed for 72 psi of pressure.

The 33.8-ft diameter cutter head is designed for hard rock and protected against wear. The cutterhead has a total of sixty four 19-inch cutter discs for high efficiency and reliability in the anticipated conditions. It can be configured for either EPB mode or open mode. Transition between the two modes is approximately a week.

The machine is fitted with a conveyor belt in open mode and a screw conveyor in EPB to expel muck from the cutting chamber. The TBM can be isolated in less than ten minutes to control flow at the heading for elevated inflows and/or face instability.

Mining has commenced in open mode and will be the primary mode for the Pawtucket tunnel. EPB mode will be used when confinement pressure is required to ensure the stability of the ground and/or to control water ingress. The conformation of the contact between the two rock formations at the northern river crossing gave credence to the selection of mining in open mode. The JV confirmed the contact did not have any fractured zones with water bearing features. Mining in open mode increases production rate and eliminates the need for soil conditioners.

The mode would transition to EPB due face instability and/or elevated groundwater inflow. The change of mode is anticipated to be executed in a week of work mainly in the cutting chamber to re-configurate the cutter head. In open mode, the muck is collected and lifted to a conveyor fitted in the center of the shield; these buckets would be removed to allow the extension of the screw conveyor to collect the muck in the bottom of the excavation chamber. The bulkhead will then be closed by retracting the conveyor belt and the machine will be able to operate in the confinement mode.

A dual mode TBM is advantageous to the project balancing production and risk management, During favorable ground conditions, JV will mine in open mode achiever higher production. In poor ground conditions, mining in EPB reduces the need for probe drilling and pre-grouting, which would be required in a single open mode TBM (Figure 3).

The TBM began mining in November 2022 from the launch shaft on the main site at the Southern end of the project area (Figure 4). The launch shaft is 62-ft diameter and 155-ft deep. Soil excavation is within a cofferdam made of secant piles and in the rock using drill and blast techniques. At the base of the shaft excavation (120-ft), a starter tunnel of 230-ft and a tail tunnel of 60-ft were excavated in two stages: a top heading and bench. The remainder of the shaft was then completed after the starter tunnel and

Figure 3. TBM in Herrenknecht factory in January 2022

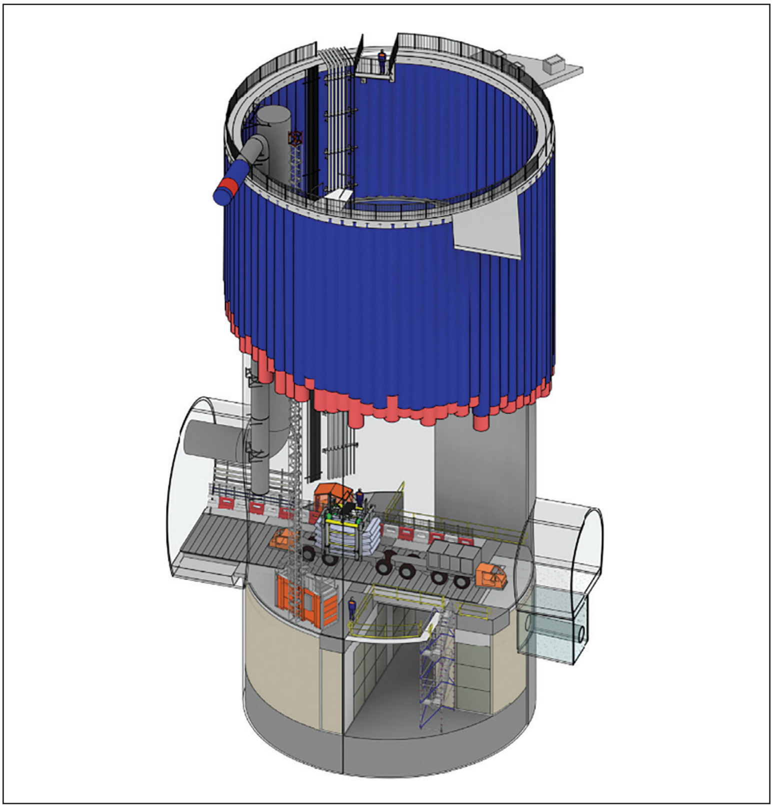


Figure 4. TBM operations at launch shaft

tail tunnel were excavated. The bottom of the shaft was backfilled, and a trench was kept below the tunnel invert to install the bottom part of the vertical conveyor. This sequence of works has avoided remobilizing the drill-and-blast team for deepening the shaft to its final level and brings benefit to the general schedule of works.

To leave sufficient time to complete the preparation works in the shaft and starter tunnel to receive the TBM, it was decided to pre-assemble the TBM in surface. The 1,665-ton machine was delivered in 82 packages of about 20 tons and for the five heaviest ones just under 100-tons. The pre-assembly on the surface made possible to lower parts into the shaft up to 375-tons. The mobilization of a 600-ton crawler crane for six weeks was necessary to lower the three elements of the shield and the cutter head. The back-up gantries are pre-assembled in half section not limited by the weight but by the size to fit inside the 62-ft diameter launch shaft (Figure 5).

Figure 5. 375-ton TBM front shield lowered with the 600-ton crawler crane in the launch shaft

Surface logistics at the main site provides the necessary support to the TBM operation. A crawler crane of 350-ton capacity handles the segments and the services inside the shaft. It is assisted by a loader to unload the segments from the delivery trucks. There is sufficient space on top of the shaft to store up to sixty rings, more than a week of TBM production. The 350-ton crawler crane is also used for the TBM assembly. It is used primarily for the pre assembly of the gantries (Figure 6 and 7).

Tunnel muck is transported from the TBM by a chain of conveyors at a rate of 1,250 tons per hour. The muck is transported out of the shaft by using a vertical bucket conveyor. At the surface, the muck is dropped by a radial stacker in a stockpile accumulating 15,000 cubic yards (the average weekly quantity excavated by the TBM).

The rest of the surface installation comprises of the following:

- Mortar and Cooling Plant
- Electrical Substation
- Water Treatment Plant
- Main Offices
- Mechanical and Electrical Workshop

SEM TUNNEL CONSTRUCTION

The Pawtucket project contains several mined tunnels (i.e., main drive, adits). In a similar fashion to the contract form and TBM selection, the mined tunnels were designed with the goal of minimizing risk. However, in contrast to TBM tunneling, mined tunneling is performed under open face conditions without the aid of a protective shield. As

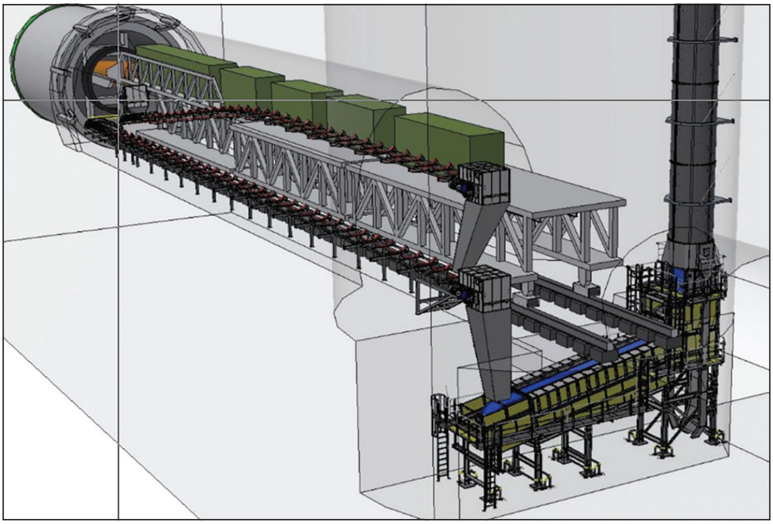


Figure 6. Conveyors system in the tunnel and shaft

Figure 7. Main site aerial picture during TBM assembly

such, to minimize risk, the Sequential Excavation Method (SEM) is employed using separate support classes depending on the expected rock behavior. The specifications also call for rock excavation and support meetings (RES meetings), in which representatives from the Engineer of Record (EOR), NBC, and JV decide the appropriate support measures based on the existing rock conditions. The design build delivery allows for a close interaction between the engineer and contractor during tunneling. This close interaction allows for efficient adjustment of rock support to ensure that what is installed is both safe and economical.

The largest mined tunnel along the alignment is the starter tunnel. The starter tunnel extends northwards from the launch shaft in the direction of the main tunnel and houses the TBM during launch. To further extend the launching area for the TBM, a shorter tail tunnel has been constructed between the launch shaft and the future pump shaft. In addition to these larger mined tunnels, The Pawtucket tunnel will be connected to four drop shafts by tunnel adits along its alignment. The adits, listed from

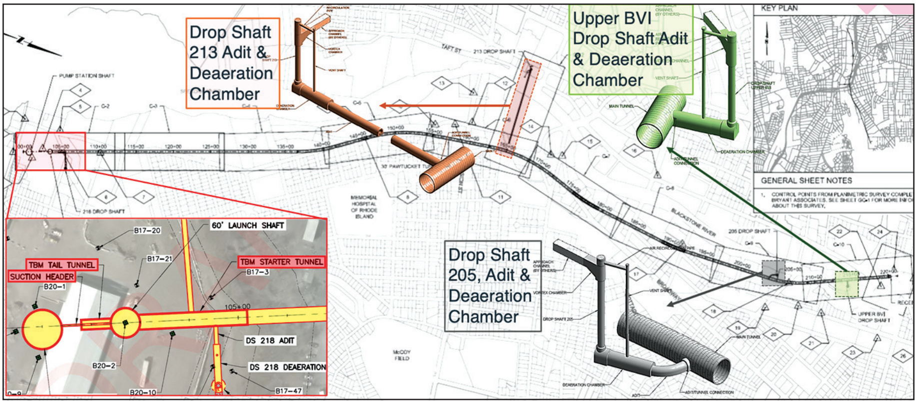


Figure 8. Layout of the Pawtucket Tunnel and connecting structures (receiving shaft is not shown)

south to north, are referred to as the Drop Shaft (DS) 218, DS 213, DS 205, and Upper Blackstone Valley Interceptor (UBVI) adits. The DS 218 adit connects to the SEM starter tunnel portion of the alignment and the DS 213, DS 205 & UBVI adits connect to the segmentally lined portion of the main tunnel alignment. The location of the adits, the tail tunnel, and the starter tunnel are shown schematically in Figure 8. At the time of writing this contribution, the starter tunnel and tail tunnel have been fully excavated.

The JV has proposed to excavate the OF-213 adit from the access shaft to the main spine tunnel by micro tunneling to mitigate the geological risks inherent to drill and blast mining initially anticipated in the BTC. The adit is over 1,000-ft in length and crosses under the Seekonk River. Additional ground investigations from the surface were limited by accesses not granted into private properties. The choice of a confined microtunnel TBM prevent the use of pre-excavation grouting and secure the schedule against geological conditions.

The JV has decided to utilize Hobas fiber reinforced plastic (FRP) jacking pipe for the 1,000-ft adit. FRP pipe was selected to attain the 100-year durability requirement for the project as well as achieving pressures needed on the gaskets. The fiberglass pipe is 96-inch in nominal diameter with a pipe wall thickness of 3-inch. The pipe joint is a flush bell and spigot joint which has an allowable safe jacking load of about 1,150-ton and a maximum allowable hydrostatic pressure up to roughly 70 psi.

Starter and Tail Tunnel

The starter tunnel is ca. 220-ft long with a design excavation width at the springline of 37'-2" and a height of 36'-11 ¾", making it the largest horizontal excavation by area along the tunnel alignment. Based on the geotechnical borings, and as discussed in the previous section on geology, the starter tunnel was expected to pass through primarily siltstone and sandstone with the potential for shale seams and coaly deposits. The rock mass was expected to have a median RMR of around 40. In addition, the contract requirements include the stipulation for a "contingency" support class be developed, in case worse-than-expected conditions should occur.

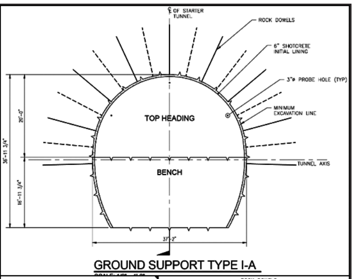
To provide greater flexibility in this relatively short tunnel, the design includes two support classes plus the contingency support class. The general support class (SCI) is intended for a rock face with a mapped RMR of 40+, a heavier support class, SCII, is intended for a rock mass with an RMR of 30–40, and the contingency support class, which is also referred to adverse ground support, is for ground/rock with an RMR of below 30, in which soil-like behavior may be encountered. Both SCI and SCII feature rock dowels with fiber reinforced shotcrete, and the contingency support class also features a closed invert. Excavation was carried out by drill and blast and the excavation sequence was subdivided into a top-heading and two benches, to match excavation levels in the connecting shafts and tail tunnel. As mentioned above, the stand-up times predicted in the GBR for the large excavations were not high. As such, all support classes stipulate that a 2-inch minimum flashcrete layer is to be applied immediately after excavation and rockbolting to ensure stability.

Rock conditions at the shaft-tunnel interface were as expected, with the greatest tunneling risk being a graphitic shale seam located at the excavation crown. The rock quality did, however, significantly improve along the length of the tunnel, with RMR values at the face consistently exceeding 50 deeper in the rock. This represented, contrary to expectations in the GBR, stable rockmasses with sufficient stand-up times. As such, the excavation procedure was modified. A third support class, SCI-A was developed with a single top heading/bench, the longest round length, and the lightest support. Figure 9 describes the support classes, their intended application range, and depicts the lightest (SCI-A) and heaviest Support Class (Contingency Support).

The tail tunnel is 65' long with a design cross section of 24'-4" width × 22'-2" height. Like the starter tunnel, three ground support classes were developed, GSI (RMR>40), GSII (30<RMR<40), and a contingency ground support class (RMR<30) for adverse ground conditions. During excavation, the rockmass was found to have higher RMR values than expected, partly because the rock mass was dipping away from the excavation. As such, it was decided to excavate the tail tunnel full-face to improve logistics. This decision was supported with experience gained from mining the starter tunnel. No significant instabilities were observed during construction of the starter tunnel top heading. Because the starter tunnel top heading has an area similar to that of the tail tunnel, it was assumed that no major instabilities would be observed in the tail tunnel even with full-face excavations.

STANDARD GROUND SUPPORT TYPE I-A	
APPLICABILITY	RMR $\geq$ 50; COMPETENT ROCK MASS IN THE CROWN
ANTICIPATED GROUND BEHAVIOR	OVERALL STABLE ROCK MASS WITH POTENTIAL FOR SMALL LOCAL GRAVITY-DRIVEN FALLING OR SLIDING OF BLOCKS
ROCK DOWEL TYPE	#8 ROCK DOWELS, GROUTED WITH CEMENT GROUT OR RESIN
ROCK DOWEL LENGTH	12 FT
ROCK DOWEL SPACING	8 FT (TRANSVERSE) X 6 FT (LONGITUDINAL)
SEALING SHOTCRETE THICKNESS	2 IN
INITIAL SHOTCRETE LINING TOTAL THICKNESS	6 IN
PROBE DRILLING	3 PROBE HOLES W/20 FT OVERLAP
EXCAVATION SEQUENCE	TOP HEADING & BENCH
MAX. ROUND LENGTH	TOP HEADING: 12 FT BENCH: 12 FT

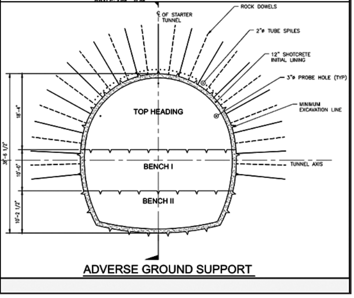
STANDARD GROUND SUPPORT TYPE I	
APPLICABILITY	RMR $\geq$ 40
ANTICIPATED GROUND BEHAVIOR	BLOCKY ROCK MASS WITH DISCONTINUITY CONTROLLED GRAVITY-INDUCED FALLING/SLIDING OF BLOCKS WITH OCCASIONAL LOCAL SHEAR FAILURE ON DISCONTINUITIES.
ROCK DOWEL TYPE	#8 ROCK DOWELS, GROUTED WITH CEMENT GROUT OR RESIN
ROCK DOWEL LENGTH	12 FT
ROCK DOWEL SPACING	8 FT (TRANSVERSE) X 8 FT (LONGITUDINAL)
SEALING SHOTCRETE THICKNESS	2 IN
INITIAL SHOTCRETE LINING TOTAL THICKNESS	8 IN
PROBE DRILLING	MIN. 3 PROBE HOLES W/20 FT OVERLAP
EXCAVATION SEQUENCE	TOP HEADING, BENCH I & BENCH II
MAX. ROUND LENGTH	TOP HEADING: 8 FT BENCH I: 16 FT BENCH II: 16 FT



GROUND SUPPORT TYPE I-A

STANDARD GROUND SUPPORT TYPE II	
APPLICABILITY	30 $\leq$ RMR < 40
ANTICIPATED GROUND BEHAVIOR	DEVELOPMENT OF SMALLER WEDGE FAILURES AROUND THE TUNNEL OPENING WITH POTENTIAL FOR CHIMNEY DEVELOPMENT.
ROCK DOWEL TYPE	#8 ROCK DOWELS, GROUTED WITH CEMENT GROUT OR RESIN
ROCK DOWEL LENGTH	12 FT
ROCK DOWEL SPACING	5 FT (TRANSVERSE) X 5 FT (LONGITUDINAL)
SEALING SHOTCRETE THICKNESS	2 IN
INITIAL SHOTCRETE LINING TOTAL THICKNESS	8 IN
PROBE DRILLING	MIN. 3 PROBE HOLES W/20 FT OVERLAP
EXCAVATION SEQUENCE	TOP HEADING, BENCH I & BENCH II
MAX. ROUND LENGTH	TOP HEADING: 5 FT BENCH I: 10 FT BENCH II: 10 FT

CONTINGENCY GROUND SUPPORT	
APPLICABILITY	RMR < 30
ANTICIPATED GROUND BEHAVIOR	BLOCKY DISTURBED, DISINTEGRATED, SHEARED ROCK MASS WITH POOR INTERLOCKING: SHALLOW STRESS-INDUCED FAILURE AND CHIMNEY DEVELOPMENT OR RAVELING IN THE TUNNEL CROWN
ROCK DOWEL TYPE	#8 ROCK DOWELS, GROUTED WITH CEMENT GROUT OR RESIN
ROCK DOWEL LENGTH	12 FT
ROCK DOWEL SPACING	5 FT (TRANSVERSE) X 3 FT (LONGITUDINAL)
PRE-SUPPORT (SPILES)	2"Ø MIN, 12" LONG @ 12" C/C, SELF DRILLING, PERFORATED TUBE PIPE SPILE (AT TUBE SPILE OR HCB 51N), GROUTED WITH CEMENT GROUT, AS REQUIRED.
SEALING SHOTCRETE	2 IN
INITIAL SHOTCRETE LINING TOTAL THICKNESS	12 IN
PROBE DRILLING	MIN. 3 PROBE HOLES W/20 FT OVERLAP
FACE WEDGE	AS REQUIRED
EXCAVATION SEQUENCE	TOP HEADING, BENCH I, BENCH II
MAX. ROUND LENGTH	TOP HEADING: 3 FT BENCH I: 6 FT BENCH II: 6 FT CONTRACTOR MAY REDUCE THE ROUND LENGTH AND SPLIT FACE AS REQUIRED BY THE GROUND CONDITIONS.



ADVERSE GROUND SUPPORT

Figure 9. Starter tunnel support class types I-A through to contingency support; The heaviest (contingency/adverse support) and lightest Ground Support type I-A are also schematically depicted

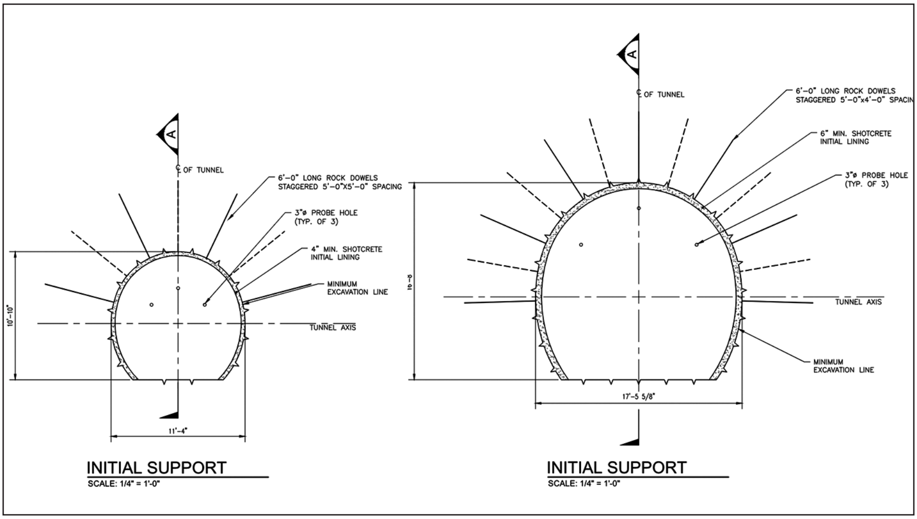


Figure 10. Adit Cross section showing ground support type 1 (on left) and Deaeration Chamber Cross section showing ground support type I (on right)

The final lining of the starter tunnel will be cast-in-place fiber reinforced concrete cast flush with the inner diameter of the TBM tunnel. Fiber reinforced concrete was selected not only out of economy, but to increase robustness of the lining against corrosion, further minimizing risk that significant damage would occur to the as-built-structure over time. The tail tunnel will be back filled.

SEM Adits

In contrast to the tail and starter tunnel, the SEM adits are much smaller in cross section. The SEM adits excavations are 11'-4" in width by 10'-10" in height and are of varying length. The adits are "preceded" by a slightly larger deaeration chamber. The deaeration chambers are immediately below the drop shafts. When water is collected in the drop shafts, it flows first through the deaeration chamber and then into the adit. The deaeration chambers all have an excavation cross section of 17'-5 ⅝" width by 16'-8" height and are all ca. 90-ft long.

Because of the smaller size of the deaeration chambers and the adits, a single support class, in addition to the contractually mandated contingency support class, was deemed sufficient. In addition, the rock quality along the tunnel alignment generally improves as the alignment stretches north, and it is therefore assumed that the adits and deaeration chambers will be built in a more stable rock mass to that of the starter & tail tunnels. The cross section of this support class, SC1, is shown in Figure 3 for both the adit and deaeration chamber.

CONCLUSION

NBC selected design build delivery for the Pawtucket Tunnel to manage risks and align design responsibilities with the DB team. The primary risk inherent to underground construction was understanding the geologic properties along the alignment and its influence on construction. The GBR is an important tool in risk management and risk allocation between the owner and the JV. At time of tender, Stantec baselined the ground conditions in the GBR-B defining properties of soil and rock along the alignment utilizing accepted statistical analysis of the data. The GBR-B baseline comprised the geological data, the interpretation of existing geotechnical conditions, and the expected ground's response to construction.

The design build delivery system offered an opportunity for the NBC and JV to jointly engage in the process of risk management while final design was on-going. The JV had an opportunity to engage their design team by providing interpretations of GBR-B in developing their approach to design and construction. The JV identified gaps in data and performed supplemental investigations. NBC and the JV then negotiated the terms of the baseline to formulate the GBR-C. The GBR-C reflected a joint understanding of the interpreted baseline conditions that was consistent with the design, the planned equipment, and the construction means and methods.

The supplemental investigation of the contact between the Rhode Island and Wamsutta formations and the absence of a fractured water bearing feature is an example of the two step GBR process having a net benefit to the project. The tunneling approach was optimized based on the results of this investigation. As such, the JV elected to use a dual mode TBM with the primary operating mode being the open or unpressurized mode. The JV engaged their design team to refine the interpretation based on the supplemental data, which culminated in a revised GBR-C. Stantec and NBC actively participated by assessing the appropriateness of the update and preventing a re-allocation of risk through the process.

The close coordination with JV and engineer team on ground conditions during SEM afforded efficient decision making in appropriate rock support. The underlying objective is for construction to proceed in a safe, efficient manner to maintain schedule. Analogous to the TBM selection process, the investigations and interpretations described in the GBR-C were used to develop an efficient SEM excavation scheme, which has proved successful.

At the time of this article, the TBM mining has commenced in November 2022. The 11,600-ft, 30-ft diameter tunnel is anticipated to be fully mined in January 2024. Final lining and site restoration is scheduled for December 2024 to allow the follow-on pump station fit-out team to install the mechanical, structural, and electrical systems for the tunnel pump station to become fully operational by December 2026.

The purpose of the paper was to highlight a few examples of the evolving design process inherent to design build delivery. The evolution leads to innovation through refinement linking selected equipment, material, and construction methods to design.

Open and effective communication have been key to successful project delivery, initiated by NBC leadership. The project has endured numerous challenges and risks from outside forces (i.e., COVID, supply chain delays, inflation) and typical project specific challenges. The JV and design team are constantly refining design and approach to manage the challenges. NBC, JV, Program Manager, and design team each understand the role in maintaining the success of the project.

ACKNOWLEDGMENTS

The authors would like to thank the leadership and support of the Narragansett Bay Commission, Stantec, CB3A, and GZ Consultants for permission to publish this paper. Special appreciation is due to Laurie Horridge, Jim McCaughey, and Rich Bernier of NBC; Raoul Fernandes and Pete Williamson of CBNA/Barletta: Mellissa Carter of Stantec: and Thomas Klingenberg and Dominic Reda from GZ Consultants.

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