2023 Outstanding Underground Project

The Rondout Bypass Tunnel Shafts – Shotcrete Lining

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Fig. 1: Welded wire reinforcement tack welded to the steel pipe.

PROJECT DESCRIPTION

The Rondout-West Branch Tunnel (RWBT), a segment of the Delaware Aqueduct (the Aqueduct), was built from 1937 to 1944 and provides about 50% of New York City's total water supply. The tunnel is concrete lined and has a finished inside diameter of 13.5 ft (4.1 m). It is about 45 mi (72 km) in length and runs in the southeasterly direction from the Rondout to the West Branch Reservoirs. Monitoring during tunnel operations consistently demonstrated that the RWBT is leaking up to 35 million gallons (130 million l) per day, mainly through locations at Roseton and Wawarsing. Leaks at the Wawarsing area will be mitigated through an extensive grouting program of the surrounding rock. The leaks originating from the Roseton area are being mitigated by constructing the Rondout-West Branch Bypass Tunnel (Bypass Tunnel).

The Rondout Bypass Tunnel in New York has two access shafts. The upper sections of the shafts are lined with steel pipe to resist a substantial net internal water head. Initial design included a ¾ in. (19 mm) thick cement mortar lining (CML) for all three components. Because of concerns with CML application on large-diameter pipes, the protective lining was redesigned for shotcrete application.

This paper discusses the design, mock-ups, and construction of the protective lining for the two access shafts of the Bypass Tunnel.

ALTERNATE LINING DESIGN

Bypass Tunnel Access Shafts 5B and 6B are located on the west and east sides of the Hudson River, respectively, and are each over 700 ft (210 m) in depth. Portions of the shafts are lined with steel pipe. The steel lining resists net internal hydrostatic head and external groundwater head during operational and unwatered conditions, respectively. The original design specified a minimum of ¾ in. thick CML for the steel access pipe for protection against corrosion. During early planning stages for the application of CML to the surfaces of the access pipe system, the contractor (Kiewit-Shea Constructors, AJV [KSC]) had concerns about CML maintaining adequate adherence during construction. The specific concern was that crews would be required to work in areas hundreds of feet long beneath the mortar in the later stages of the project.

To save time on the schedule, KSC planned to apply the CML to the access pipe sections prior to shaft installation. To demonstrate the adequacy of CML application and performance through a mock-up, KSC used a section of steel pipe that was a spare from the Bypass Tunnel final lining operation. In April 2021, KSC pneumatically applied CML without any reinforcement to an area of the spare liner pipe in accordance with the design. On a different area of the same pipe, KSC tack welded 4 by 4 in. (100 by 100 mm) welded wire reinforcement (WWR) before applying CML (Fig. 1). KSC planned to pick the mock-up pipe sections with a crane to evaluate the performance of the CML after it underwent any deformation changes during the crane pick. However, this never became necessary as the unreinforced CML fell off the pipe before the crane arrived to do the test pick (Fig. 2). The mortar with the WWR stayed in place and did not show signs of distress following the test pick.

Alternate Design Options

The New York City Department of Environmental Protection (NYC DEP) requested that Delve Underground (the department's tunnel consultant on the Bypass Tunnel Project) design an alternate shaft protective lining. Delve Underground considered reinforced CML, reinforced shotcrete, epoxy, and polyurethane systems. In different lining evaluations, adequate surface preparation to install a suitable anchor profile, anticipated temperature and moisture conditions in the shaft, and the availability of skilled labor necessary for successful application were considered. Epoxy and polyurethane coatings became undesirable options since neither technology would support an extended design life without maintenance. Of the reinforced CML and shotcrete options, reinforced shotcrete was selected because of NYC DEP preference and the historically poor performance of CML when subjected to wetting and drying cycles caused by tunnel unwaterings and restarts.

Fig. 2: Pipe after application of CML.

ALTERNATE DESIGN APPROACH

The primary purpose of the reinforced shotcrete lining is to protect the steel access pipe from corrosion and to optimize the design life. The steel access pipe was designed solely to withstand the full net internal pressure head during operation and the external groundwater pressure head upon unwatering without any load sharing from the surrounding rock. Although the reinforced shotcrete lining serves as a protective barrier and is not required as a structural component, a portion of the loads will inherently be transferred to it during both operating and unwatered loading conditions based on its relative stiffness to the other components of the final system. In addition, gravitational loads needed to be accounted for. To support self-weight of the shotcrete and its reinforcement, headed concrete connectors were required. The headed concrete connectors were welded to the steel components evenly throughout the interior of the steel access pipe to provide locations for the reinforcement cage to be secured during shotcrete application.

DESIGN AND SERVICEABILITY REQUIREMENTS

Design Requirements

The design requirements of the reinforced shotcrete lining included meeting the minimum required shotcrete compressive strength per ACI 318-19. The shotcrete lining was designed conservatively following plain concrete design requirements, including applying a reduction factor of 0.6. Therefore, only nominal reinforcement was required for early-age shrinkage and crack control. Minimum reinforcement requirements were set at 0.25% of the gross cross-sectional area of the shotcrete lining, consistent with project criteria. This minimum reinforcement requirement was set considering a combination of ACI 318-19 and ACI 350-20 requirements. The minimum clear cover requirement for the shotcrete reinforcement and headed concrete connectors was set at 2.5 in. (63 mm), which is also consistent with project criteria.

Serviceability Requirements

Reinforced shotcrete lining serviceability requirements included a smooth trowel finish primarily to achieve a visual similar to a formed finish and to control crack widths. Design for crack control included limiting the stresses in the steel reinforcement following ACI 350 (Eq. 10-4) requirements and considering normal environmental exposures. Following this criterion prevents both early-age shrinkage cracking and cracking due to internal hydrostatic pressures upon Bypass Tunnel operation.

Loading Conditions

Loading conditions include operational (when the Bypass Tunnel is in service) and unwatered (when the Bypass Tunnel hydraulic grade line [HGL] is lowered below the access pipe elevation). Gravitational loads include the shotcrete lining and reinforcement self-weight. The operational and unwatered loading conditions are further defined in the following sections.

Operational Loading

During Bypass Tunnel operation, the access shafts will be filled with Aqueduct water that is pressurized based on the HGL at the shaft locations and the elevation of the shaft pipe system. Because of external groundwater pressures, a net internal hydrostatic pressure (total internal hydrostatic pressures minus external groundwater pressures) will act on the access pipe. The steel access pipe was conservatively designed for the maximum net internal hydrostatic head without any load sharing based on the assumption that gaps could form between the pipe and the refill concrete, preventing any load transfer to the surrounding rock. The shotcrete lining, although not structurally required to support the net internal hydrostatic pressure, will experience load within the access pipe. Steel reinforcement is required to control the width of the cracks.

UNWATERED LOADING

When the HGL is lowered below the bottom of the access pipe, the total net pressure will be acting externally on the access riser pipe; therefore, the external groundwater pressure will be greater than the internal pressure based on the position of the HGL. Upon loading, the access pipe will deform inward against the shotcrete lining, which will absorb a portion of the load based on the relative radial stiffness between the two liner components. About 40% and 30% of the total external hydrostatic load is estimated to be transferred to the shotcrete lining at the Shaft 5B and Shaft 6B locations, respectively.

Shotcrete Design

The tensile hoop stresses in the steel reinforcement during operation and the compressive hoop stresses in the shotcrete lining during unwatering were estimated using Roark's (Budynas and Sadegh, 2020) closed-form solutions for hoop stresses due to uniform loading on a cylindrical shell (Eq. 1). Even though no load sharing was considered for the access pipe design to check reinforcement, and shotcrete stresses for the protective liner, load sharing between the access pipe and shotcrete reinforcement and between the access pipe and shotcrete liner, was considered during Aqueduct operation and unwatering, respectively. The load-sharing distribution as a percentage was estimated based on the relative radial stiffness between the two load-sharing components (Eq. 2).

Hoop stress of a circular pipe due to uniform pressure is as follows:

$$S_h = \frac{P \times R}{t} \qquad \text{Eq. 1}$$

Where, Sh = hoop stress (ksi), P = applied uniform pressure (ksi), R = pipe radius (in.), and t = thickness of pipe (inch).

Load sharing between two shaft lining components resisting hoop stresses is as follows:

$$LS_{1,2} = \frac{\frac{E_{1,2} \times A_{1,2}}{{R_{1,2}}^2}}{\frac{E_1 \times A_1}{{R_1}^2} + \frac{E_2 \times A_2}{{R_2}^2}} \times 100\% \qquad \text{Eq. 2}$$

Where, LS1,2 = load share of components 1 or 2 (%), E1,2 = elastic modulus of components 1 or 2 ksi (7 to 14 MPa), A1,2 = cross-sectional area of components 1 or 2 (in$^{2)}$, and R1,2 = radius of components 1 or 2 in.

The compressive stress in the shotcrete lining was checked against requirements per ACI 318-19. A final minimum comprehensive strength and thickness of the shotcrete lining was determined to be 4,000 psi (28 MPa) and 4.5 in. (114 mm), respectively. A WWR of 4x4 -W4.0xW4.0 (102x102 - MW26xMW26) was selected based on the contractor's means and methods. During aqueduct operation, the tensile stress in the shotcrete reinforcement was confirmed to be less than that required by ACI 350-19 Eq. 10-4 and met crack control requirements.

Headed Concrete Connector Design

The headed concrete connectors were designed to withstand the self-weight of the reinforced shotcrete. The vertical load induced on each shear connector is dependent on the circumferential and vertical spacing of the connectors along the access pipe steel surface. The nominal shear resistance of the connector embedded in the shotcrete liner was determined following AASHTO LRFD Chapter 6.10.10 (2020).

The final required spacing of the headed concrete connectors to support the reinforced shotcrete lining was determined to be 2 ft by 2 ft (0.6 by 0.6 m) along the entire shaft height and circumference. Headed concrete connectors with ½ in (13 mm) diameter and ultimate strength of 61,000 psi (420 MPa) were selected.

SHOTCRETE MOCK-UP

A mock-up was necessary because, although shotcrete is a viable alternative, it requires a high degree of quality control. If not performed correctly, the results could be undesirable. Goals of the mock-up included demonstrating the following:

1. Surface preparation of the steel plate using high pressure water washing is adequate for proper shotcrete application.
2. Welded headed concrete connectors are installed and pass verification testing.

Fig. 3: Mock-up: Shotcrete placement.

3. Circumferential bar reinforcement is adequately secured to the welded headed concrete connectors.
4. WWR is adequately secured to the welded headed concrete connectors/circumferential bar system prior to shotcrete application.
5. Approved shotcrete mixture performs satisfactorily during application, (i.e. bonds well to steel plate, no evidence of sagging through set-up, and no excessive rebound).
6. Shotcrete minimum depth and cover are met and adequately encapsulate the reinforcing steel.
7. Shotcrete as installed over the WWR contains minimal voids, sand pockets, or debonded material.
8. Shotcrete surface finish by troweling is smooth.
9. ACI-certified nozzlemen used to apply mock-up shotcrete are prequalified and subsequently assigned to install shotcrete during the actual work for consistency.
10. Qualified and skilled individuals providing oversight of the mock-up is also present to provide oversight during the actual work.

The mock-up was performed in February 2022 using an available 10 ft (3 m) section of the steel interliner initially procured for the tunnel. The mock-up included all components of the design (pressure washing of the steel pipe, shear connector and WWR installations, and shotcrete) but on a smaller scale. Enough WWR sheets to overlap and form at least three circumferential (vertical) laps, in addition to a longitudinal lap at each circumferential lap location, were installed and shotcreted in the Engineer's presence. This duplicated the worst-case lap of three WWR sheets layered on top of each other and thus could prove the nozzleman's

Fig. 4: Mock-up: Completed.

Fig. 5: Core from mock-up.

ability to properly encase the most dense reinforcing layout. The mock-up quality control included core testing to confirm "very good" steel encasement per ACI 506.6T-17, panel testing to confirm shotcrete mixture strength, and thickness and cover verification. Figures 3 and 4 are from the mock-up. Figure 5 shows a core from a mockup whose quality was "very good."

This mock-up was successful, and the design was finalized and issued for construction.

SHOTCRETE LINING INSTALLATION

Access

The key to a productive operation is good access to the work. Considering that the work was to take place more than 600 ft (180 m) above the bottom of the shafts posed some unique challenges. The project team had extensive knowledge of working throughout the shaft, from placing concrete shaft liner to placing and installing the steel access pipe itself. Two work decks were designed and fabricated to be used at each shaft to allow for concurrent operations.

The access decks were designed to handle loading for all the steps of the operations listed and described in the following sections. To ensure the safety of the workers on the deck, a roof was incorporated into the lifting frame above the deck. The roof was designed to withstand the loading from dropped objects. The lifting frame located above the deck also had lighting installed. Additionally, the open diamond grading of the work deck allowed for air movement up and down the shafts to reduce the concentration of airborne particles from the shotcreting operation.

The decks were suspended from a Favco crane on the 5B side and a Cobelco crane on the 6B side.

As secondary access to the deck, a backup crane with a bullet cage was available.

Work Sequence

There were four major components of work to install the shotcrete lining, all of which were performed in June and July 2022: pressure washing of steel lining; headed concrete connector and wire mesh installation; applying, finishing, and curing shotcrete; and final cleanup.

Pressure Washing of Steel Lining

Total quantity of work was 17,762 ft^2 (1650 m^2) between the two shafts, and the work was completed with a 3000 psi (21 MPa) pressure washer located on the work deck. Design required that any rust scales, grime, oil, and dirt be removed prior to shotcrete application.

Headed Concrete Connector (Nelson Studs) and WWR Installation

Nelson studs were used as headed concrete connectors. KSC rented Nelson stud guns and received training in stud installation from the supplier. A total of 4394 EA studs were installed in the two shafts: a row of 28 EA studs per 2 feet vertically. A #4 (#13M) rebar was bent to the diameter of the inside of the studs every other lift of studs at 4 ft (1.2 m) centers. The purpose of this bar, which is nonstructural, was to provide stiffness to the WWR and prevent it from vibrating during the shotcrete application. Further, it expedited the WWR installation as the wire did not have to be aligned on the mesh exactly with the studs. Figure 6 is a view down the inside of the steel liner from the work deck, showing the #4 bar and stud detail, prior to WWR installation. WWR was inspected during installation to ensure stiffness and correct overlap. See Figure 7.

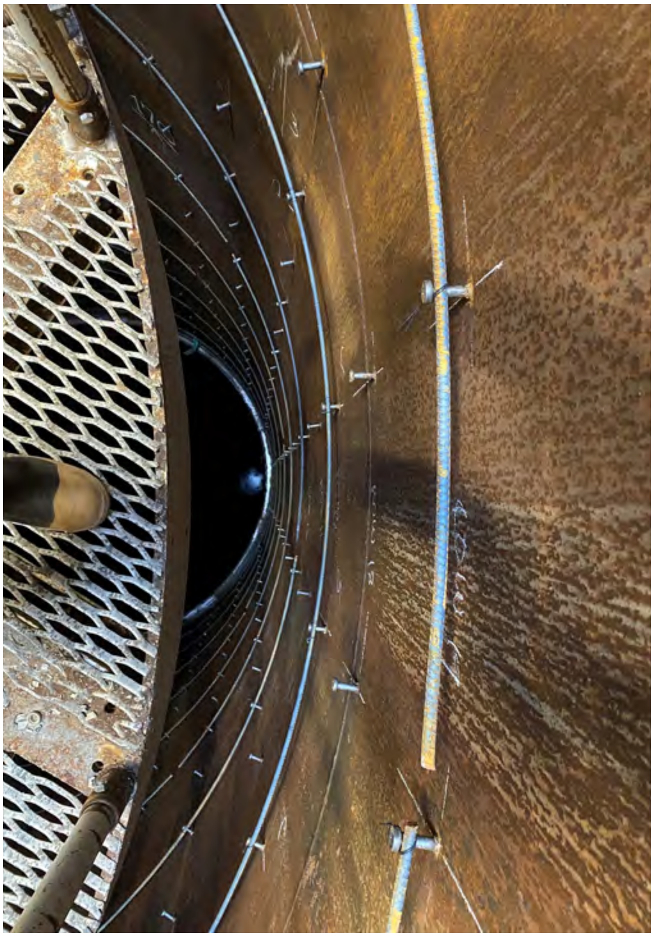

Fig. 6: Detail of #4 bar tied to the studs.

Fig. 7: Inspection to ensure the correct overlap of WWR.

Applying, Finishing, and Curing Shotcrete

The shotcreting operation was performed by a specialty subcontractor on a single shift operation. The shotcrete crew consisted of six personnel on the deck: a bottom lander, a nozzleman, and four finishers. A second shift was used for applying curing compound to the finished shotcrete and to clean up and prepare the work deck for the following day's operation. The total quantity of shotcrete for the work was 17,762 ft^2. At a thickness of 4.5 in., this is 246 yd^3 (188 m^3) in volume of concrete.

Prior to starting the shotcrete operation, the specialty subcontractor tied a horizontal pencil rod to the wire mesh to serve as a screed for the finishers and to ensure the adequate cover of shotcrete over the WWR. The pencil rods were removed on the back shift.

The shotcrete equipment consisted of two high-pressure shotcrete pumps: one main and one spare; a 2 in. (50 mm) steel slick line to the top of the access pipe; and a 2 in. bull hose down to the work deck and the nozzle applicator. Air was delivered to the nozzle from KSC's on-site compressor though a ¾-in. hose. No accelerator was used for the shotcrete. See Figure 8 for a view down the finished 5B Shaft.

Fig. 8: The completed 5B Shaft from above.

Shaft Bottom Cleanup

Despite having placed heavy plastic sheeting on the shaft bottom, the cleanup operation turned out to be more encompassing than anticipated. Lessons were learned from 6B, which was the first shaft to be shotcreted.

First, the quantity of waste shotcrete exceeded the volume anticipated. This was mainly due to the relatively thin lining where a few inches of overspray is a large percentage of the total. One inch of overspray on a 4.5 in. lining is over 20%. Typically, the subcontractor would overspray the pencil rods with 1 in. minimum and then trowel the surface back to the pencil rod to achieve the required smooth trowel finish. Over the depth of the access pipes, this resulted in 50 yd^3 (38 m^3) of shotcrete ending up in the bottom of the shafts.

Second, the shotcrete would "splatter" up the sides of 6B when it hit the shaft bottom following a 600 to 800 ft (180 to 240 m) drop. Therefore, at Shaft 5B, KSC installed sheets of heavy plastic 20 ft (6 m) up the walls and covered the entrances to the Bypass Tunnel, which had received a good amount of "splatter" during the earlier shotcrete installation at Shaft 6B.

The third lesson learned was that the subcontractor would drop the discarded pencil rods down the shaft. These pencil rods would get embedded in the wet concrete and create a hardened concrete porcupine, which was a painful experience to remove.

Conclusion

Mockups are valuable in identifying issues with an initial approach and later to verify a design and application method; this includes an evaluation of the personnel actually performing the work.

This small, but important, piece of work on a large project exemplified the importance of having a collaborative environment between project owner, construction manager, designer, contractor, and specialty subcontractor to tackle a technical and operational challenge in order not to delay the project.

Application and trowel finishing of shotcrete linings require highly skilled and trained personnel. Never underestimate the need for clean up after a shotcrete operation.

For Bypass Tunnel Shafts 5B and 6B, the quality of the shotcrete finish was exceptional and similar to a formed concrete surface.

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2023 OUTSTANDING UNDERGROUND PROJECT

Project
Rondout Bypass Tunnel

Project Location
New York, NY

Designer
DELVE Underground

Shotcrete Contractor
Patriot Shotcrete

Materials Supplier
Bonded Concrete

General Contractor
Kiewit Shea Constructors, AJV

Owner
New York Department of Environmental Protection

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