DESIGN OF HYBRID PRECAST SEGMENTAL TUNNEL LININGS FOR THE PAWTUCKET CSO TUNNEL PROJECT

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ABSTRACT: This paper describes the design hybrid precast segmental tunnel linings used at TBM tunnel-SEM adit interfaces for the Pawtucket CSO Tunnel Project in Providence, Rhode Island in the USA. The tunnel is 3.57 km long with 9.14 m finished diameter and is constructed in complex sedimentary rocks. Special features of the segments include a large keystone and no connector used on radial joints. Typical segments are steel fiber reinforced, and hybrid segments include additional steel rebars and shear bicones. The hybrid segments will be used around the adit openings without use of any structural framing. Important design considerations are discussed, including special 3D segment to adit connection analyses performed.

1. PROJECT OVERVIEW

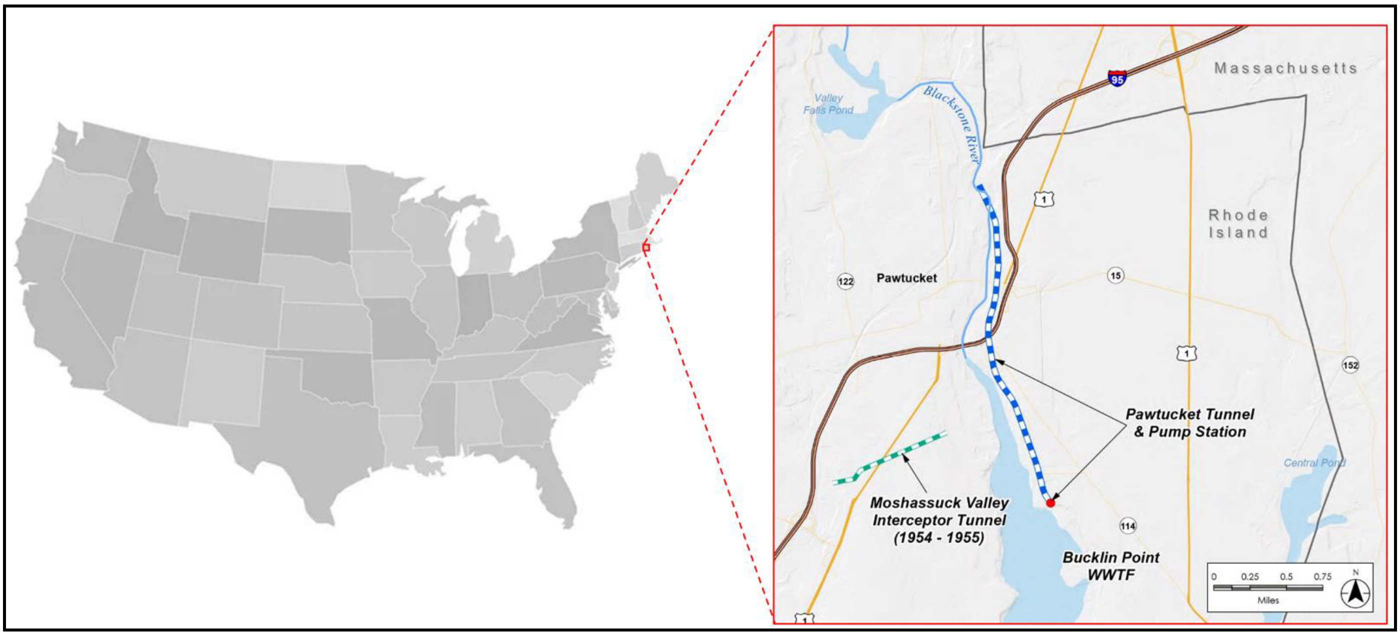


Figure 1: Project area map

The Pawtucket Tunnel Project is the first phase of the Narragansett Bay Commission (NBC) Phase III Combined Sewer Overflow (CSO) Program designed to reduce CSOs from the communities of Pawtucket and Central Falls in Rhode Island, USA. The location of the project is provided in Figure 1. Phases I and II of the program were focused on the Providence area and were completed in 2008. The Pawtucket Tunnel is planned to have a finished inside diameter of 9.14 m and a length of approximately 3.6 km. The tunnel will be in rock with an invert depth ranging from 35 to 47 m. The tunnel will be excavated using a tunnel boring machine (TBM) and lined with precast concrete segments. This project is being implemented using a design-build delivery process. The Design-Build Contractor, CB3A, is a joint venture (JV) of CBNA and Barletta. Gall Zeidler Consultants (GZ) is a sub-contractor to AECOM, The prime designer. In addition to GZ, GEI Consultants (GEI), Mueser Rutledge Consulting Engineers (MRCE) and the BETA Group, Inc. (BETA) have been brough on for various design tasks.

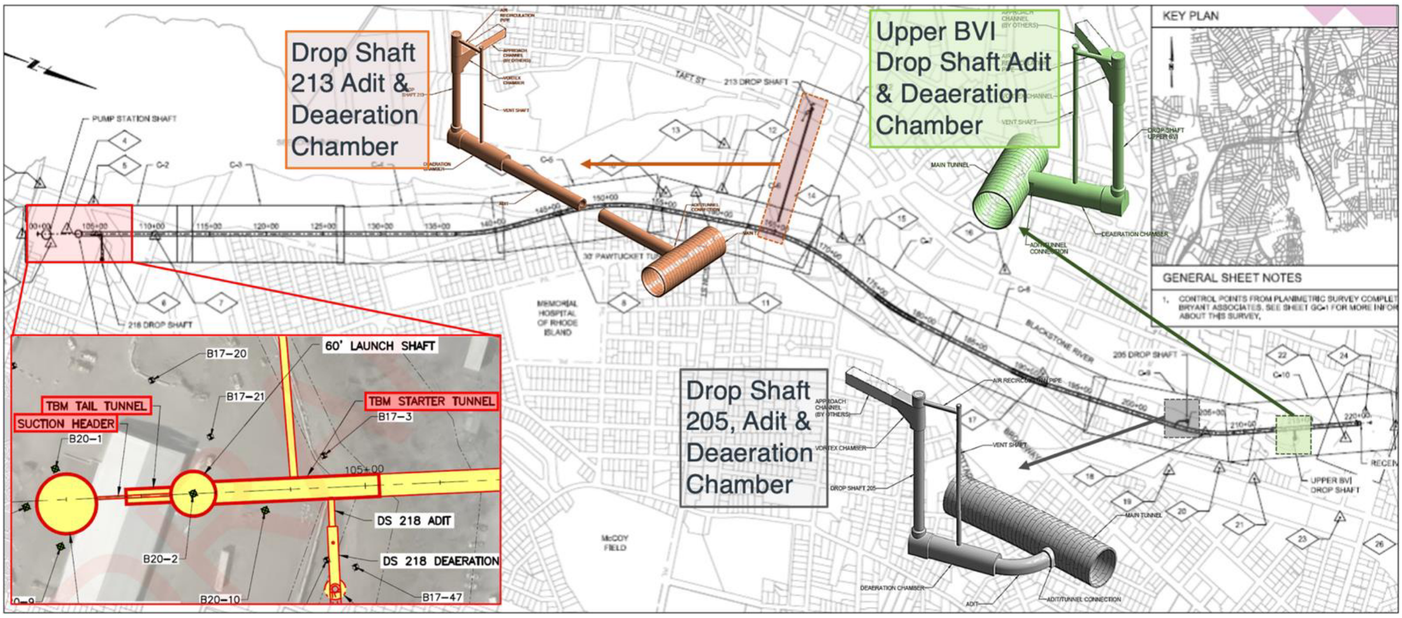


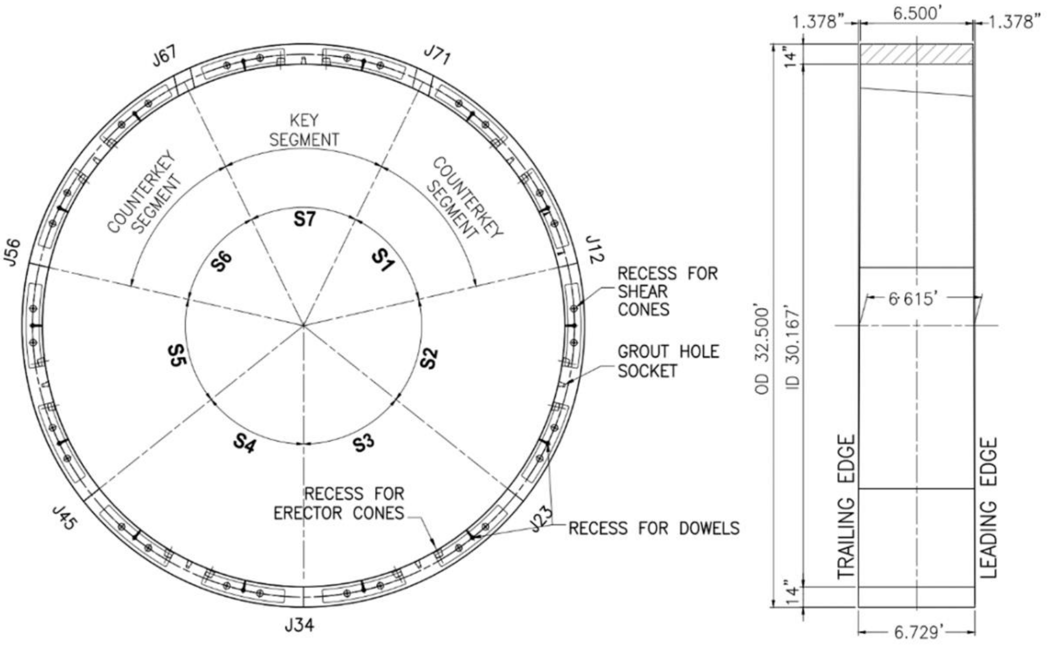
Figure 2: General arrangement of the major structures along the Pawtucket alignment. Note that the geometry is schematic, and that actual design details differ slightly.

The Pawtucket Tunnel Project includes the construction of a main conveyance and storage tunnel, a launch shaft and receiving shaft for the TBM, a tunnel pumping station, drop and vent shafts and connecting adits. The arrangement of the structures is provided schematically in Figure 2. GZ is the lead designer for all the SEM tunnels, the adit-TBM tunnel Connections, and the final lining and waterproofing of the pump shaft, launch shaft, and receiving shaft. The tunnel construction will be performed with a hybrid TBM, capable of operating in an open or closed, pressurized-face earth pressure balance (EPB) mode as conditions warrant. It is planned that the TBM will drive the entire tunnel in open-face mode. As the TBM advances, the tunnel will be lined with precast steel fiber reinforced concrete segments. At the time of the writing of this paper, the TBM has launched, and excavation of the large diameter shafts is completed.

The main conveyance tunnel will be a deep rock tunnel with the invert located around 37 m deep at its downstream end. The tunnel will rise in grade at a proposed slope of 0.1% to its upstream end. Due to a change in elevation of the ground surface, the invert depth at the upstream end will be around 38.4 m deep at the TBM receiving shaft. The tunnel boring machine Launch Shaft will be 18.3 m in diameter and extend approximately 56 m below existing ground. It is located 51.8 m, shaft center-to-center, northwest of the Tunnel Pumping Station (TPS) Shaft in alignment with the tunnel. The Launch Shaft will be connected to the TPS Shaft with a 3 m diameter Suction Header Tunnel. The TBM Tail Tunnel will extend 22.9 m to the southeast of the Launch Shaft. The TBM Starter Tunnel will extend approximately 67 m along the tunnel alignment. There are four drop shaft (DS) locations across the project site: DS-218, DS-213, DS-205, and the Upper Blackstone Valley Interceptor (UBVI) DS. The TBM Receiving Shaft is in a parking lot north of the Blackstone River and west of Roosevelt Avenue. The Receiving Shaft will be 11 m in diameter and extend approximately 40 m below existing ground.

2. TYPICAL SEGMENTS

The entire length of the tunnel will be constructed in the siliciclastic bedrock of Rhode Island formation overlain by glacial till deposits and other fill materials and will be located below the groundwater table. A seven-piece universal tapered ring system, as shown in Figure 2, was adopted. The tunnel lining ring is 101 mm-thick, 9.2 m in internal diameter, and 2 m in length, and consists of four (4) regular segments of rectangular geometry, two (2) counter-key segments of right trapezoidal geometry, and one (1) wedge-shaped key segment. All segments will be staggered to avoid creating cruciform joints which could cause leakage and structural distress due to stress concentration. As the key segment cannot always be installed at the tunnel crown, the TBM will need to be able to hold segments in place during ring assembly using erector and support roller system. The length of the ring was selected by balancing between the constructability factors (ease of transportation, assembly, and ability to negotiate curves) and the utility factors (limiting joint number to reduce leakage and production cost and to increase tunnel advancement rate). The selected ring length is close to the upper bound of those recommendation by the ITA [1] for the size of the tunnel.



(a) Segmental Lining Ring Front View (above) (b) Segmental Lining Ring Side View (above)

(c) Schematic View of Developed Intrados (below)

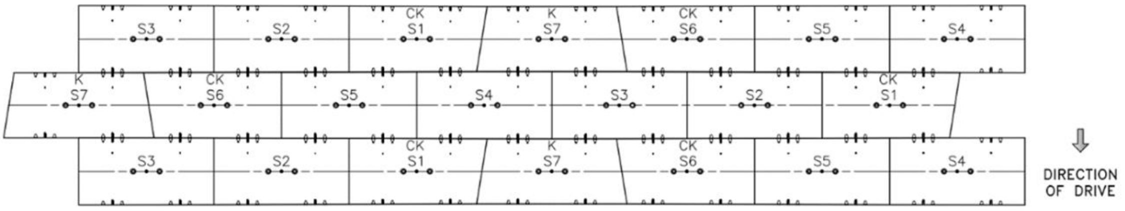


Figure 3: Adopted Tunnel Lining Design

All tunnel segments, including the keystone, are similarly sized. The chord lengths at centerline are around 4.3 m for all the segments. The regular spacing of the longitudinal joints within the ring reduce eccentric ring distortions. A larger key segment also reduces the size of the regular segments, and therefore also potentially the number of longitudinal joints. The segments will not be bolted to each other at the longitudinal joints because holding force is available from thrust jacks. This increases the TBM advance rate because bolting can often be time-consuming. Rings will be connected to each other at the ring joints using fourteen (14) equally spaced dowels (SOF FAST 110). In addition, fourteen (14) pairs of equally spaced shear connectors, i.e., shear bicones with a steel core (Optimas Sofrasar F500) were specified at the ring joints for centering and shear recovery purposes at the tunnel adit openings as described later.

For waterproofing purposes, all-around ethylene propylene diene monomer (EPDM) compression gasket (Datwyler M389 33 "Doha") profile is specified which fits into an about 13.5 mm deep groove installed at ring and longitudinal joints. The compression gasket is anticipated to resist up to 25 bars of hydrostatic pressure under the design compression and allowable offset scenario, which was sufficient to withstand the maximum anticipated groundwater pressure of 5 bars. The typical segments will be reinforced by steel fibers (no less than 35 kg/m^3). The minimum required strength at 28-day adopted for the design was f_c'=44.8 MPa of the characteristic compressive strength and $f_{150}'^{D}$=4.8 MPa of residual flexural strength at 3.5 mm crack mouth opening displacement (CMOD). The segment thickness was selected to withstand all short-term and long-term loading cases and service conditions. To achieve the desired 100-year service life, the selected segment thickness (355 mm) includes 60 mm of sacrificial concrete layer as a measure to protect the tunnel lining from concrete degradation due to hydrogen sulfide (H2S) gas from the CSO water. The tunnel lining was designed in a way that the loss of a maximum 63.5 mm sacrificial layer does not impact the structural integrity of the tunnel lining system at the end of its design life. The large amount of sacrificial concrete thickness was due to the use of non-calcareous granitic aggregates, since limestone aggregates cannot be sourced easily for the project.

3. HYBRID SEGMENT DESIGN AT TBM TUNNEL – SEM ADIT CONNECTIONS

The Pawtucket tunnel is connected to four drop shafts by tunnel adits along its alignment. The tunnel adits are named after the drop shafts to which they connect. The adits, from 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 is therefore constructed as a typical SEM to SEM connection. The DS 213, DS 205 & UBVI adits, however, connect to the segmentally lined portion of the main tunnel alignment. The DS 205 & UBVI adits are planned as SEM adits. The DS 213 adit will be constructed by pipe Jacking and microtunneling by MTBM. The SEM tunnel adits will be constructed by making a cut within the segmental lining and mining outwards towards the base of the drop shaft structures. The DS 213 adit will be constructed from within the drop shaft and be jacked towards the main TBM tunnel. Regardless of construction, it is foreseen that the adits be constructed after the TBM has passed the corresponding adit connection point.

To simplify construction, the connection design to all three adits has been standardized to the largest degree possible. First, a two-segment wide rectangular cut will be made within the segmental lining. The cut dimensions on the inside face of the segmental lining will be approximately 4 m wide by 3.65 m tall. The cut will be made along the longitudinal joints of the segmental lining on the sides of the cut, and through the segments along the top and bottom of the cut. The cut opening will be temporarily supported by additional reinforcement and shear elements included within the segments of the four TBM rings at and immediately adjacent to the opening. The specially reinforced segments around the opening have been designed such that no additional external bracing or framing is necessary for the temporary support of the opening. As described previously, the standard TBM lining design along the alignment is pure steel fiber reinforced concrete (SFRC) with two shear dowels installed at each jacking pad. Each segment features two jack pads, and each ring is composed of 7 segments, including an oversized keystone (7+0) arrangement. The lining has an inner diameter of 9.2 m, and the segments are 1.16 m thick. The specially reinforced segments around the segment opening feature a heavy rebar cage as well as 2 additional high-capacity shear cones per segment ring joint installed in the middle of the jack pads between the shear dowels. The geometry of the specially reinforced segments is equivalent with that of the typical segments. A schematic of the cut and segment layout is shown in Figure 4.

After making the cut in the TBM lining, a short 1.52 m long, SEM stub tunnel will be excavated. The excavation diameter will roughly follow the rectangular dimensions of the cut but will have slightly rounded sides and a crown to allow for some rock arching. The temporary support of excavation will consist of crown and sidewall bolts along with a protective shotcrete layer along the sidewalls, roof, and face of the excavation. Excavation of the DS 205 and UBVI adits will immediately follow the construction of the stub tunnel by drill & blast (D&B). Excavation will progress outwards from the stub towards the drop shafts. In the case of the DS 213 Adit, which will be constructed by pipe jacking & MTBM, the stub tunnel will act as a reception area for the MTBM. The MTBM will break through the face of the stub tunnel and be pulled out through the main TBM tunnel.

After excavation of the adits are complete, a monolithic cast-in-place (CIP) concrete collar will be cast around the opening and within the stub tunnel. A long section of the collar is shown in Figure 4. The collar will be constructed of SFRC with additional rebar reinforcement. The outer dimensions of the collar will follow those of the SEM excavation, whereas the inner portion of the collar will be cast to be flush with the 2.4 m diameter adits (the jacked MTBM pipe inner diameter is slightly less than 2.4 m). The CIP collar is designed to assume all long-term loadings to which the connection will be subject to.

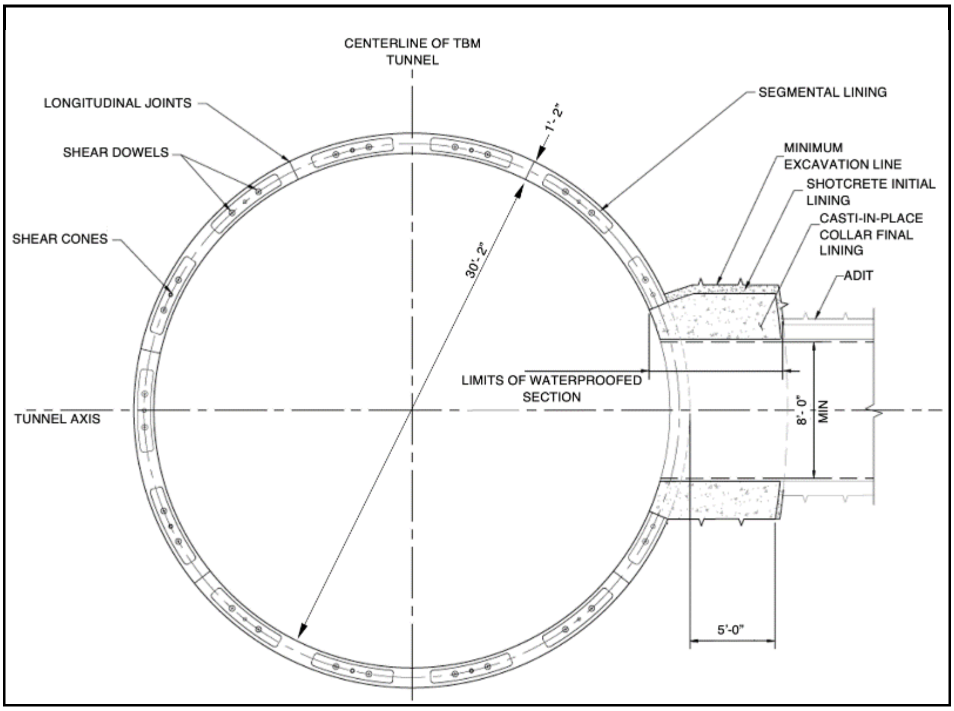


Figure 4: TBM adit opening ring cut with final cast-in-place concrete collar and adit.

3.1 DESIGN CONSIDERATIONS

The in-situ ground pressures, the temporary and permanent ground water loads, the friction between rings, and the durability of the lining concrete were determined to be the critical design factors. These were considered as follows:

- In-situ earth pressures: The Geotechnical Baseline Report (GBR) predicted horizontal in-situ earth pressure coefficient values, K_0, of up to 5. As such, a K_0 of 5 was assumed to be the base case for the design. In addition, as the tunnel alignment runs through competent rock, a case in which the ground opening is completely self-supported (i.e., the lining assumes no loads) was considered.
- Water pressures: In the permanent case, both high and low ground water loads based on 100-year levels were considered. In the temporary case, only dry conditions are considered. Although the permeability of the rock mass is expected to be low, dry conditions before cutting the segments will be ensured by drilling probe holes through the segments and into the rock and locally dewatered before making the cut.
- Ring Friction: A major stabilizing factor in the lining system is the residual ring friction present between successive rings due to ring compression resulting from TBM jacking. It is difficult to determine the magnitude of this force. As such, temporary load cases with and without an active frictional force due to pre-compression were investigated. Friction in the long-term case is only assumed to be engaged passively due to relative ring deformations.
- Durability: The greatest threat to durability of the TBM tunnel lining is expected to be concrete corrosion due to hydrogen sulfide attack. This is especially critical at the TBM adits connections as they feature rebar reinforcement in addition to the steel fibers, and a minimum rebar cover must be maintained. To avoid excessive section loss due to hydrogen sulfide attack, the specially reinforced segment concrete mix considered use of calcareous aggregates, whereas the standard segment concrete mix will use granitic aggregates. The alkalinity of the calcareous aggregates will mitigate concrete corrosion and it is expected that section loss in this case will only be less than 12 mm.

3.2 STRUCTURAL ANALYSIS

3.2.1 Model Setup

To account for the design factors listed above, a staged Finite Element (FE) model was developed for the structural analysis of the lining and collar at the TBM tunnel-adit cut locations using the SOFiSTiK software package. An image of the model is shown in Figure 5.

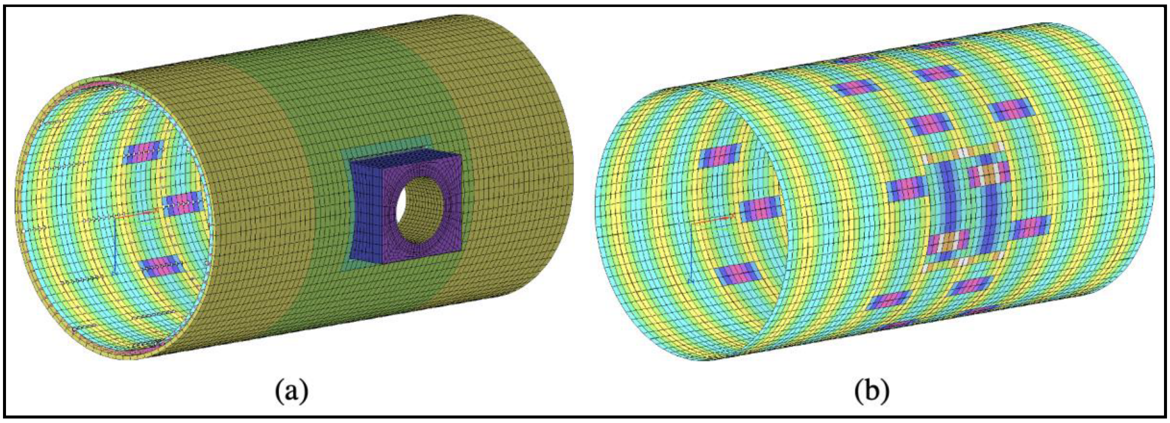


Figure 5: Model of adit connections: a) adit collar; b) isometric view of segmental lining ring.

The outer surface of the model is composed of volume elements representing the annular grout. The grout is modeled with a Mohr-Coulomb material behavior and is connected to the ground with tangential and radial springs. The radial bedding modulus is determined using the method described in the DAUB & ACI 544 [2,3]. The tangential bedding modulus is assumed to be a factor of 1/(2+2ν) smaller than the radial bedding modulus in analogy to the relationship between the shear modulus and young's modulus.

The segmental lining is modeled using shell elements. The coupling of the segmental lining to the annular grout is modeled with high-stiffness frictional springs that are allowed to fail in tension. With these assumptions, the springs are effectively equivalent to a small-strain frictional contact condition. A total of nine lining rings are modeled. Two and a half rings of regular segments are modeled at the front and back of the model, and four rings composed of specially reinforced segments are modeled in the center of the model around the cut. Each successive ring is rotated by half a segment. The lining is modelled using a SOFiSTiK-supplied non-linear steel fiber reinforced concrete material law which considers the peak and residual strengths of the fibers. Two sets of springs are modeled in the longitudinal joint, one set simulates the transfer of normal and shear forces, and the other set simulates the transfer of moments. The eccentricity of the longitudinal joint contact surface relative to the segment axis is explicitly considered by offsetting the spring contact point with a stiff plate. Circumferentially oriented springs with a very high stiffness mimicking a hard contact transfer the normal forces between segments. The springs also include a stiff perpendicular component to transfer shear forces in radial and longitudinal directions. To limit the size of the shear force in the contact zone, a friction coefficient of $\nu = 0.25$ is applied. The rotational behavior of the moment springs in the concrete hinge of a longitudinal joint is modeled according to the nonlinear behavior specified in the DAUB & ACI 544 Recommendations [2,3]. The relationship between the rotation, φ, and the transferable moment, M, is individually determined for each spring at the longitudinal joint based on the magnitude of the normal force, N, in each calculation step.

The coupling between adjoining rings is simulated with springs pre-stressed in longitudinal direction. Coupling is induced through pre-stressing by the thrust forces of the TBM and exerted through friction. The friction coupling in the ring joint is implicitly calculated in analysis through a friction criterion and a transversal stiffness in the springs. The magnitude of the coupling force is proportional to the differential displacements of neighboring rings and to the respective normal force. As initial ram forces during operation will decrease due to the repeated interim release of the rams following ring erections and due to relaxation of the concrete, a reduced force of 50% of the operational thrust is applied as a pre-stressing force in the structural analyses.

In addition to the frictional coupling between rings, the shear connectors between rings (both bicones and dowels) are explicitly modelled by means of non-linear spring elements. This ensures that the local shear force concentration acting on the segments due to the stiff connector behavior is accurately accounted for in the model. The non-linear behavior of the springs is based on the actual load displacement behavior of the shear elements, which is taken from manufacturer supplied loading diagrams as shown in Figure 8. As the dowels are made of a synthetic material, their stiffness is reduced for all long-term load cases to account for relaxing of the synthetic over time.

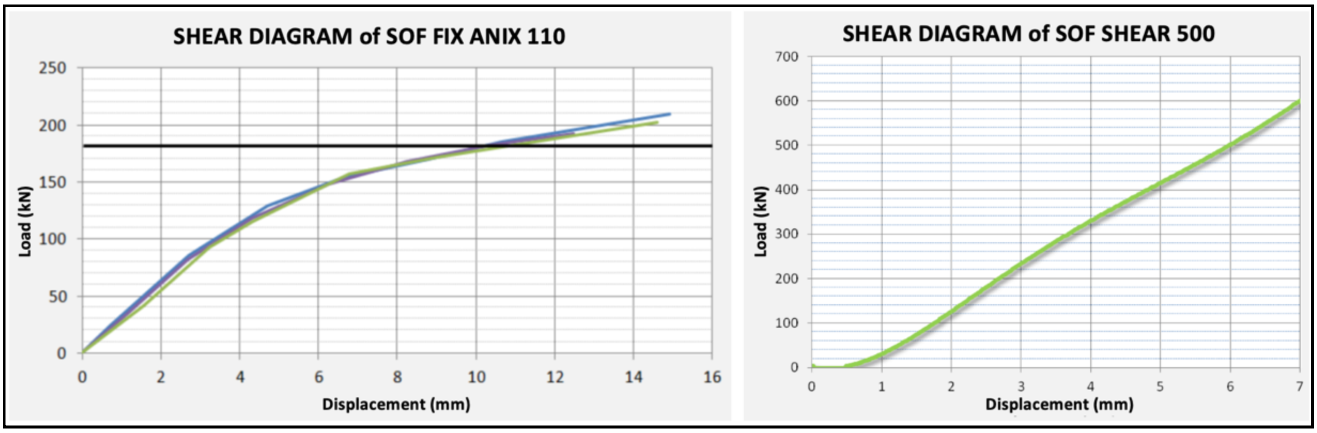


Figure 6: Shear Connector Behavior. Dowels on left and Bicones on right.

The collar structure is explicitly modeled with volume elements. Due to the massive structure of the collar, it is assumed to behave linear elastically. On the outer surfaces of the collar, shell-elements provide the bedding for the collar with the same bedding stiffness as for the annular grout. The load transfer from the cut segmental lining and the annular grout onto the collar structure is modeled with high stiffness springs along the cut perimeter.

3.2.2 Loadings

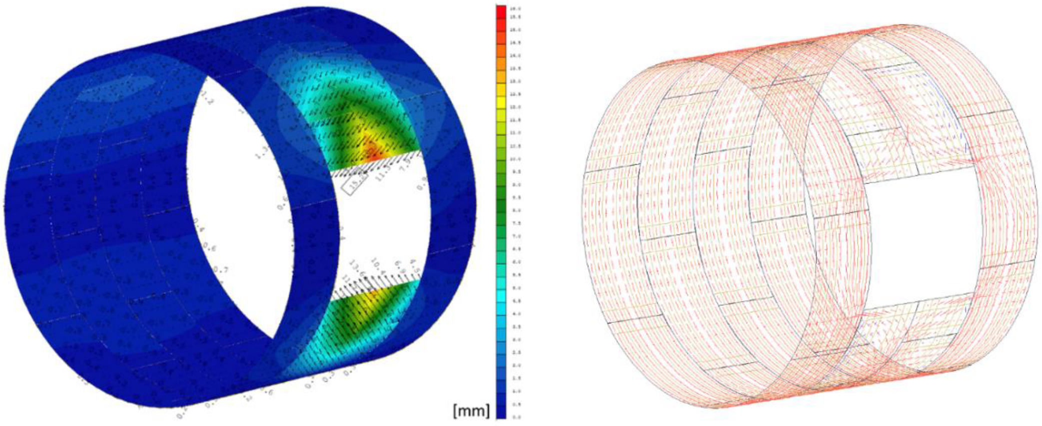
To ensure that the proper loading history is accounted for, the FE model is solved in the following staged loading sequence:

1. Apply ground loads. The ground loads are derived by calibrating the loading of the shell model to arrive at similar stress resultants as those derived in the tunnel lining using a plane strain pseudo-3D continuum model of the lining in the ground. The pseudo-3D Model involves assuming a ground relaxation before installation of the lining. To obtain conservative design loads, the pseudo-3D continuum model assumes the ground conditions of the tunnel at the maximum overburden along the alignment. Cases were investigated in which ground loadings derived from an 80% ground relaxation were applied to the tunnel lining as well as the case in which the tunnel lining assumes no rock load (i.e., 100% relaxation of the rock) this last case is considered a reasonable design choice due to the high rock quality along some stretches of the alignment.
2. Apply secondary grouting pressure.
3. Make the cut in the lining. This takes place under dry conditions as previously discussed due to local dewatering. Both cases in which ring joint friction/prestressing is actively and passively present were investigated. This represents the short-term loading.
4. Install collar and apply water loads. This represents a “middle-term” loading. Both high water table and low water tables were investigated.
5. Account for creep of shear elements (dowels and shear cones) and remove active prestressing/friction in ring joint (if accounted for). This represents the long-term loading.

As is evident from the above, several load combinations were investigated. The model used accounts for non-linear material behavior, so only characteristic loads were used. All stress resultants were conservatively factored by 1.4 in accordance with ACI 318 [4] to arrive at design stress resultants for dimensioning.

3.2.3 Analysis Results

The structural analysis indicates that the most critical case for design is the temporary loading of the segments immediately following the cutting of the lining and before installation of the CIP collar. Specifically, the load case in which the ground load is considered is most critical. An image of the predicted displacements of the segments in this loading scenario is provided in Figure 7(a). The maximum displacement is 15.2 mm and occurs above the opening at the ring joint. Large displacements only occur in the two middle rings which are completely opened. The uncut special rings, one on each side of the opening, exhibit much lower maximum displacements of 2.7 mm. The corresponding principal membrane forces are provided in Figure 7(b). Red vectors represent compression, blue vectors represent tension, and the longer vectors in the crosses depict the direction of the maximum principal force. The load distribution around the opening is clearly visible from the inclination of the principal forces. Areas of high compression and tension occur in the segments directly above and below the opening as the compressive load in the ring is transferred around the segments. As such, high compression occurs in the corners of the opening. Similarly, the load transferred through the shear elements and through friction results in higher compressive forces in the uncut rings next to the opening, especially at points close to the ring joints. The tensile forces that can be observed at the ring joints immediately above and below the sides of cut develop as a counter-reaction to the transfer of the compressive forces around the opening.



(a) (b)

Figure 7: Deformations (a) and principal force orientations (b) immediately around segment cut.

The tensile forces as shown in Figure 7 (b) are too high to be carried by steel fibers alone and result in a requirement for circumferential rebar reinforcement along the segments. In addition to these tensile forces, splitting forces resulting from increased normal force at longitudinal joints, shear resulting from increased bicone, and connector loads, and longitudinal bending within the segments all contribute to the increased reinforcement requirements.

3.3 HYBRID SEGMENT DESIGN

In total, to carry the design loadings, the special segments are reinforced with a heavy rebar cage amounting to approx. 190 kg/m3 rebar reinforcement. The high reinforcement density is, however, partially a product of the slim dimensions of the segments (355 mm thick) and the larger cover requirements on the inside face due to durability issues (57 mm cover on the inner face vs. 38 mm on the outer face). A typical reinforcement scheme is shown in Figure 8.

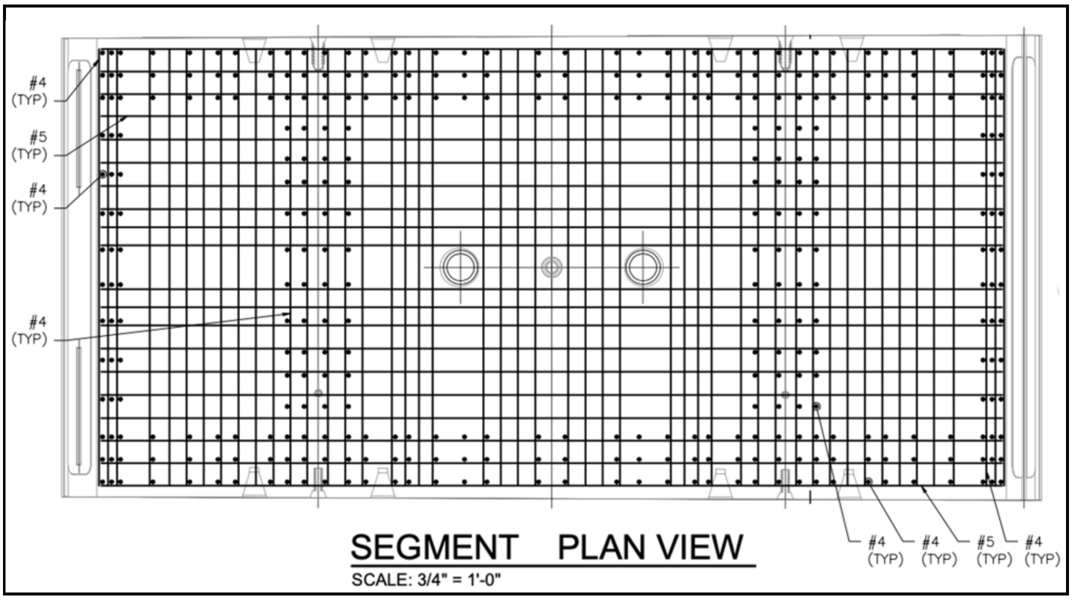


Figure 8: Typical hybrid segment reinforcement layout

To ensure controlled behavior of the specially reinforced segments at the cuts during construction, a ring immediately at the cut, as well as two rings ahead of and two rings behind the cut will be monitored (3 rings in total at each cut). This monitoring plan ensures that rings of the same segmentation, i.e., same longitudinal joint locations are monitored. The rings ahead and behind the cut ring will act as control deformations against which the deformations of the cut ring can be compared against.

The collar, in contrast to the segments, experiences the largest loads in the long-term condition when the creep of the shear elements is considered. This is to be expected, as the creep of the shear elements and loss of ring friction results in more bearing against the collar over time. The loading of the collar is, however, not critical for design as the collar is sufficiently large enough to account for any needed reinforcement.

3.4 MANUFACTURING CONSIDERATIONS

Close spacing of reinforcement bars can complicate segment production during casting. In the case of the Pawtucket tunnel, some reinforcement bars are only 102 mm apart. In addition, the reinforcement cages for the hybrid segments are welded and are produced off-site before segment casting. Furthermore, the design calls for a cast-in gasket, which requires the segment mold to be completely closed before installation, and installation of the gasket in the mold with the cage already lowered is not possible due to space constraints. As such, the welded reinforcement cage needs to be lowered into the molds after the segment molds are closed and the gasket is installed. This, in turn, requires the bicone and dowels molds to be installed after the cage is already placed in the segment molds, which is also difficult due to space constraints.

To alleviate these production issues, the design of the welded cage was modified slightly during construction to allow for the removal and subsequent re-tying of some of longitudinal reinforcement bars immediately over the bicone molds to better access the bicone inserts. Similarly, because the fibers that were chosen for the SFRC mix were rather large (Dramix 4D 80/60), casting of the hybrid segments with SFRC was difficult. As such, some later segments were redesigned during construction to include only regular concrete instead of SFRC to speed up segment production.

4. CONCLUSIONS

This paper describes design of the tunnel segmental lining for the Pawtucket CSO Tunnel Project for both the typical standard segments as well as the special segments around the tunnel adit openings. The design considered stages or sequence in the segment loadings starting from the segment erection inside the TBM tunnel, grouting, tunnelling, and segment cutting for the adit construction. Short-term and long-term loadings on the segment were analyzed including estimated degradation or concrete loss over the project 100-year design life. Although not specifically covered here, the segment design also included other handling and construction related loadings such as lifting and stacking, transporting, and thrusting by the TBM rams inside the tunnel.

The presented analysis and design show that it is possible to cut a TBM segmental lining without the necessity for any external supporting elements, provided that sufficient reinforcement and high-capacity shear connectors are designed for within the segments immediately surrounding the cut. Doing so provides several benefits to construction as it eliminates the need for tedious frame constructions to take place within the confined space of a TBM tunnel. The cut can be made immediately following the passing of the TBM and therefor simplifies construction logistics. Furthermore, casting reinforced segments ahead of time improves QA/QC processes, as the rings supporting the cut are produced in a factory environment and their construction can be better controlled.

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