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New advancement in durable segments for combined sewer overflow tunnels, USA

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ABSTRACT: The Blacksnake Creek and stormwater runoff in St. Joseph, MO, is currently piped along with sewage in a 100-year old pipe not large enough to carry all the stormwater and sewage to the wastewater treatment plant and it overflows to the Missouri River after most rainstorms. The Blacksnake Creek Stormwater Separation Project will convey stormwater directly to the Missouri River. This will reduce water quantity in the existing sewer during storms and the quantity of combined stormwater and wastewater overflowing to the river. Currently, a 2.75 m ID and 2 km long segmental tunnel is under construction as part of the Separation Project. This project is an America's First, using segments solely reinforced with macro synthetic fibre (MSF). This paper addresses the solutions to the technical challenges of the project, the design of the segments and the benefits associated with the use of MSF.

1 INTRODUCTION

1.1 *Fibre reinforced concrete tunnel segments*

Fibre reinforced concrete (FRC) is becoming widely utilized in segmental linings due to the improved mechanical performance, robustness and durability of the segments. Further, significant cost savings can be achieved in segment production and by reduced repair or reject rates during temporary loading conditions. The replacement of traditional rebar cages with fibres further allows changing a crack control governed design to a purely structural design with more freedom in detailing.

Macro synthetic fibres (MSF) are non-corrosive and thus ideal for segmental linings in critical environments. Although fibre reinforcement for segments is relatively new, recent publications such as the ITAtech guideline (ITAtech 2016), the British PAS 8810 (2016) and the FIB state-of-the-art report (FIB 2017) have now given more credibility to this reinforcement type and the basis for design.

It seems that the industry globally has picked up MSF for segments, mainly for the durability reasons the synthetic fibres provide, as compared to steel fibres. A major reference for the use of MSF as sole structural reinforcement for precast tunnel segments is the Santoña–Laredo General Interceptor Collector in Northern Spain (Winterberg et al. 2018a). The experience gained in the Santoña-Laredo project showed that macro synthetic fibre reinforced segments perform very robust and satisfactory even under difficult conditions (Winterberg et al. 2018b).

Also the US started to embrace this technology and there are a couple of innovative people among the design consultants, contractors and owners supporting this drive. After successful completion of the final lining of the starter and end tunnel, and successful trials for the Euclid

Creek tunnel in the NEORSD sanitation project (Wotring et al., 2016), now the first MSF segmental tunnel is on its way in St. Joseph, Missouri.

This America's First is even more significant as the new ACI guideline on FRC tunnel segments basically exclusively deals with steel fibre (ACI 544.7R 2016). That shows that innovative drivers can overrule conservative practice for beneficial and sustainable solutions. In this particular case, all parties involved had the common target to make it a world's first in North America.

1.2 *Project description*

The Blacksnake Creek Stormwater Separation Improvement Project is required as part of the City of St. Joseph, Missouri's Combined Sewer Overflow (CSO) Long Term Control Plan in order to improve water quality as mandated by the Federal Clean Water Act. The CSO control mandate is described in the Combined Sewer Overflow Control Policy as administered by the Environmental Protection Agency (EPA).

Blacksnake Creek is currently directed into the City's combined sewer system through a double box culvert, and the creek flow is conveyed through the sewer system to the Water Protection Facility and unnecessary treated 365 days of the year. During wet weather events, storm water runoff exceeds the capacity of the combined sewer system and causes combined sewer overflows to the Missouri River. The overflows are a mix of stormwater and sanitary sewage and result in adverse water quality problems. To combat the discharge, the project will intercept and redirect Blacksnake Creek stream flows away from the City's combined sewer system to a new and dedicated stormwater conveyance system that flows directly to the Missouri River, thus reducing the frequency, volume, and impacts of combined sewer overflows to the river.

The Tunnel Bid Package (TBP) was a critical portion of the project, as the topography of the area did not allow for construction of a new and dedicated stormwater canal via traditional trench excavation without significant impacts to the public. The TBP primarily consisted of the following components and key facts:

- Contractor: Super Excavators, Inc. Menomonee Falls, WI
- Bid Award Amount: $27,991,000 USD
- Duration: 2018 to 2019
- 2.74 m ID by 2 km long segmentally lined tunnel with macro synthetic fibre reinforcement.
- 11 m ID Baffle Drop Structure
- 15 m Reinforced Concrete Box Culvert
- Energy Dissipation Structure

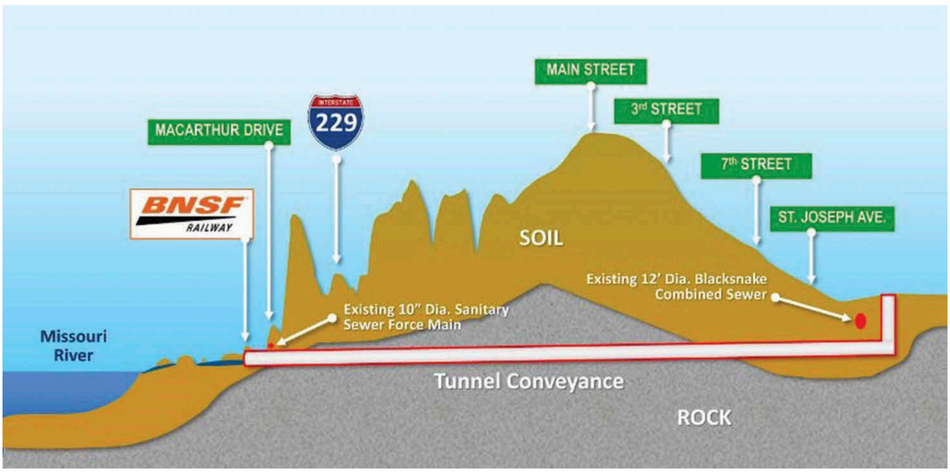

Figure 1. Tunnel alignment.

2 GROUND CONDITIONS

The tunnel is to be constructed in soft ground and mixed ground conditions, including soils and shale and combinations of both at interfaces. The soils to be encountered vary from silty clay, silty sand, clayey sand, and sandy clay. The sections with higher sand content may lead to great instability in the excavation and could result in greater groundwater inflows and flowing ground.

The shale to be encountered is low in strength, has low to medium-low durability, is easily excavatable, and has low hydraulic conductivity. Groundwater along the tunnel varies along with the topography from 12 m to 45 m of groundwater head.

The general geography and topography of the project site is located in north-western St. Joseph, Missouri between St. Joseph Avenue and the Missouri River. The overburden along the tunnel alignment consists primarily of fill material and alluvial deposits with alternating beds of silt, clay, silty-clay and clayey silt. The minimum overburden on the project occurs at the launch shaft with approximately 9 meters of cover. As you progress away from the launch shaft at the peak of the topography on Highland Avenue between Main Street and 2^{nd} Street there is 36 meters of cover and by the time you reach the receiving shaft this reduces down to 18 meters. The primary rock conditions predominantly consists of shale and claystone along the tunnel horizon. A limestone bed is present above the tunnel crown for approximately 1,280 meters.

The percentage of the alignment for the various different ground conditions consists of: soft-ground 23% of alignment, rock 63% of alignment and mixed-ground 14%. The tunnel will transition between soft ground and rock along each end of the tunnel alignment and mixed-faced conditions shall be anticipated for reaches along these subsurface transitions. The soil to rock transitions on each end of the alignment may be gradual. Meaning, that rock or soil may be present for a length, and then not present in the excavation face over these transitional mixed-face areas. It is anticipated that the tunnel groundwater inflow will not exceed a steady state of flow greater than 50 GPM.

3 TBM DESIGN AND LAUNCH

3.1 *TBM design*

Considering the ground conditions along the tunnel alignment and the contract specifications, the tunnel must be excavated with an EPB tunnel boring machine in order to migrate risks. The TBM was newly commissioned, engineered by LOVSUNS in Canada, and manufactured and fully tested at their parent company Liaoning Censcience Industry Co. Ltd. Facilities in China. Details of the TBM are presented in Table 1.

Figure 2. TBM factory acceptance in China.

Table 1. Technical data of the EPB TBM.

Parameter	Value
Excavation Diameter	3,314 mm
Total Length	78 m
Min. Turning Radius	250 m
Max Speed - Cutting Head	9.21 rpm
Maximum Torque	981 kNm
Main Drive Motors	4 No.
Thrust Capacity	900 Tonne
Thrust Cylinders	12 No.

3.2 *TBM launch*

Prior to the TBM arriving onsite in late June of 2018, a cradle was placed inside the secant pile launch shaft. This cradle consisted of two I-Beams cast in a concrete floor to fit the curvature of the machine. All the shaft and tunnel utilities were established inside the shaft prior to lowering any machine components (Figure 3 right). A special electrical and hydraulic umbilical assembly was designed and used to help launch the TBM. Note the secant launch shaft diameter is 15 m and the entire TBM assembly is 78 m of length.

The first stage was receiving the 18 truckloads of the disassembled machine from Port of Seattle in Washington, and transporting to St. Joseph, MO. The shipment took roughly three weeks at completion. It took one month to ship the TBM from China to Seattle by boat.

The entire machine was methodically aligned in two rows consisting of Row # 1, Main TBM Parts: cutterhead, telescopic shield, gripper shield, and tail skin; and Row # 2, Backup System: all the gantries and backup equipment including the electrical substation (Figure 3 left). The TBM cutterhead, gripper shield and telescopic shields were nearly completely assembled at the surface due to the ease of assembly at the surface versus the shaft. A 500 Tonne mobile crane was mobilized to the project site and used to lower the heavy components into the shaft.

Once the major components were lowered down into the shaft, one crew began hooking up the electrical and hydraulic lines while another crew continued to work on assembly of the gantries. The gantries included such items as: the operator's cabin, electrical substation, air compressor, main drive motors, grease pumps, ground conditioning system, ventilation cassette and cable festoons.

Figure 3. TBM Carrie's main parts (left) and launch cradle in the secant shaft (right).

Figure 4. Launching the TBM (left) and half-ring installation for TBM propulsion (right).

The special hydraulic and electrical umbilicals were used to link the gantries on the surface to the main TBM body in the launching cradle on the bottom of the shaft. At this point of time, the TBM could begin the functional testing and troubleshooting process.

After finishing assembly of the initial configuration for the machine, the excavation has started. During this process, the primary propulsion cylinders pushed off of beams welded to the I-Beam in the cradle. This allowed for the advancement of the cutterhead, telescopic shield and gripper shield to advance forward and penetrate the secant shaft. A short screw conveyor was utilized to control the material in front of the TBM (Figure 3 right).

After the TBM was launched, and most of the components installed and in the ground as mentioned above, the next step was to disconnect the complete electrical and hydraulic cables/hoses, which allowed the following tasks to be completed:

- Remove the short launch screw conveyor
- Install the longer screw conveyor
- Install the tail shield
- Install the segment transporter belly pan
- Re-hook up the electrical and hydraulic cables/hoses.

During this stage, a precast concrete segmental tunnel liner “half-ring” structure has been used to push and advance the TBM further into the excavation (Figure 4 right).

Once the tailskin reaches the secant shaft wall the full ring will begin to be installed. A support bracket will be braced off the secants to hold the first segment ring in place while the TBM advances forward. The gantries will be lowered down into the shaft one by one until all nine are buried directly behind the TBM. Then, full production tunnelling can begin.

4 SEGMENTAL LINING

4.1 *Introduction*

The lining for the Blacksnake Creek Stormwater Separation Tunnel consists of a precast concrete segmental tunnel lining. The segmental lining is composed of six fibre reinforced concrete segments with rubber gasket frames inserted between the segments and adjacent rings to create a watertight lining. When assembled, the six trapezoidal segments form a ring with an internal diameter of 2743 mm (Figure 5).

The universal rings of 1219.2 mm length have a taper of 12.7 mm in order to accommodate a turning radius of 300 meters. Kinematic control during installation is provided by means of drifting bolts and alignment indicators on the segments. The radial joints are connected with galvanised steel bolts.

The precast concrete segments are produced by CSI Tunnel Systems Inc.'s plant in Macedonia, Ohio, and were shipped by truck to the project site in St. Joseph, Missouri. Segments are installed within the tunnel during the excavation process by completing a segment ring with each advancement. Each individual segment is placed using a segment erector located in the shield trailing the TBM and segments are manually bolted together. Annular grouting is performed through grout ports built into each segment after the rings are erected.

BarChip 54 Macro Synthetic Fibres were used to reinforce the precast concrete segments as an alternative to steel fibre or traditional deformed steel bar reinforcement. This alternative was chosen to reduce material costs while ensuring compliance with American Iron and Steel provisions of the Contract Documents. The use of synthetic fibre reinforcement further eliminates the risk of corrosion and increases the service lift of the tunnel lining. This, in turn, reduces future maintenance cost of the tunnel. The Blacksnake Tunnel will be the first tunnel in North America to be lined with precast concrete segments that are solely reinforced with synthetic fibre reinforcing.

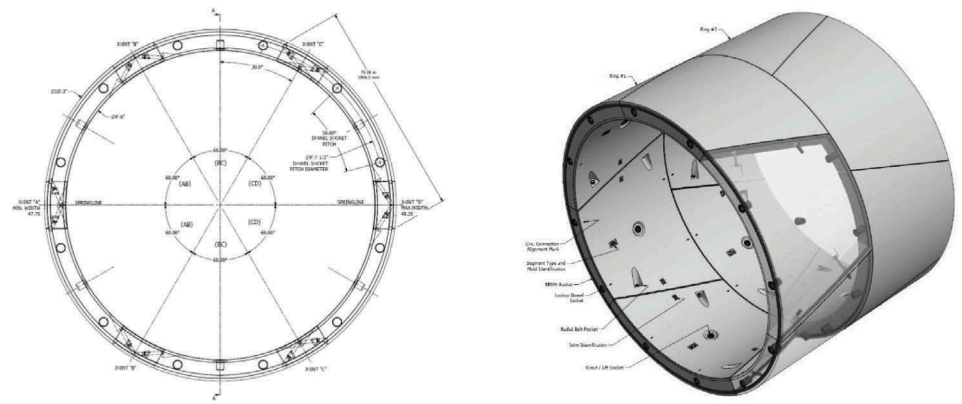

Figure 5. Ring segmentation (left) and tunnel ring assembly (right).

Figure 6. MSFRC segments in the Ohio factory (left) and on site (right).

4.2 *Structural design*

To better accommodate the fibre reinforced concrete solution, smaller segments were adopted in order to limit the segments' aspect ratio. The tunnel has an internal diameter of 2.743 m with a segment thickness of 190.5 mm. The segmentation was selected to be six trapezoidal segments (Figure 5). This yields a segment aspect ratio of 8.1, which is well below the acknowledged limit of 10 to ensure segment robustness for temporary load cases (ITAtech 2016).

The FRC segments are made using a concrete class C40/50 (f'_c 48 MPa) at 28 days age, with a stripping strength of 14 MPa. The residual strength was specified to 3.2 MPa at l/150 according to ASTM C1609. BarChip 54 is the chosen fibre, based on the good experience made in the Euclid Creek tunnel project (Wotring et al. 2016). A dose rate of 7 kg/m^3 of this fibre was sufficient to exceed the residual strength specification.

The design approach adopted for the FRC segmental lining in ultimate limit state (ULS) is the use of Normal Force-Bending Moment interaction diagrams or Moment-Thrust Capacity Limit Curves. The factored design load couples acting on the section must remain within the N–M envelope (Nitschke and Winterberg, 2016). The FRC material properties are herein derived from the beam tests, which are eventually used as the basis to determine the stress-strain relationship of the concrete on the tension side. The idealized stress-strain diagram enables setting up the capacity limit curves, which are obtained by equilibrium iterations on the given cross-section.

Cooperating with the contractor's design team, L-7 Services from Denver, CO, the Technical Department of BarChip Inc. (formerly known as Elastoplastic Concrete or EPC) was asked to conduct a feasibility study for the use of macro synthetic fibres as the sole reinforcement for the lining.

The structural design for ULS also comprised a simulation of 1% ground loss. The initial check for 1% ground loss simulation showed a slight outlier (Figure 7 right), however, the factored load couple was later revised to a lower value of bending moment to fit the capacity envelope.

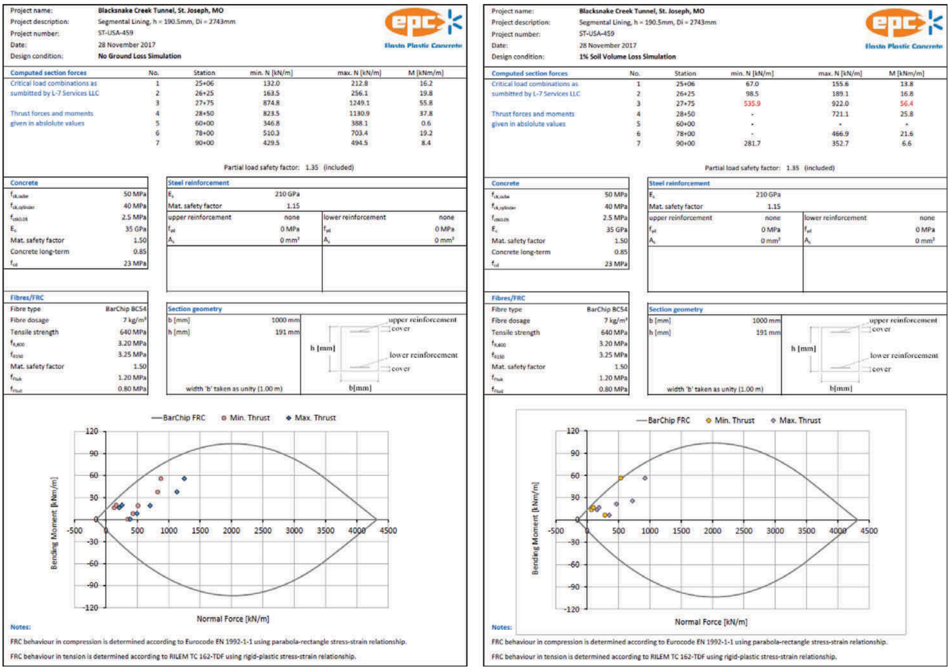

Figure 7. N-M section analysis for no ground loss (left) and 1% ground loss simulation (right) in ULS.

All checks for temporary load cases as well as the checks for serviceability limit states (SLS) have been performed with Finite Element Analysis using Atena (JKP 2017).

5 TUNNEL DRIVE

Full tunnel production has just started at the time of submittal of this paper. Experiences during the tunnel drive, i.e. segment/ring installation, evolution of TBM thrust forces, handling of eccentric thrust forces and behaviour of the segments, etc. will be presented in detail in the presentation of this paper. However, the experiences of the TBM launch and installation of the first rings are described here.

After receiving the TBM from Liaoyang, China to St. Joseph, MO (United Stated), performing the complex assembly and functionality testing on the surface, and receiving the fibre reinforced concrete segmental liner sections, now it's time to discuss the approach to the initial tunnel drive.

As previously discussed, space in the launch shaft is very limited compared to the entire length of the TBM, thus requiring the launch process to occur in phases. This process was explained in greater detail under the launching section of this paper.

The initial tunnel drive launched in soft ground, and then transitions into mixed ground conditions fairly quickly. To control alignment and grade during the launching process, and throughout the tunnel drive, a TAC's system is implemented. The TAC's system provides continuous information about how the machine axis is aligned with respect to its designed alignment, and in what direction it is moving. The system also determines how the six piece segmental liner will be installed, dependent on the position of the rings with the taper, which determines the straightness or curve of the tunnel drive.

To date, there are roughly 30 segment sections installed (approx. 36.5 meters). The initial tunnel drive installation has proven that the fibre reinforced segments are robust enough to withstand the temporary load cases, i.e. transportation, hoisting, handling and installation, without experiencing damage to the segments. In addition, the half-ring segment sections used in the shaft for the launching process were inspected after the initial push and no damage

Figure 8. Segment erector inside the tail can (left); erected segments in the tunnel (right).

occurred to the segments. We haven't experienced high forces during the initial tunnelling drive due to the fact we haven't encountered the rock section thus far. Also, the forces while launching through the concrete secant shaft were insignificant. We don't expect any issues to arise when the rock section is encountered due to the fact the segments and TBM are designed to handle the anticipated ground conditions.

This particular TBM uses a bulkhead type mechanical segment erector inside the tail can to erect the six piece segmental ring. It utilizes a ball type pick up system, where the ball head bolt is screwed into a threaded socket in the centre of the segments (Figure 8 left). The erector has a safe working load of 130% of the segment weight. The rotational speed is fully variable even when loaded between 0–2 RPM. The erector is capable to reach segments over the two inner most rows of the tail seal brushes.

It is anticipated based on the performance of the TBM, robustness of the segments, and ground conditions that are expected to be encountered, that the advancement should be between 14.6 to 18.2 meters per 10 hour shift once full production mining commences.

6 CONCLUSIONS

Being the first contractor in North America to utilize a Lovsuns TBM, and macro synthetic fibre as the sole reinforcement of the precast concrete segments, is a very exciting aspect to this project. Launching the TBM with an extensive amount of umbilical cords, in a relative small size shaft compared to the overall length of the TBM, and a unique launching process has been challenging but a lot of knowledge has been gained for future launching of this TBM on other projects.

The durability and performance of the macro synthetic fibre reinforced segmental lining has outperformed expectations to date. The indicating factors of the performance of the machine, durability and robustness of the segments, and performance of the crew, will meet the project goals once production mining commences.

Ongoing research and continuous developments on macro synthetic fibre and macro synthetic fibre reinforced concrete have made it today being a modern and cost-efficient construction material. Eliminating durability issues with regard to corrosion of the primary reinforcement yields significant advantages for the design, since it is no longer governed by serviceability limits.

The experience gained so far in the drive of the Blacksnake tunnel project shows that macro synthetic fibre reinforced segments perform very robust and satisfactory even under difficult conditions during the TBM launch phase.

The successful completion of this "America's First" project will build further confidence in macro synthetic fibre reinforced segmental linings. The success and gained experience of this project will lead to the implementation of this technology in other segmental tunnel projects.

These types of utility tunnelling projects (e.g. sewage, power, irrigation or gas transfer tunnels) are widely existing in the world market and they present a huge opportunity for MSF reinforced concrete linings, benefiting from the given advantages.

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