Hard Rock Tunnel Boring in Challenging Conditions at the Jefferson Barracks Tunnel

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ABSTRACT

The Metropolitan St. Louis Water District's Project Clear is a 28-year program targeting wastewater capacity throughout St. Louis, MO. The extensive program includes the Jefferson Barracks Tunnel, running parallel to the Mississippi River at 2 m ID and 5,400 m long.

A rebuilt Robbins Main Beam TBM began boring but hit challenging conditions about 2,400 m in, including water inflows. A larger 4.1 m Robbins Main Beam machine will complete the remaining 3,050 m in limestone, dolomite, and shale. The TBM will utilize a high-powered, high breakout torque cutterhead along with enhanced 360-degree probing & grouting capabilities to detect any karst formations.

INTRODUCTION

MSD Project Clear, for the Metropolitan St. Louis Water District, is tackling aging infrastructure head on in a massive scheme to target water quality and wastewater concerns in St. Louis, Missouri, and surrounding areas. The USD $6 billion program was originally scheduled to take 23 years, but it is now a 28-year program with five more years to do additional work. The extensive program involves multiple tunnels, including Deer Creek, a 6.3 km (3.9 mi) long tunnel bored with the largest TBM ever used in the St. Louis area (6.5 m/21.5 ft in diameter). Another tunnel, Jefferson Barracks, began excavation with a TBM launched from one of the largest diameter shafts ever built in the U.S. (27 m/88 ft in diameter). Both projects, being constructed by SAK Construction (SAK), are critical components of the area's wastewater system. While MSD Project Clear involves more than just tunneled underground works—the plan also includes an underground storage facility, surface rainscaping, system improvements, maintenance and repairs—the tunneled portion has perhaps been the most challenging.

The Jefferson Barracks tunnel is a key component of MSD Project Clear. The 5,400 m (17,800 ft) long, 2 m (7 ft) internal diameter tunnel runs parallel to the Mississippi River and extends to the Lemay Wastewater Treatment Plant located at the confluence of the River des Peres and the Mississippi. The Jefferson Barracks Tunnel service area currently conveys and collects wastewater through a series of pump stations, force mains, sanitary sewers, and combined sewers that are easily overtaxed during heavy rains. The 36 to 67 m (120 to 220 ft) deep tunnel, along with new combined sewers and a new pump station, will alleviate much of the problem. The deep tunnel will also allow the MSD to eliminate two intermediate pump stations and replace the existing trunk sewer (see Figure 1).

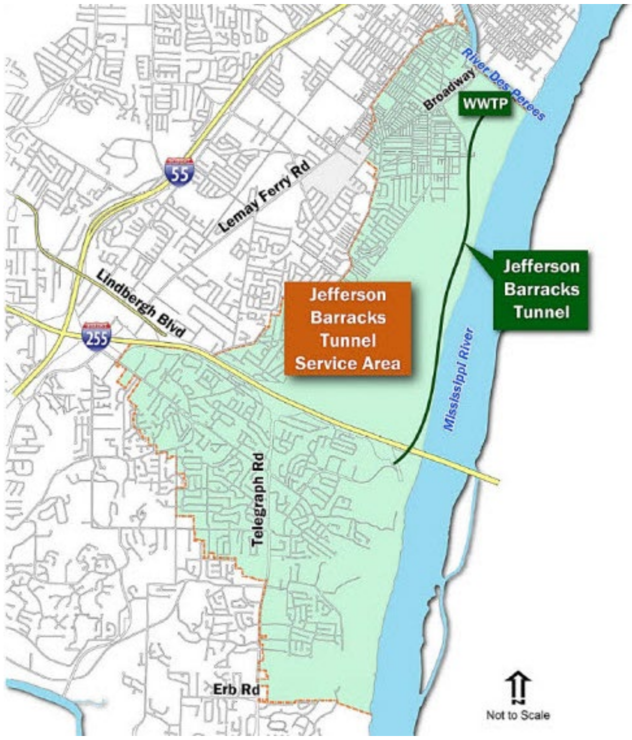


Figure 1. Detail of Jefferson Barracks Tunnel alignment. ***Image credit: MSD (www.msdprojectclear.org)***

ORIGINAL JEFFERSON BARRACKS MACHINE DESIGN

The original Jefferson Barracks TBM was refurbished from 3.43 m (11.25 ft) diameter to 3.35 m (11.0 ft) diameter, and fitted with 27, 17-inch diameter cutters and 900 kW (1200 HP) electric drive motors. The SAK team also built customized drill platforms for the small machine. Components of the TBM are made up of two veteran machines—one of those is "Chelsea the Chomper", the Robbins TBM used at the Lemay Redundant Force Main in 2014, and in 2011 at the Lemay Wet Weather Expansion Outfall, all part of MSD Project Clear in St. Louis. The Lemay Redundant Force Main was the machine's 13th project, bringing it to over 40 km (25 mi) of tunnel bored in its long career.

Components of another Robbins Main Beam TBM were also used on the machine—that of the machine known as "Miss Colleen", most recently used at Baltimore's Bi-County Water Tunnel. The 3.0 m (9.8 ft) diameter machine was one of the world's longest running TBMs in operation. It had been used on at least ten different projects between 1973 and 2011, totaling at least 50 km (31 mi) of hard rock tunnels (see Figures 2A and 2B, and Figure 3).

Figure 2A (left). "Miss Colleen", the Main Beam TBM for the Bi-County Water Tunnel
Figure 2B (right). "Chelsea the Chomper" breaks through at the Lemay Redundant Force Main in 2014

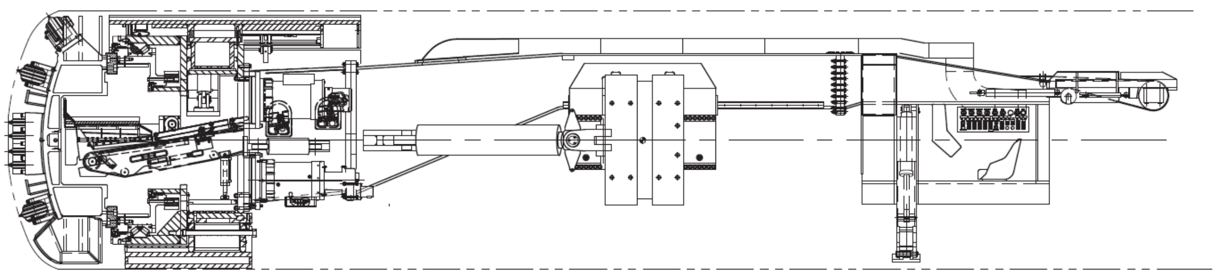


Figure 3. Original Jefferson Barracks TBM profile

TUNNELING AT JEFFERSON BARRACKS WITH ORIGINAL TBM

Work at Jefferson Barracks began with the large diameter launch shaft in April 2018, site of a future pump station, which was constructed in karstic limestone conditions on the edge of a paleochannel along the Mississippi River. Pre-excavation grouting was performed to limit the potential for large groundwater flows into the shaft.

Shaft construction involved a secant pile wall extended into the bedrock. Excavation of the overburden began in late April 2018 using a tracked excavator. Drill and blast methods were used to break the underlying bedrock into pieces small enough to be removed by the excavator, as well as buckets and a crane. The 27 m (88 ft) diameter by 50 m (166 ft) deep shaft was completed in October 2018, and was followed by a starter tunnel, also excavated by drill and blast, for the Robbins Main Beam TBM that would bore the Jefferson Barracks tunnel. Tunneling began on October 31, 2018 (see Figure 4).

Figure 4. The 27 m diameter Jefferson Barracks shaft

The Robbins TBM bored through limestone and dolomite with layers of shale and a shale invert, in what was largely good ground, although some areas within the shale invert became soft after excavation. Crews achieved rates of up to 24 m (80 ft) per shift using the original TBM, working in two 9-hour shifts per day while installing rock bolts between 60 and 120 cm (2 to 4 ft) long and wire mesh. Groundwater was a challenge for the crew, with water flowing into the tunnel at rates of 300 l (80 gal) per minute that had to be pumped out.

Encountering the Sinkhole

Around 2,400 m (7,900 ft) into the tunnel on May 7, 2019, the TBM hit a large void, the size of which could not be determined, along with flowing, unstable ground conditions. The location of the void was approximately 120 m (400 ft) from the Mississippi River and 3.7 m (12 ft) from a building built in 1866 right after the Civil War. The building, designated a historic landmark, had been purposefully built at the base of a naturally occurring sinkhole, several of which can be found throughout the historic Jefferson Barracks location, each with buildings in them. The strategy of these building locations was that during times of conflict, opposing forces would be unable to see the building structures while they were on the river or on the opposite bank. In addition, a network of near-surface tunnels was built during the Civil War at the Jefferson Barracks site to transfer munitions and ammunitions from the river and from a railroad track that ran alongside the Mississippi River.

The historical structures resulted in a confluence of events that made the encountered void difficult to stabilize. In the design and planning phase the sinkholes and karst locations and depths were estimated, and the tunnel was designed to be built far below those features in stable bedrock (see Figure 5).

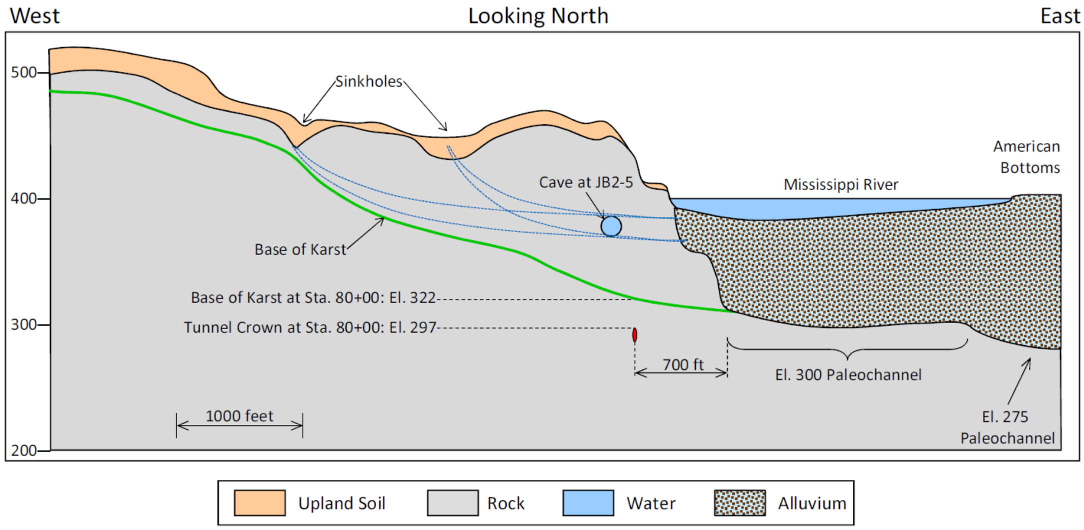


Figure 5. Estimated geology including karst features from the geotechnical baseline report (Jacobs, 2016)

The surface depth of the sinkhole was 11 to 12 m (35 to 40 ft) at the surface and the Jefferson Barracks tunnel was 60 m (200 ft) deep. It turned out that the vertical feature that led to the sinkhole was a deep karstic cave filled with mud, sand, gravel and tumbled rock that had been compacted into the void over the last Ice Age. In order to avoid damaging the historic building, the contractor and MSD would need to fine tune a complex strategy.

While various options including ground freezing were considered, they were ultimately deemed infeasible because the upper and lower features of the void were not distinct but combined, and highly erratic in nature. Core drillings of the area revealed drastic changes every 1.5 m (5.0 ft), with some cores showing solid rock starting at 6ft from the surface down to 58 m (190 ft), and others showing rock for 18 m (60 ft), then 4.6 m (15 ft) of void, and back into rock again. Other cores revealed up to 18 m (60 ft) of mud while some showed frequent transitions between mud and rock. Simply backing up the machine as little as 7 cm (3 in) resulted in a cascade of mud, sand and gravel flowing into the tunnel invert through the open cutterhead windows around the main bearing and up into the main beam. The TBM had to remain in place, acting as a plug until the cave could be stabilized. After the cave was stabilized the TBM could then be removed from the tunnel.

It was decided to build a recovery shaft and adit to stabilize the area and remove the machine in what would be an intensive and ultimately successful undertaking (see Figure 6).

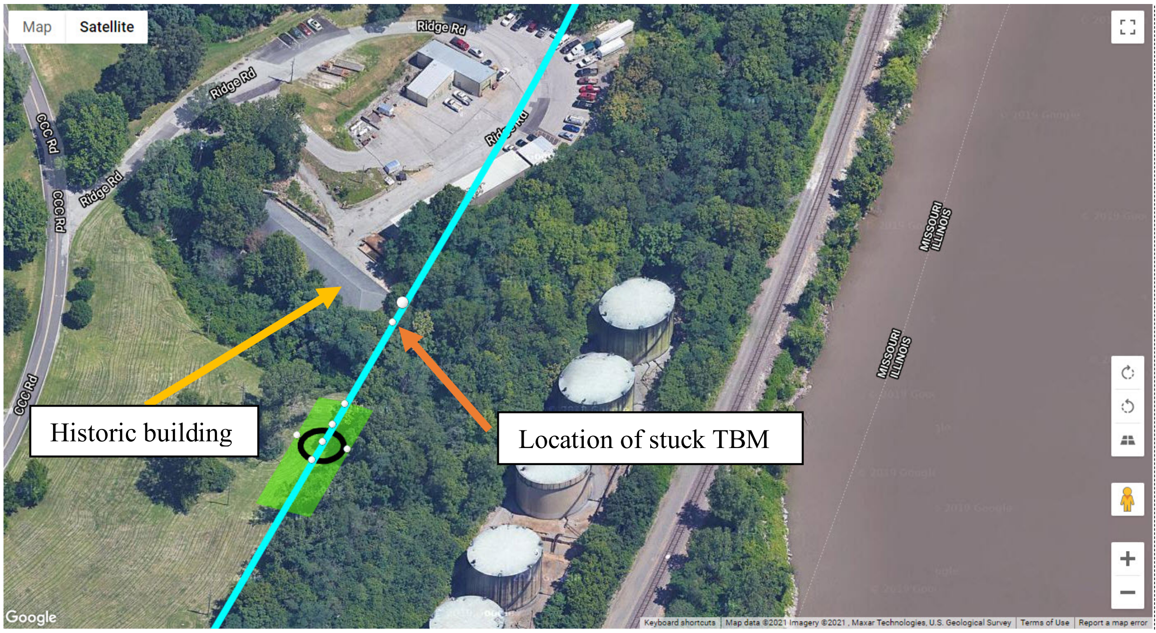


Figure 6. The historic building and area of the stuck TBM, showing the area of the recovery shaft (black circle) along the tunnel alignment (blue). The green rectangle depicts an archaeological dig area that required investigation prior to excavation

Excavating the Recovery Shaft and Adit

Drill and blast construction of the 62 m (205 ft) deep x 12 m (40 ft) diameter shaft on the other side of the sinkhole feature from the TBM started in July 2020 and was completed in October 2020 with hand-mining of the 60 m (200 ft) long x 6 m (20 ft) wide horseshoe tunnel, serving as the recovery adit, beginning soon after. To counter the karstic ground conditions and allow excavations to reach the trapped machine, SAK proposed grouting together with spiling and steel sets, designed to stabilize the ground according to conditions actually encountered (Rowland, 2021).

Recovery efforts proceeded in steps. Spiling of the hand-mined recovery adit began once the karstic feature was encountered mining back to the TBM. A 3 m (10 ft) thick concrete wall was constructed which allowed for high pressure displacement grouting to be conducted from within the adit tunnel. Two rows of 24 m (80-ft) –long canopy tubes were installed which spanned the karstic feature and extended back over the top of the TBM to stabilize the area ahead of and around the machine. Lagged steel ribs were stood every 90 cm (3 ft) as excavation progressed. Flash coats of shotcrete and grouting behind the steel ribs were conducted to further solidify the ground and provide a safe working environment (see Figures 7-8).

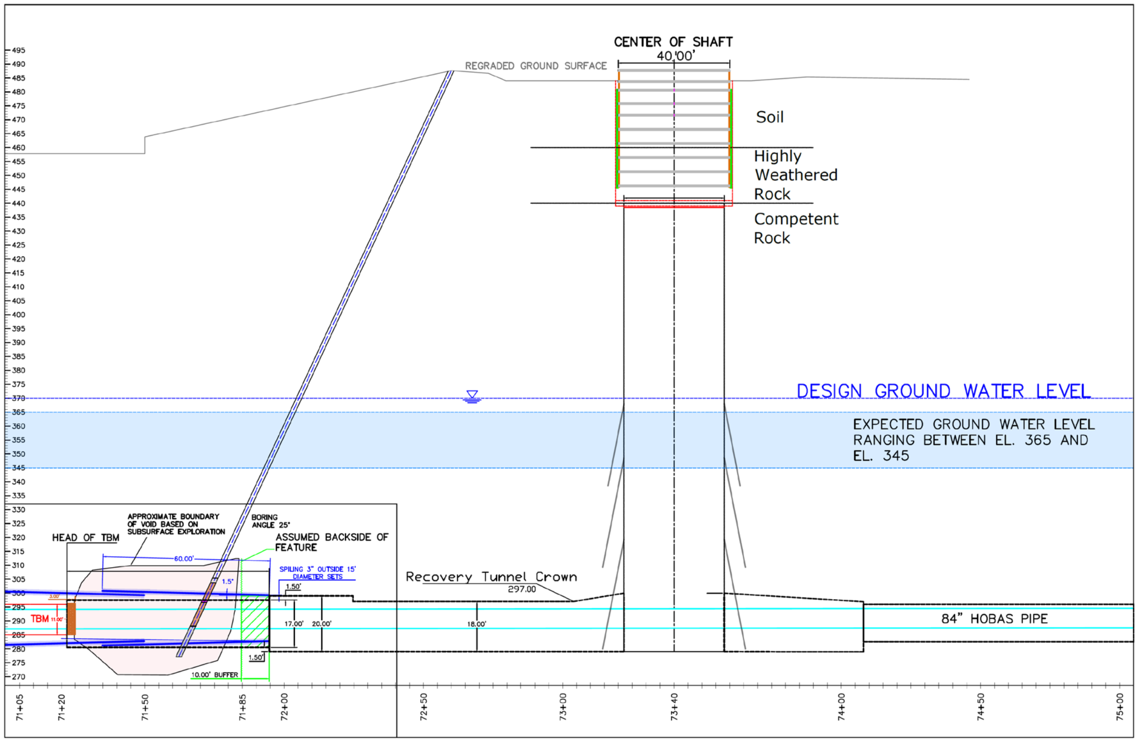


Figure 7. Overview of recovery shaft and horseshoe adit

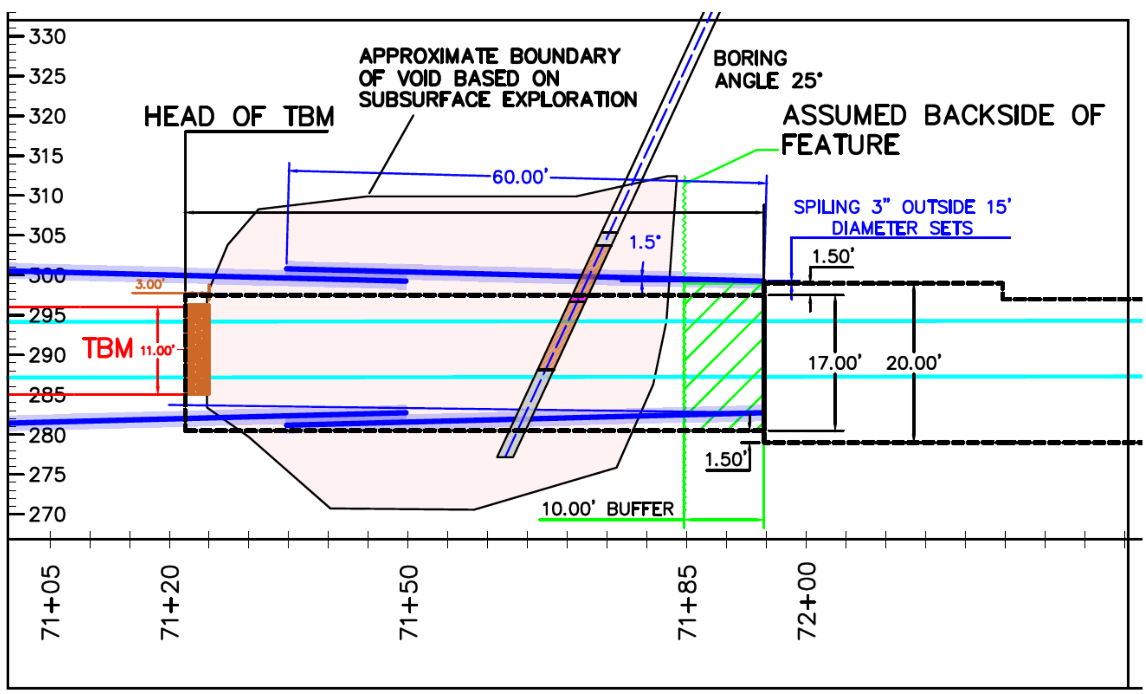


Figure 8. Closeup of the void area and stuck TBM, with spiling from the recovery adit

JEFFERSON BARRACKS 2 TBM DESIGN

With 3,050 m (10,000 ft) left to excavate and the original machine being damaged due to the water and material inrush, SAK's only option to complete the project was to introduce a second machine. The concept of using a second machine to complete the project was agreed by the Owner. SAK then looked for options to procure a machine in order to complete the project. Robbins was able to provide a machine with a quick delivery based on a machine that was in their inventory and had previously been manufactured for a project in Chile. The machine had not been used and was available due to the project in Chile being cancelled. The Robbins inventory machine was an Open Main Beam machine at a diameter of 4.1 m (13.5 ft), which was larger than the original machine that had become trapped.

There were concerns that the balance of the tunnel could encounter the same geological conditions, so the advantage of the larger machine was it allowed the installation of additional ground support including probe/grout drills for ground consolidation in advance of the excavation. The machine is a High Performance (HP) type machine, which is capable of 360-degree probing and grouting to detect any future karst zones (see Figures 9A-9B). It also includes roof drill systems, a ring beam erector, and the ability to install wire mesh and the McNally ground support system with steel slats for crown support. In addition, the TBM utilizes 19-inch disc cutters for greater thrust capacity (see Figure 10).
The specifications of the second machine are as below in Table 1.

Table 1. Jefferson Barracks 2 TBM Specifications

Project Information	
Project Name	Jefferson Barracks Phase 2
Project Location	St. Louis, Missouri, USA

TBM	
Type	Hard Rock Main Beam / Open Gripper
Machine Diameter	4.13 m (13 ft - 6.5 inches) with new cutters

Cutters	
Cutter Type	Series 19-inch Wedge-Lock™
Number of Discs	27
Recommended Individual Cutter Load	Nominal 311 kN (70,000 lb)
Penetration Rate	Maximum 12 cm (4.8 in) / min

Cutterhead	
Curve Radius	
Horizontal Crab Steering	Minimum R350 m (R1,150 ft)
Vertical	Minimum R1,000 m (R3,280 ft)
Maximum Operating Cutterhead Thrust	8,397 kN
Cutterhead Drive	VFD electric motors, 2-stage gear reducers
Cutterhead Power	4 x 330 kW = 1,320 kW
Cutterhead Speed	0 – 12.65 RPM
Cutterhead Torque	996 kNm @ 12.65 RPM 1,212 kNm @ 0 – 10.4 RPM
Breakout Torque (150% Max. Torque)	1,818 kNm

Main Bearing	
Type	High Capacity, Tri-Axis
Lubrication of Bearing	Recirculating, Filtered, Monitored
Front Sealing	3 x Lip Type, heavy duty
Lubrication of Sealing	Oil / grease flushing

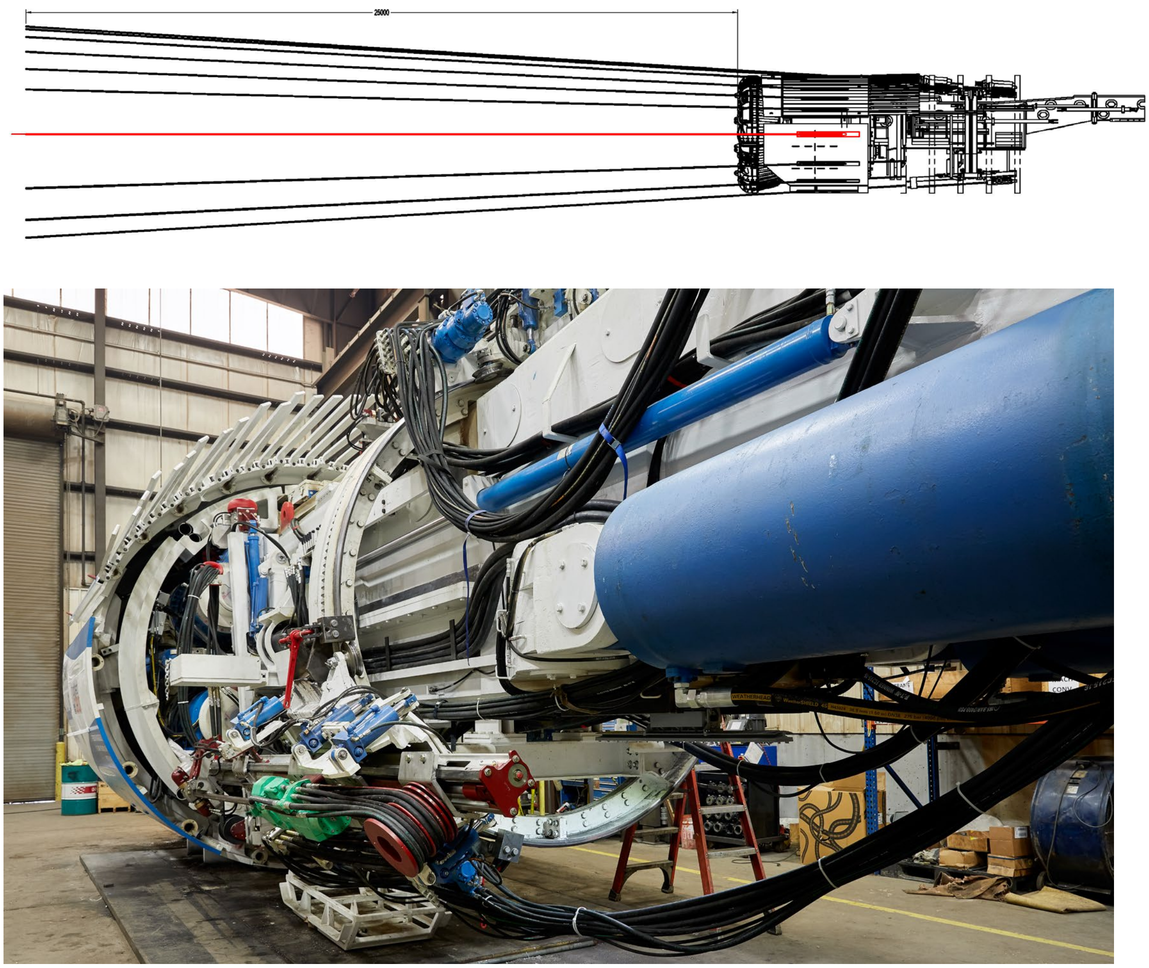
Thrust Cylinders	
Number of Cylinders	2
Stroke (Effective)	2,007 mm (79 in)
Maximum Advance Rate	12 cm (4.8 in) / min =7.3 m (24 ft) / hr
Maximum Thrust Force	9,000 kN at 283 bar

TBM Belt Conveyor	
Belt Width	711 mm (28 in)
Capacity	317 Metric Tons (350 US Tons) / hr

Ground Support Equipment

The installed ground support equipment includes the following:

- Work Platforms for installation of wire mesh and other rock support
- Two (2) Roof Drills
- Ring type positioner for two (2) probe/grout drills
- Slat or McNally system and standard finger shield
- Ring beam erector



Figures 9A-9B. Probe drills for 360-degree drilling around periphery

Figure 10. Replacement TBM under manufacturing at Robbins workshop

The new machine will be launched from the recovery adit after being lowered down the recovery shaft. It will launch from a starter tunnel extended out by 90 m (300 ft), and will be serviced by the existing infrastructure, including 7.6 cubic meter (10 cy) muck cars and 13.6 metric ton (15 U.S. ton) locomotives with intermittent California switches, running from the original working shaft to the planned reception shaft. Originally due for completion in April 2020, the Jefferson Barracks tunnel is now provisionally expected to complete in May 2024. Once complete, the Jefferson Barracks tunnel will be lined with a 2.1 m (84 in) diameter fiberglass pipe liner in an operation that will take three to five months, followed by new intake structures that will connect up with six tunnel adits to intercept surface flow, diverting it from gravity sewer systems.

CONCLUSIONS

The Jefferson Barracks project offers unique opportunities and lessons learned for the tunneling industry. Chief among these is that a good geological profile allows for planning of the required ground support. A larger diameter machine can prove to be a benefit, particularly in the Jefferson Barracks case, because it offers a larger array of ground support and increased capabilities for probing and grouting. It also offers good working space around the machine to enable the increased ground support operations. Probe drilling in advance of boring is and will be essential to determine the location of any future karst features.

REFERENCES

Jacobs Engineering Group. 2016. Geotechnical Baseline Report, Jefferson Barracks Tunnel. Pg. 41.

Jonathan Rowland. 2021. Replacement TBM needed to finish St. Louis CSO drive. https://www.tunneltalk.com/USA-14Jan2021-New-TBM-for-St-Louis-CSO-as-original-remains-trapped-underground.php

MSD Project Clear Initiative. 2021. www.msdprojectlclear.org.