CONSTRUCTION GROUTING OF THE BAUMGARTNER TUNNEL

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ABSTRACT

The Baumgartner tunnel collects sanitary sewage and conveys it to a treatment plant near the mouth of the Meramec River. The nearly 6.2 km (4 mile) long, 3.8 m (12.5 foot) diameter tunnel is 49 to 55 meters (160 to 180 feet) below the Meramec River. During construction, a previously unidentified water-bearing zone containing hydrogen sulfide gas was encountered in the bedrock. The zone, first encountered above the tunnel, eventually intersected the tunnel and was also encountered during the excavation of the screen and lift station shafts. It was necessary to grout the seams within this zone ahead of the tunnel boring machine (TBM) to mitigate water inflow and the risk of encountering dangerous levels of gas.

INTRODUCTION

Grouting programs were undertaken in the screen structure and lift station shafts and for the tunnel excavation during construction of the Baumgartner Tunnel in order to decrease groundwater inflows from an unforeseen and unusual water-bearing feature in the bedrock. After excessive groundwater inflow was encountered during rock excavation in the screen shaft, additional borings and packer testing performed during construction indicated that the same feature was present within the tunnel excavation and the adjacent lift station shaft. The Metropolitan St. Louis Sewer District's (MSD) proactively partnered with the Contractor to perform additional explorations and grouting prior to rock excavation in the lift station shaft and ahead of the TBM to mitigate impacts on construction and resulting delays.

PROJECT DESCRIPTION

Baumgartner Tunnel was part of the MSD's approximately $220 million Lower Meramec River System Improvements. The Lower Meramec River System Improvements were conducted as part of a project to close the Meramec and Baumgartner Lagoons and included construction of a new wastewater treatment plant, the Baumgartner Tunnel, sewer connections to drop shafts on the new tunnel, and closure of the Meramec and Baumgartner Lagoons.

The project was located in South St. Louis County near the confluence of the Meramec and Mississippi Rivers. The tunnel is approximately 6.2 km (20,200 feet) long and conveys wastewater by gravity from MSD's Meramec Lagoon and Baumgartner Lagoon service areas, which are part of MSD's Meramec River drainage basin, to the new wastewater treatment plant. The project involved construction of an approximately 3.8 m (12.5 foot) diameter tunnel with a 2.44 m (96 inch) diameter, reinforced concrete pipe installed in the tunnel. Also included were construction of two large diameter shafts; three permanent access shafts along the alignment at Stations 2+380, 4+914, and 6+187 (Stations 78+09, 161+23, and 202+99, respectively); and five drop shafts to convey wastewater from existing sewers into the tunnel. The two large shafts were located at the new wastewater treatment plant and included a 30.5 m (100 feet) diameter lift station shaft at Station 0+000 (Station 0+00) and a 11.6 m (38 feet) diameter screen structure shaft at Station 0+058 (Station 1+90).

The majority of the tunnel alignment is located beneath the Meramec River floodplain in both St. Louis and Jefferson Counties, crossing the Meramec River at two locations and running adjacent to an active rock quarry near the north end of the alignment. The deep tunnel sewer was bored at depths of about 49 to 55 m (160 to 180 feet) below the ground surface through the underlying bedrock. The two large shafts and the access shafts were excavated 30.5 to 40 m (100 to 130 feet) through the overlying alluvium and extended through the bedrock to the tunnel elevation. Along the tunnel alignment, the tunnel passes through two rock formations: the Warsaw and Keokuk-Burlington Formations. Bedrock encountered along the alignment consisted of limestone, claystone, and shale.

MSD contracted with the Baumgartner Tunnel JV (BTJV), a joint venture of Frontier-Kemper Constructors and Gunther Nash, for excavation of the shafts and tunnel and installation of the carrier pipe. Shannon & Wilson served as the construction manager for MSD.

GEOLOGIC SETTING

The majority of the tunnel alignment is located beneath the Meramec River floodplain. The bedrock floor of the Meramec River Valley generally lies at elevation 91.4 to 97.5 m (300 to 320 feet), overlain by 24.4 to 30.5 m (80 to 100 feet) of alluvium, with a level floodplain at approximately elevation 400 feet. The floodplain deposits consist of heterogeneous strata of intermixed and interlayered clay, silt, sand, and gravel. The upper alluvium generally consists of silt and clay to about elevation 103.6 m (340 feet). Below this elevation, the alluvium is generally sandy gravel with variable silt and clay content.

The bedrock underlying the area is of the Mississippian System, Meramecian Series. This includes the Salem and Warsaw Formations. The Salem is younger and primarily consists of limestone to dolomitic limestone with occasional shale partings. Regionally, the Salem is quarried since the limestone is relatively pure and a good aggregate source. The Warsaw Formation generally consists of interbedded limestone and calcareous shale. The upper half of the unit is predominately shaly limestone and dolostone while the lower half contains mudstones interbedded with thin calcareous mudstones. The Warsaw-Salem contact is usually difficult to differentiate because the bottom of the Salem Formation is similar to the top of the underlying Warsaw.

The Burlington-Keokuk (Keokuk) Formation of the Mississippian System, Osagean Series, underlies the Warsaw Formation. The Keokuk consists of alternating limestone and beds of chert or bands of irregularly shaped chert nodules and grades upward into the Warsaw Formation. The limestone is typically medium bedded and medium to coarsely crystalline. The chert is spread erratically throughout the formation but appears to have higher concentrations in the upper and lower parts.

The contact between the Warsaw and Keokuk Formations is transitional and arbitrarily placed at the top of the gray and brown mottled chert found in the Keokuk. A general geologic section of the area is shown on Figure 1.

No known fault features exist within the project. The nearest known fault feature is in Jefferson County about 4.8 km (3 miles) south of the project and is possibly an extension of the Valmeyer Anticline in Illinois. The Valmeyer Anticline is an asymmetric anticline trending north 15 to 40 degrees west and plunging gently to the southeast. The western limb dips up to 25 degrees.

PENNSYLVANIAN SYSTEM				
MISSISSIPPIAN SYSTEM	CHESTERIAN SERIES	STE. GENEVIEVE LIMESTONE	Description	
	MERAMECIAN SERIES	ST. LOUIS LIMESTONE	Fine crystalline, medium to massive bedded limestone. Limestone breccia present in the lower part with shale infilling.	
		SALEM FORMATION	The lower part is a fragmentally fossiliferous, argillaceous limestone while the lower part is dolomitic.	
		WARSAW FORMATION	Fine to coarse crystalline, fossiliferous limestone containing geodes in its lower part.	Contact
	OSAGEAN SERIES	BURLINGTON- KEOKUK LIMESTONE	The Keokuk underlies the Warsaw and is a medium to coarse crystalline, medium bedded limestone with abundant chert layers. The Burlinton is a medium to coarse crystalline , medium to thick bedded and often coarse-stratified cherty limestone.	
		FERN GLEN FORMATION	A calcareous shale overlain by fine crystalline to sub lithographic cherty limestone.	
	KINDER-HOOKIAN SERIES	CHOUTEAU GROUP UNDIFF.		
UPPER DEVONIAN SYSTEM				

Figure 1. Generalized geologic section

DISCOVERY/RECOGNITION OF PROBLEM

Baseline Groundwater Inflow Quantities

Baseline groundwater inflow volumes were provided in a Geotechnical Baseline Report (GBR) provided by as part of the contract package. For baseline purposes, the Contractor was required to handle a total groundwater inflow of 7,570 L/m (2,000 gpm) for the lift station and screen structure excavations. A water tight slurry wall, socketed 2.7 m (9 feet) into bedrock was specified for the screen and lift shafts; therefore, these inflows were anticipated to come from the excavated rock section of these shafts. For all other shafts, the Contractor was required to handle a total baseline groundwater inflow of 3,785 L/m (1,000 gpm).

The estimated maximum cumulative sustained groundwater inflows into the tunnel were baselined at 7,570 L/m (2,000 gpm) for the full length of the tunnel, exclusive of the shafts. In addition, the Contractor was to assume encountering three occurrences of localized peak flush flows at the tunnel heading of 1,135 L/m (300 gpm). The

Contractor was required to develop plans for pressure grouting where locally heavy groundwater inflows were encountered and to develop an approach for treatment and disposal of accumulated groundwater.

Screen Shaft Excavation

Construction on the project began in January 2004 with construction of the slurry wall for the screen shaft structure. The slurry wall provided support for excavation through the alluvium and upper 2.7 m (9 feet) of bedrock. Bedrock was encountered in the screen shaft at about elevation 96.3 m (316 feet). Drill and blast techniques were used to extend the excavation through bedrock to the planned excavation bottom elevation of 70.7 m (232 feet). During a drilling cycle for a blast on June 24, 2004, groundwater inflow occurred through several of the vertical production round holes drilled in the shaft bottom. The excavation bottom at the time of the water inflow was at about elevation 81.7 m (268 feet) with the water-bearing zone encountered at about elevation 78.6 to 79.2 m (258 to 260 feet). The inflow into the shaft was estimated on the order of 757 to 946 L/m (200 to 250 gpm) through approximately eight drill holes scattered across the shaft bottom, indicating the possible presence of a near-horizontal water-bearing feature.

Screen Shaft Grouting

A grouting program was initiated by the BTJV from within the screen shaft excavation to mitigate the risk of a larger groundwater inflow into the shaft from the water-bearing zone. Attempts were made to plug production holes; however, this was not totally successful. The grouting program was conducted from within the shaft. Grout holes were drilled through the sidewall of the shaft around the entire perimeter to create a grout curtain around the shaft. Thirteen primary grout holes were initially drilled in the sidewall at about elevation 83.8 m (275 feet) and angled outward at 45 to 48 degrees. Eleven of the thirteen primary grout holes encountered water at flow rates of 114 to 284 L/m (30 to 75 gpm). Secondary, tertiary, and quaternary grout holes were also drilled through the shaft wall and angled outward to create the grout curtain. It was initially difficult to construct the grout curtain because there was extensive communication with the blast holes, requiring the use of an accelerator with the grout. During the grouting program about 70 cubic meters (2,472 cf) of grout were injected into the water-bearing feature. Due to the high percentage of grout holes drilled around the perimeter of the shaft and encountering water, it was theorized that the water-bearing zone was a horizontal feature.

Geotechnical Baseline Report Review

Following the unexpected encounter with relatively high groundwater inflow in the screen shaft, Shannon & Wilson performed a review of conditions depicted in the GBR and on the borings drilled during design by the designer's geotechnical engineer with respect to the actual conditions encountered in the screen shaft. This included reviewing retained core samples for indicators of possible features having a high transmissivity. The zone of water inflow in the screen shaft appeared to correlate with a zone in which packer testing was performed during design of the project. A packer test was performed in a boring located between the screen and lift station shafts. The test was performed between a depth of 42.7 and 45.7 m (140 and 150 feet) and reported an average field packer permeability of 1.2×10^{-3} cm/s. Packer field permeabilities on the order of 8.2×10^{-4} cm/s to 1.6×10^{-3} cm/s were also reported in borings drilled along the tunnel alignment between the screen shaft and the Meramec River at Stations 0+299, 1+516, and 1+847 (Stations 9+81.50, 49+73, and 60+61, respectively). In the

Table 1. Summary of designer's packer testing

Boring	Station	Elevation of Packer Test Top (m)	Elevation of Packer Test Bottom (m)	Elevation Tunnel Invert (m)	Permeability (cm/sec)
C-19	1+847 (60+61)	80.18 (263.06 ft)	77.13 (253.06 ft)	73.17 (240.06 ft)	8.2×10^{-4}
C-19	1+847 (60+61)	76.83 (252.06 ft)	73.78 (242.06 ft)	73.17 (240.06 ft)	1.2×10^{-8}
C-22	1+021 (33+50)	77.09 (252.92 ft)	74.04 (242.92 ft)	72.82 (238.92 ft)	7.6×10^{-8}
C-22	1+021 (33+50)	72.52 (237.92 ft)	227.92 (227.92 ft)	72.82 (238.92 ft)	3.7×10^{-8}
C-25	0+299 (9+81.50)	79.46 (260.71 ft)	76.42 (250.71 ft)	72.15 (236.71 ft)	2.4×10^{-7}
C-25	0+299 (9+81.50)	74.89 (245.71 ft)	71.84 (235.71 ft)	72.15 (236.71 ft)	1.3×10^{-3}
C-27	0+023 (0+74)	81.47 (267.28 ft)	78.42 (257.28 ft)	71.71 (235.28 ft)	1.2×10^{-3}
C-27	0+023 (0+74)	75.37 (247.28 ft)	72.32 (237.28 ft)	71.71 (235.28 ft)	5.8×10^{-6}
D-8	1+516 (49+73)	79.28 (260.12 ft)	75.93 (249.12 ft)	72.88 (239.12 ft)	1.6×10^{-3}
D-8	1+516 (49+73)	75.02 (246.12 ft)	71.66 (235.12 ft)	72.88 (239.12 ft)	3.0×10^{-4}
D-9	0+058 (1+90)	91.48 (300.12 ft)	88.12 (289.12 ft)	71.36 (234.12 ft)	2.7×10^{-4}
D-9	0+058 (1+90)	78.07 (256.12 ft)	74.71 (245.12 ft)	71.36 (234.12 ft)	2.4×10^{-5}

borings at Stations 1+516 and 1+847, the location of the packer tests were directly above the tunnel crown and in the vicinity of the contact between the Warsaw and Keokuk Formations, as defined by the designer's geotechnical engineer. The packer test performed in the boring at Station 0+299 was below the defined contact between the Warsaw and Keokuk formations and within the tunnel bore. Results of these packer tests are summarized in Table 1.

ADDITIONAL EXPLORATIONS

Tunnel Alignment

Based upon the geologic cross-sections provided in the GBR the water-bearing feature was thought to be associated with the transitional contact between the Warsaw and Keokuk formations. The generalized subsurface profile along the tunnel alignment is shown in Figure 2. The high groundwater inflows along this contact in the shafts raised concerns as to whether the water-bearing contact would be encountered by the TBM and what risks it would pose. The GBR projected this contact crossing the tunnel alignment between Stations 2+103 and 2+377 (Stations 69+00 and 78+00) which is in the vicinity of the first crossing under the Meramec River.

Several issues needed to be addressed. The quantity of water inflow could become an issue and the water could carry hydrogen sulfide and methane, known to exist in solution in the groundwater. These gases may have formed in the soft organic clay present under the deep sediment in the river valley and could be transported by the

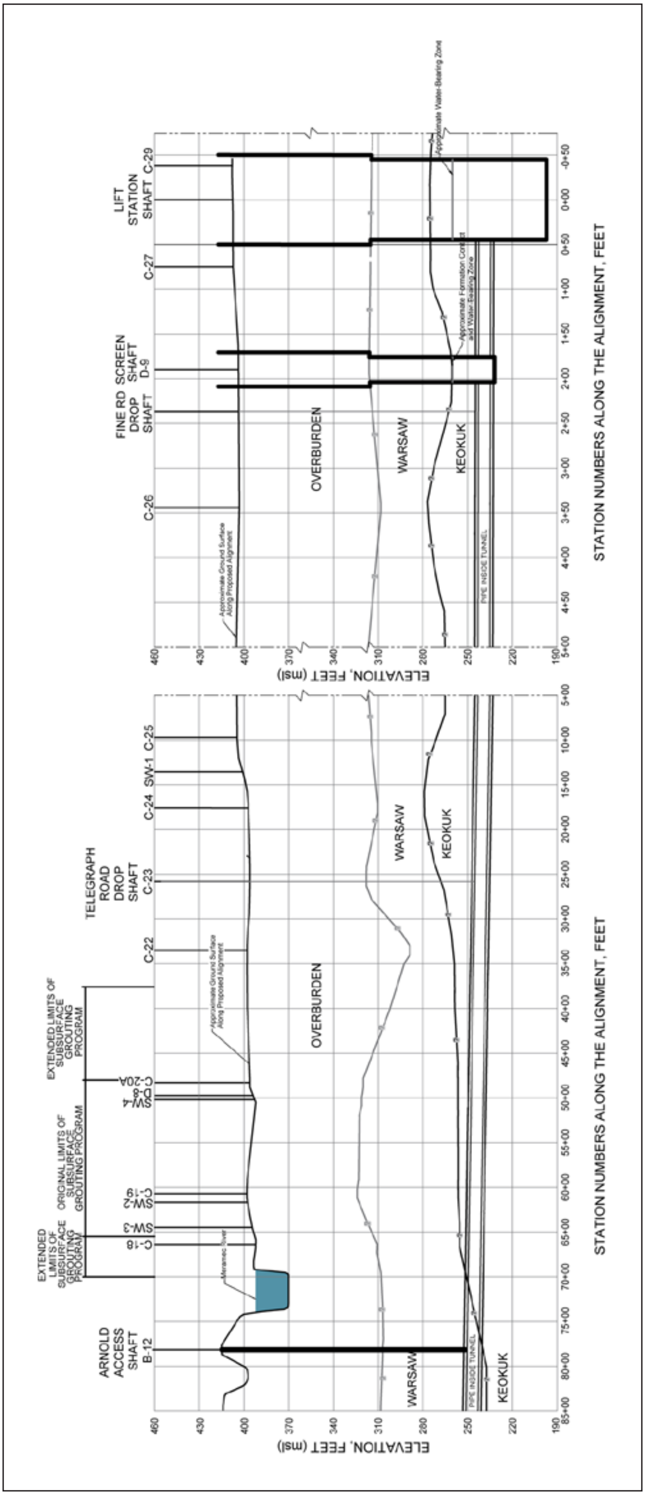

Figure 2. Generalized subsurface profile along tunnel alignment

groundwater gradient that resulted from dewatering for construction. These hazards could delay the project and increase the cost.

Following discussions with MSD, Shannon & Wilson performed additional explorations along a stretch of the tunnel alignment between the screen shaft and the access shaft in Jefferson County at Station 2+380 (Station 78+09). The purpose of the explorations was to more accurately define the location of the transitional contact between the Warsaw and Keokuk Formations, the potential permeability of the contact zone, and the potential presence of hydrogen sulfide and methane in the groundwater where the contact crossed the tunnel alignment.

The additional explorations consisted of drilling six borings along the tunnel alignment between Stations 0+407 and 2+344 (Stations 13+34.5 and 76+90). Borings were advanced within the bedrock using NX-sized wireline coring equipment. The total depth of the borings was determined based upon the depth of the tunnel invert and the depth of the contact between the formations. Borings were extended a minimum of 1.5 m (5 feet) below the tunnel invert, unless the formation contact was deeper, in which case the borings were extended to locate the contact.

Water losses during coring operations were noted in an effort to define the location of the contact zone. In two of the borings, drilling water circulation was completely lost upon encountering the contact zone. However, drilling water circulation was gradually lost during coring operations in the remaining borings and was not a useful indicator of the location of the contact zone in these instances. To define the location and permeability of the contact zone, packer testing was performed in the bedrock.

Packer testing was generally performed within and above the tunnel horizon. Packer testing performed during the explorations encountered the high permeability zone about 3.35 m (11 feet) above the crown of the tunnel at Station 0+407 and at or within 0.3 m (1 foot) of the tunnel invert at Stations 1+881 and 1+966 (Stations 61+70 and 64+50). The permeability of the potential water-bearing zone as measured by the packer tests at Stations 0+407 and 1+881 was estimated to be on the order of 1,000 to 5,000 lugeons or about 1×10^{-2} to 5×10^{-2} cm/sec. Packer testing of the zone at Station 1+966 had net heads of zero, indicating that the permeability of the zone exceeded the capacity of the testing equipment. At Station 1+530 (Station 50+20), the permeability of the potential water-bearing zone as measured by the packer tests was estimated to be about 20 to 30 lugeons or about 2×10^{-4} to 3×10^{-4} cm/sec. The contact between the formations was below the tunnel invert and less permeable at Stations 2+278 and 2+344 (Stations 74+74 and 76+90), which were drilled on the northern side of the Meramec River.

Lift Station

The BTJV was directed by Shannon & Wilson and MSD to drill a probe hole in the center of the lift station shaft to assess and determine if a similar high permeability zone was present. The lift station was larger and approximately 38 m (125 feet) from the screen shaft excavation. The probe hole was drilled by the Contractor at the top of rock elevation from within the shaft. Groundwater was encountered in the probe hole at a depth of about 16.5 m (54 feet) below the top of rock, elevation ± 95.7 (± 314 feet). The elevation of this water-bearing zone was about 79.2 m (260 feet) and coincided with the elevation of the water-bearing zone encountered within the screen shaft. Water flow from the hole was initially estimated at 57 to 76 L/m (15 to 20 gpm). A pressure gauge placed in the hole registered a pressure of 1.9 to 2.1 bars (28 to 30 psi), which corresponded to a groundwater elevation of about 115.8 m (380 feet). The water level of the Meramec River at that time corresponded to about elevation 115.8 m (380 feet), indicating a possible direct link between the water-bearing feature and the river and thus providing possibility of the feature being recharged by the river.

PROPOSED SOLUTION

The additional explorations demonstrated that a zone within the transitional contact between the Warsaw and Keokuk formations had the ability to transmit a large volume of flow, possibly in excess of the rates quantified in the GBR. Discussions were held between the construction management team, design team, MSD, and the Contractor regarding the results of the additional testing and the potential risks. During design, major inflows into the tunnel were thought to be associated with vertical joints in the bedrock that intersected the tunnel bore alignment, so the TBM was required to probe ahead and be prepared to grout similar features. Grouting the the near-horizontal contact zone from within the tunnel would be difficult as the contact zone was essentially horizontal and the TBM was not well suited to drill and grout horizontal seams. Alternatively, grouting from the ground surface would not interrupt the operation of the TBM, grout holes would not miss the contact zone, and grouting pressures would not be limited by the proximity of the TBM; however, the contact was 42.7 to 48.8 m (140 to 160 feet) below the ground surface. Based upon the results of the packer testing performed by Shannon & Wilson along the alignment and the probing in the lift shaft excavation, recommendations were made to MSD to perform a grouting program from the ground surface along the tunnel alignment, from Station 1+463 to 1+996 (Station 48+00 to 65+50), to mitigate the potential for high groundwater inflows exceeding the baseline volumes and accompanying high hydrogen sulfide and methane inflows, either of which could have at least temporarily shut down the tunneling operation.

GROUTING PROGRAM

Lift Shaft

A grouting program for the Lift Station Shaft excavation was proposed by the BTJV to mitigate the risk of a large groundwater inflow into the shaft from the water-bearing zone. Based on the contract documents, the Contractor was responsible for handling groundwater inflow of 7,570 L/m (2,000 gpm). MSD agreed to share in the cost of the grouting program with the BTJV to reduce the risk of groundwater inflow into the shaft exceeding the baseline flow volume.

The grouting program was designed by Soletanche Bachy and consisted of constructing a grout curtain around the shaft at the depth of the water-bearing zone. Grouting was performed from within the shaft and at the top of rock, elevation ± 95.7 m (± 314 feet). Grout holes were 6.35 cm (2½ inches) in diameter and inclined outwards at 13.5 to 15 degrees so that they intersected the water-bearing seam beyond the zone influenced by blasting. Holes were drilled along the perimeter of the shaft with primary grout holes spaced at 2.44 m (8 feet) on center and secondary grout holes drilled to split space the primary grout holes. Thirty-one primary grout holes were drilled with fifteen of the holes encountering water which flowed at rates of 3.8 to 189 L/m (1 to 50 gpm). Stage-up grouting methodology using three stages was used to grout all holes. Grout takes for the first stage ranged from 34.4 liters (1.2 cf) to a maximum planned volume of 1,000 liters (35.3 cf) in four holes. Grouting pressures typically ranged from 1 to 13.7 bars for the grout holes encountering water. Average grout takes for all of the holes were 293 liters (10.3 cf) for the first stage, 175 liters (6.2 cf) for the second stage, and 115 liters (4.1 cf) for the third stage of grouting. Grout takes were highest in the grout holes encountering water. For these holes, average grout takes were 492 liters (17.4 cf) for the first stage, 311 liters (11 cf) for the second stage, and 188 liters (6.6 cf) for the third stage.

Thirty-one secondary grout holes were drilled with only two of the holes encountering water which flowed at a rate of 3.8 L/m (1 gpm). Again stage-up grouting methodology was used. Average grout takes for the secondary grout holes were 63 liters

(2.2 cf) for the first stage, 68 liters (2.4 cf) for the second stage, and 132 liters (4.7 cf) for the third stage. One anomaly in the grouting was that one of the dry holes accepted 1,000 liters (35.3 cf) of grout during the first stage grouting.

Four tertiary grout holes were drilled in areas of large grout takes. These holes did not encounter any water and had average takes of 37 liters (1.3 cf) in first stage, 22 liters (0.8 cf) in the second stage, and 14 liters (0.5 cf) in the third stage. During the grouting program, about 26.8 cubic meters (945 cf) of grout was injected around the shaft into the water-bearing zone.

Tunnel Alignment

Designing and grouting ahead of the TBM from the surface was the responsibility of the BTJV with the concurrence of Shannon & Wilson. Hayward Baker was contracted by the BTJV to design and perform the grouting. Hayward Baker's design included construction of a grout curtain along the sides of the tunnel using two parallel grout lines offset from the tunnel centerline by about 2.44 m (8 feet). Grout holes in each line were spaced 4.9 m (16 feet) on center with the holes between lines staggered such that grout holes in the two lines were offset by 2.44 m (8 feet). Grout holes were drilled to a depth of 50.3 m (165 feet) with the grouted zone limited between depths of 41.2 and 50.3 m (135 and 165 feet).

The limits of the surface grouting program were initially established from Station 1+463 to 1+996 (Station 48+00 to 65+50) based on available information from packer testing performed by the Design Team, the additional packer testing performed by Shannon & Wilson, and a review of the geology in the GBR. The water-bearing zone was thought to either cross the tunnel alignment or be in close proximity to the tunnel crown between these stations. Grouting commenced at the upstream or north end, Station 1+951 to 1+981 (Station 64+00 to 65+00) while areas to the south were cleared and access roads constructed. Grouting was generally conducted in five passes with a 12.2 m (40-foot) spacing between first pass grout holes and the subsequent passes used to fill in between the first pass holes. Communication between holes generally dictated the drilling and grouting pattern as connection between grout holes up to 36.6 m (120 feet) apart was noted during drilling.

The limits of the grouting program were extended southward to Station 1+143 (Station 37+50) due to conditions encountered during tunneling at about Station 1+136 (Station 37+27). Mining operations were stopped on February 5, 2005, after encountering water with a strong hydrogen sulfide odor during installation of ground support. About 378 to 567 L/m (100 to 150 gpm) water inflow occurred from a hole drilled for rock bolt installation. The flow was from a zone about 1.2 to 1.5 m (4 to 5 feet) above the tunnel crown. Following completion of additional explorations and packer testing in the vicinity of Stations 1+228 and 1+396 (Stations 40+30 and 45+80), it was determined that the groundwater inflow was related to the high permeability, horizontal contact zone that was being grouted between Stations 1+463 to 1+996. This subsequent testing indicated that the high permeability zone was nearer the tunnel crown in this area than originally anticipated.

The limits of the grouting program were later extended northward to about Station 2+134 (Station 70+00) due to additional packer testing performed during the grouting operations. Grouting under the Meramec River was accomplished by angle holes from the river bank at Station 2+073 (Station 68+00) without any particular difficulties.

The initial grouting program crossed three properties with some wetland impacts identified. Rights-of-entry were required from landowners and permits were filed with the United States Army Corp of Engineers for impacts to the forested wetland. Two additional properties were impacted when the grouting program was extended southward to Station 1+143. Once rights-of-entry were acquired, tree clearing and

Figure 3. Tunnel sidewall at Station 1+311

construction of access roads and construction pads commenced. Grouting operations began in January 2005, which was later than expected because the grout staging area was flooded by the Meramec River, and were completed in April 2005.

High flow rates and low injection pressures were experienced in grouting the first pass holes with grout takes generally lower for subsequent passes. The upper limit for the first pass grout takes was initially set at about cubic meters 4.6 cubic meters (6 CY); however about 7.6 cubic meters (10 CY) were placed in several holes due to low injection pressures. A meeting was conducted between the BTJV, Hayward Baker, and Shannon & Wilson because of the larger-than-expected grout takes at the start of the grouting program. During the meeting, a cutoff volume of 2.3 cubic meters (3 CY) was agreed upon for primary/initial grout holes. The intent was not to completely pump grout out along the contact zone a large distance from the tunnel, but to create a grout curtain along the perimeter of the tunnel. The starting grout mix was also changed from a 1:1 ratio by volume to a thicker 0.7 to 1 mix.

Mining with the TBM restarted on March 14, 2005. The surface grouting was completed about 152 m (500 feet) in front of the TBM at the time of restart and stayed ahead of the TBM throughout the remainder of the grouting program. The tunnel was noticeably wetter upstream of Station 1+128 (Station 37+00). The highest inflows while tunneling through the grouted zone were from localized secondary features, such as solution cavities along the bedding. Localized groundwater inflows in the grouted area were generally estimated on the order of 3.8 to 19 L/m (1 to 5 gpm) with maximum inflows in the range of 37.8 to 189 L/m (10 to 50 gpm) in isolated areas. Cement grout was visible in places and present over time as a white leachate deposited on the tunnel walls by seepage water.

Packer testing was also performed in a limited number of grout holes prior to grouting to verify the presence and depth of the zone. These packer tests measured high permeability zones within and immediately above the tunnel throughout the length of the alignment that was grouted. The estimated permeability of the zones from these packer tests confirmed measurements from the explorations by Shannon & Wilson.

The grouting was successful in limiting the water inflow into the tunnel and the levels of hydrogen sulfide were not an issue. About 12,657 cubic meters (16,555 CY) of grout was injected into the contact through 384 grout holes. Eleven confirmation holes were drilled following completion of the designed grouting program to confirm the effectiveness of the program within an area prior to the TBM mining that area. A photograph of seepage conditions along a horizontal seam encountered within the tunnel at Station 1+311 (Station 43+00) is shown on Figure 3.

LESSONS LEARNED

Grouting was successful in managing the quantity of water inflow and the potential for harmful gas within the tunnel. During review of the design there was concern of water inflow on vertical seams as these seams are a factor near the top of rock and visible in outcrops of these formations. However, it became apparent that at depth, these vertical seams, where present, were tight. A zone within the transitional contact between the Warsaw and the Keokuk formations was the issue. Procedures used for water pressure testing during the exploration phase were not successful in highlighting this issue. If this issue had been identified earlier, it may have been practical to better define the grouting limits prior to construction and to pre-grout the contact well in advance of the TBM. The situation highlighted the importance of identifying potential conditions that may fall out of the boundary conditions contained in the GBR and responding with action to mitigate the potential for claims. Also, obtaining agreed terms for right-of-entry on the ground surface above the tunnel may be prudent when pre-grouting is not planned.

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