CONSTRUCTION OF A MIXED FACE REACH THROUGH GRANITIC ROCKS AND CONGLOMERATE

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ABSTRACT

The San Vicente Pipeline Tunnel Project involves the construction of an 8.5-foot-diameter water pipeline in an 11 mile tunnel in San Diego, California. The tunnel is located in extremely variable geologic conditions of strong granitic and volcanic rocks, weak sedimentary rocks, abrasive conglomerates, and mixed face conditions. One reach of the tunnel is a 5,200-foot mixed face reach that includes Friars Formation Conglomerate overlying granitic rock. Due to the variable ground conditions in this reach, the use of a TBM was deemed too risky and the contract documents required drill-and-blast and hand mining methods. Although it was not required, the contractor elected to construct this reach using NATM methods. This paper describes the geology of the 5,200-foot mixed-face reach, the design evaluation, and the construction challenges faced on this project.

INTRODUCTION

The San Vicente Pipeline (SVP) is an 11-mile, 102-inch-ID raw water transmission pipeline that is part of the San Diego County Water Authority's Emergency Storage Project (ESP). The ESP is intended to ensure that water is available to the San Diego region in the event that an earthquake or severe drought interrupts the delivery of imported water. The ESP involves the construction of a system of reservoirs, pipelines, flow control structures, and pumping stations. As part of this system, the SVP will help supply water in an emergency. It will also improve the operational efficiency of the Water Authority's overall system. The SVP project links the San Vicente Reservoir (SVR), located on the east side of San Diego County, and the Water Authority's Second Aqueduct, located west of Interstate 15 (see Figure 1).

The SVP project includes the construction of: a tunnel that is approximately 57,230 feet long, two vertical riser access structures (one at the west end of the tunnel and the other near the midpoint of the tunnel), an isolation vault and drive-in vault access structure at the east end of the tunnel.

The tunnel is located in extremely variable geologic conditions of strong granitic and volcanic rocks, weak sedimentary rocks, abrasive conglomerates, and mixed face conditions. One reach of the tunnel is a 5,200-foot mixed face reach that includes Friars Formation Conglomerate overlying granitic rock.

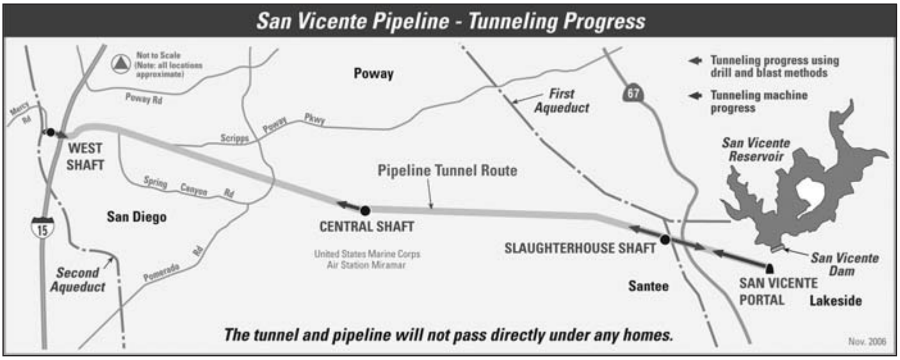

Figure 1. Project location map

This paper discusses some of the important design considerations for the mixed-face reach, designated as Reach R-5, and describes the ground conditions encountered and the construction methods used in the variable conditions. The project is currently under construction, with an estimated completion date of December 2008.

PROJECT AREA GEOLOGY

The project is located in San Diego County in the Peninsular Ranges geomorphic province. Along the western side of the Peninsular Ranges, sedimentary rocks overlie the basement rocks. The sedimentary rocks are generally flat-lying or dip gently to the southwest. They include sandstone, siltstone, claystone, and conglomerate. The basement rocks include Jurassic metamorphic rocks and Cretaceous igneous rocks of the Southern California batholith.

REACH R-5 GEOLOGY

The tunnel alignment within Reach R-5 extends through both the Friars Formation Conglomerate and granitic rocks of the Southern California Batholith. The actual contact of the conglomerate with the granitic rocks in this reach is irregular and undulating (see Figure 2). Therefore, this reach was anticipated to encounter alternating zones of granitic rock and conglomerate in various proportions, including a full face of either rock type or mixed faced conditions at any location within the reach. In this reach, the cover over the tunnel invert ranges from 55 to 240 feet. This reach of the tunnel passes beneath Slaughterhouse Creek, and the entire reach is below the water table. Groundwater levels ranged from about 55 to 90 feet above the tunnel invert.

Friars Formation Conglomerate

The Friars Formation is part of the Eocene La Jolla Group, and conformably underlies the Stadium Conglomerate. It is horizontally bedded to gently dipping (less than about 20 degrees). The Friars Conglomerate consists of medium gray to grayish green, moderately indurated, matrix-supported gravel/cobble conglomerate with occasional boulders. Figure 3 is a photograph of an outcrop that illustrates the high cobble content of this formation. The matrix consists of silty to clayey sand, and the unit contains localized interbeds of sandstone and siltstone. Although it is generally uncemented, it is

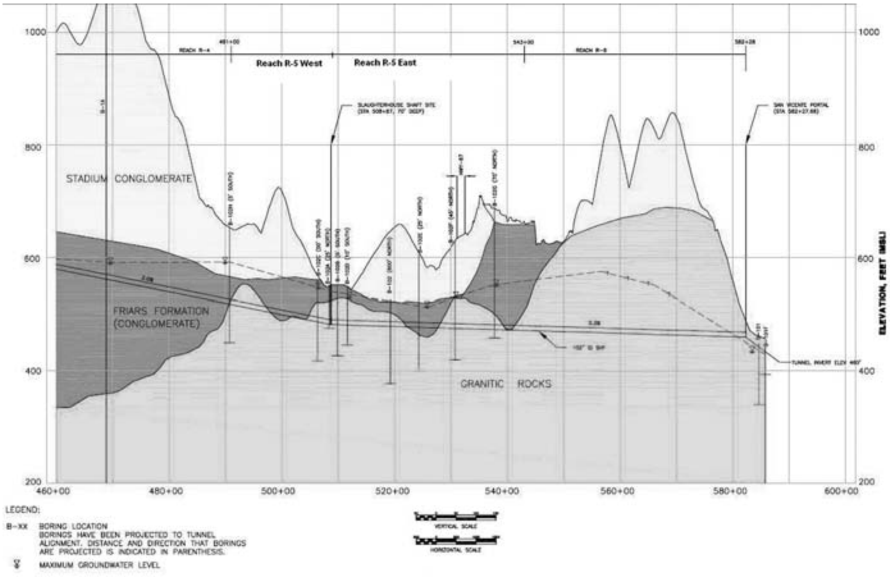

Figure 2. Reach R-5 geologic profile

Figure 3. Conglomerate outcrop

weakly to strongly cemented in some places. Induration of this unit is due more to the tightly compacted matrix than to the degree of cementation.

The percentage of clasts (typically gravel size and larger) in the formation varies and the clasts are typically surrounded by the matrix (i.e., matrix-supported). However, there are intervals within the unit in which less matrix is present and the clasts are in contact with each other. The clasts in the formation typically consist of extremely strong (i.e., unconfined compressive strengths up to 60,000 psi), metamorphosed rhyolite, dacite, metasandstone, and quartzite. Figure 4 shows the grain size distribution of the conglomerate and its matrix. The average clast size is typically in the cobble

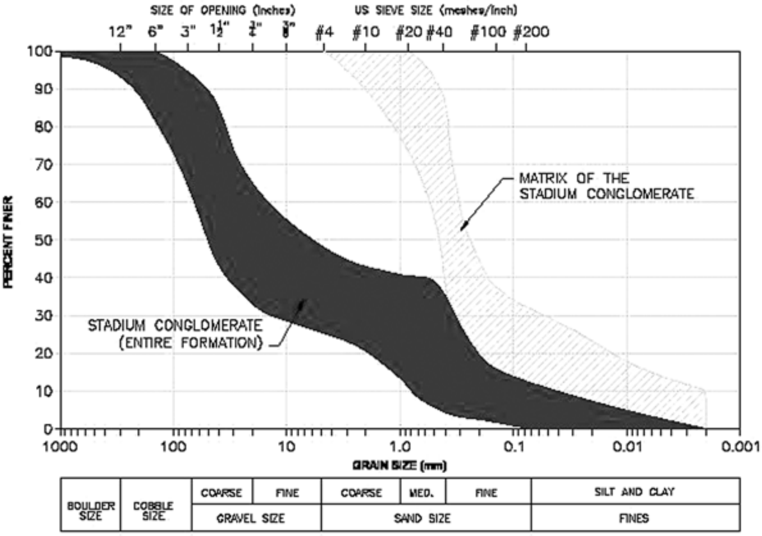

Figure 4. Grain size distribution of the conglomerate and its matrix

range (i.e., 3 to 12 in.). However, boulder-sized clasts of up to 6 feet were encountered in the borings.

The conglomerate exhibits a wide range of strength characteristics depending on the clast compositions, degree of matrix cementation, and grain size distribution. Local quarry operators report that these rocks are some of the most abrasive in the United States.

Cretaceous Granitic Rocks

Cretaceous Granitic Rocks of the Southern California batholith outcrop near the eastern and western ends of the SVP tunnel alignment. They are overlain unconformably by the sedimentary rock units described above. The granitic rocks in the vicinity of Reach R-5 consist of a group of older, variably metamorphosed granitic rocks that possess a metamorphic texture and alteration believed to be related to the emplacement of the large bodies of Cretaceous Granitic Rocks to the east and west. Weak to strong gneissic textures have been observed in these rocks and locally these rocks are schistose. The rock types in this older body include granodiorite, quartz diorite, diorite, tonalite, gneiss, gabbro, schist, and gneissic granodiorite. In addition to being locally altered, these rocks are typically more deeply weathered than the younger granitic rocks to the east and west. As a result, these rocks tend to be weaker.

Unconfined compressive strength (UCS) tests of slightly weathered to fresh granitic rock in this reach exhibited strength values ranging from 5,400 to 28,500 psi with an average value of 14,000 psi. UCS tests of highly to moderately weathered granitic rock in this reach exhibited strength values ranging from about 1,500 to 8,500 psi with an average value of 4,500 psi. Fifty percent of the granitic rock in this reach is anticipated to be fresh to slightly weathered and 50 percent to be highly to moderately weathered.

Discontinuities observed in the granitic rock core within this reach consisted primarily of joints that are smooth to slightly rough and tight to moderately wide. The

Table 1. Summary of RMR, Q-Value, and RQD for reach R-5 granitic rock

Classification System	Rock Quality Description (percent of cored footage in Reach R-5)				
	Very Good	Good	Fair	Poor	Very Poor
RMR	7%	33%	53%	7%	0%
Q-System	13%	47%	20%	0%	20%
RQD	26%	27%	7%	13%	27%

Table 2 . RMR, Q-Value, and RQD correlation to Terzaghi's descriptions

Rock Quality Description	RMR Range	Q-Value Range	RQD Range	Approximate Correlation to Terzaghi's Description
Very Good Rock	>80	>100	90–100	Massive or hard and intact
Good Rock	60–80	10–100	75–90	Massive, moderately jointed
Fair Rock	40–60	1–10	50–75	Moderately blocky and seamy
Poor Rock	20–40	0.1–1	25–50	Very blocky and seamy
Very Poor Rock	<20	<0.1	0–25	Crushed

joints typically strike to the northeast and northwest and have steep to vertical dips to the southeast, southwest, and northwest.

DESIGN EVALUATIONS

Design evaluations for Reach R-5 focused on: determining the properties of the granitic rocks and conglomerate formation; determining the location and nature of the contact between the conglomerate and the granite; establishing the proportions of the reach that would encounter conglomerate, granite, or mixed face conditions; establishing the groundwater conditions and potential for groundwater inflows into the tunnel; and identifying appropriate tunnel excavation and support methods. The geotechnical investigation program performed within this reach included nine soil test borings ranging in depth from 70 to 210 feet, one test pit for gradation sampling, and nine seismic refraction lines.

Evaluation of Granitic Rocks

The granitic rocks in this reach were characterized using the Rock Mass Rating (RMR) System developed by Bieniawski (1984); the Q-System developed by Barton, Lien, and Lunde (1974); and the Rock Quality Designation (RQD) developed by Deere et al. (1970). A summary of the results of these analyses is shown in Table 1.

The RMR, Q, and RQD values were divided into several categories as suggested by Bieniawski (1984). Table 2 shows the approximate correlation with rock condition terms developed by Terzaghi (1946) for each category based on correlations developed by Barton (1974) and Deere et al. (1970).

Based on these analyses, it was estimated that: 25 percent of the granitic rock in Reach R-5 would be in rock that is massive, moderately jointed; 45 percent would be in moderately blocky and seamy rock; and 30 percent would be in very blocky and seamy rock.

Evaluation of Friars Formation Conglomerate

The parameters used to characterize the conglomerate were: the density of the formation, the gradation of the clasts, the amount and degree of cementation of the matrix, the strength of the clasts, and the groundwater conditions. The information obtained from the borings in Reach R-5 indicated that the matrix is typically 97 to 100 percent uncemented and 0 to 1 percent strongly cemented. Stand up time tests performed for the nearby San Diego State (SDSU) Tunnel (Boone et al., 2001), excavated in the Stadium Conglomerate were analyzed. The Stadium Conglomerate is a similar formation to the Friars Formation Conglomerate in Reach R-5. The results of the SDSU test pits indicated no signs of collapse for 96 hours in a 2-foot-deep test pit above the groundwater level. A similar test pit in saturated conditions collapsed after about 45 hours. Flooding of the shallow test pits above the groundwater level resulted in collapse after about 8 to 16 hours. This information was supplemented by observations of local quarry exposures that indicated that the Friars Formation Conglomerate is generally a stable formation. Excavated slopes 150 to 200 feet high with an inclination of 0.2:1 (horizontal to vertical) above the groundwater level have been stable for decades with virtually no spalling or raveling of the slopes. These observations generally indicated that stand up time would be good above the groundwater level and less favorable below the groundwater level.

For the section of Reach R-5 encountering conglomerate, firm to slow raveling ground was anticipated above the groundwater table and slow to fast raveling ground was anticipated below the groundwater table. Where the conglomerate matrix is very weak, cobble and boulder clasts are not firmly held in place by the matrix, and it was expected that the clasts would fall from the tunnel roof, sidewalls, and face if not supported.

Geologic Contact

The geologic investigation indicated that the surface of the granitic rock below the conglomerate is very irregular and the tunnel in this reach would encounter granitic rocks and conglomerate in a complex arrangement, including mixed face conditions. Based on the available data, a geologic profile was developed for Reach R-5 as shown in Figure 2.

Near the contact, ground conditions were expected to be highly variable with the granitic rock ranging from slightly to highly weathered. Boulders were expected to be present at the contact. Based on the boulders encountered in the borings, it was estimated that 2.5 percent of the conglomerate (by volume) would consist of boulders and that 50 large boulders (between 2 and 8 feet in maximum dimension) would be encountered in this reach. The large boulders were expected to be encountered mainly along the irregular contact.

The entire reach is below the groundwater table and the high core loss in the borings within this reach indicated the potential for unstable ground conditions and large groundwater inflows, especially close to the contact between the conglomerate and granitic rocks.

Groundwater Inflow Analyses

For the general tunnel alignment, groundwater inflow analyses were performed using the method outlined by Heuer (1995). This method used permeability data from borehole packer tests to develop permeability distributions that were used along with groundwater elevation to estimate steady state groundwater inflows and maximum heading inflows. This method is applicable for distributed sources of water inflow due to rock mass features such as jointed and bedding planes. The method also takes into

Table 3. Summary of results of groundwater inflow analyses

Heuer Method		Probabilistic Method	
Maximum Sustained (Steady-State) Inflow	**Instantaneous (Peak) Heading Inflow**	**Maximum Sustained (Steady-State) Inflow**	**Instantaneous (Peak) Heading Inflow**
104 GPM	43 GPM	300 GPM	225 GPM

account groundwater head above the tunnel and recharge conditions. However, in Reach R-5 it was anticipated that the majority of the inflows would be associated with the contact. Therefore, a probabilistic approach was also used to analyze the potential groundwater inflows in Reach R-5. The probabilistic method accounts for high groundwater inflows that could occur through high permeability features which are more likely to be present at the contact. This approach utilized steady-state and transient equations developed by Goodman (1965). The Goodman equations provide a more conservative estimate of inflow for fracture flow in granitic rock as compared to the Heuer (1995) method. The risk analysis program @Risk (Version 4.5) was used to perform the Monte-Carlo simulation for the probabilistic approach. The predicted groundwater inflows for both the Heuer (1995) and probabilistic methods are shown in Table 3.

Design Stage Recommendations

Hydraulic, operational, and general tunnel alignment and profile constraints (i.e., right of way, shaft locations, etc.) resulted in a relatively narrow alignment/profile window for Reach R-5. Therefore, it was not possible to locate this tunnel reach entirely within either the conglomerate or the granite and some amount of mixed face ground was unavoidable. The risk analyses performed for the project established that using a TBM within this reach would involve a relatively high risk for significant ground related delays. The granitic rocks were judged to be locally too strong and abrasive to be mined efficiently with a roadheader. Further, given that a shaft site was located within this reach and recognizing that it would be possible to commence mining out of this shaft with short lead time equipment, the decision was made to specify that this reach be mined using drill and blast or hand mining methods. This approach was judged to entail significantly less risk due to the adaptability to variable ground conditions. Steel sets were judged to be the most appropriate initial ground support given the variable ground conditions. Presupport measures were anticipated to be required in the mixed face conditions to address low stand-up time and raveling conditions. Presupport was expected to consist of forepoling, crown bars, or combinations thereof. In addition, a probe/drain hole was required to be drilled and maintained ahead of the tunnel face throughout this reach to check for potential groundwater inflows, investigate geologic conditions ahead of the tunnel, and to drain the groundwater ahead of the tunnel excavation. This approach was anticipated to be the most effective and economical way to construct this reach of tunnel.

CONTRACTOR'S EVALUATION OF THE REACH

The contractor, Traylor/Shea JV, recognized that a flexible and adaptive excavation and support approach was needed to cope with the wide variety of ground conditions that were anticipated along Reach R-5. The GBR advised that mixed conglomerate and rock face conditions below the water table could be present anywhere along the reach and that "Conditions will vary widely over short distances and could change rapidly with little warning." The Traylor Shea JV decided that the "toolbox" of ground support measures provided

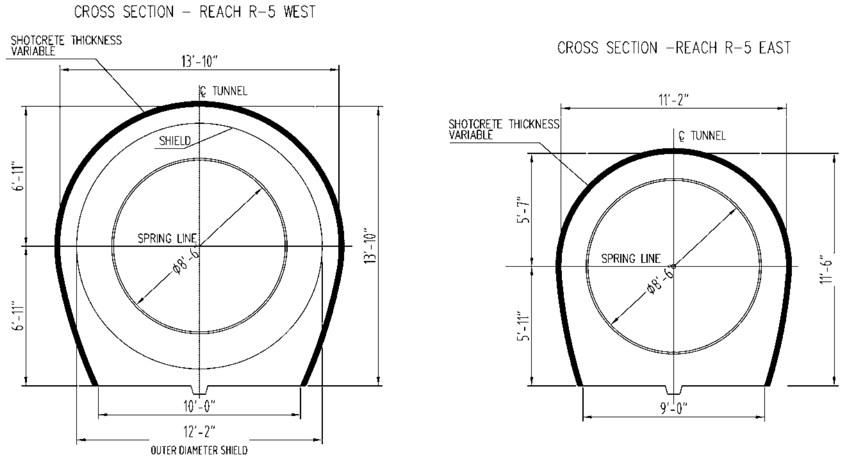

Figure 5. Reach R-5 East and West tunnel cross sections

by the New Austrian Tunneling Method (NATM) adequately matched the requirements of the reach. The Joint Venture decided to employ the services of Beton-und Monierbau (BeMo) of Innsbruck, Austria to aid in the development of mining methods, selection of equipment, and design of initial tunnel support.

Design

Reach R-5 was divided into two drives; one drive trended east from the Slaughterhouse Shaft and one drive trended west from the Slaughterhouse Shaft (see Figure 2). The east drive, designated as Reach R-5 East, was 3,413 feet in length and the west drive, designated as Reach R-5 West, was 1,787 feet in length. Once completed, the Slaughterhouse Shaft and Reach R-5 West will be used as the primary means of access to launch a digger shield, which will be used to mine another reach of the SVP. Because the 12-foot, 2-inch diameter digger shield will need to be walked through Reach R-5 West to begin mining, this heading was planned to be larger in size than the Reach R-5 East heading, which was sized to accommodate the 8-foot, 6-inch diameter steel pipe and annular space backfill. The Reach R-5 West heading was designed with a nominal height and width dimension of 13 feet, 10 inches. The East heading was designed with a nominal height and width dimension of 11 feet, 2 inches. The tunnel dimensions varied slightly depending on the support classification. A general layout of the tunnel cross sections can be seen in Figure 5.

A ground support design concept was developed for each of the ground conditions that were anticipated during the tunneling, with the main support categories including structural support design for fresh granite, weathered granite, and conglomerate. Each main category was further broken into three sub-categories to address the particularities of the ground behavior within each category. The final design drawings detailed a total of nine support classes, summarized in Table 4.

Support Class 1—Granitic Rocks. Generally, Support Class 1 encompasses the range of ground conditions from fresh granite that is slightly fractured to slightly weathered granite that is moderately fractured. Ground support for this class includes spot installation of rock bolts and a flashcoat of shotcrete or chain link mesh as required as a surface treatment. It was anticipated that material in this class would be excavated using drill-and-blast methods with round lengths of 6 to 10 feet.

Table 4. Support class description

Support Class	Rock Mass Description	Support	Presupport
1.1	Fresh granite, massive to slightly fractured	Spot bolting	None
1.2	Fresh to slightly weathered granite, moderately jointed in the crown	Spot bolting, flashcoat of shotcrete in the crown	None
1.3	Fresh to slightly weathered granite, moderately jointed in the crown and bench	Spot bolting, flashcoat of shotcrete in the crown and bench	None
2.1	Slightly weathered granite, blocky and seamy	Systematic bolting, 2" of shotcrete in the crown and bench	None
2.2	Moderately weathered granite, very blocky and seamy	Systematic bolting, 5" of shotcrete in the crown and bench	None
2.3	Highly weathered granite, very blocky and seamy, disintegrated	Systematic bolting, 3" of shotcrete in the crown and bench, lattice girders	Spiles optional
3.1	Strongly to moderately cemented conglomerate	4" of shotcrete in the crown and bench, lattice girders	Spiles optional
3.2	Moderately to weakly cemented conglomerate	4" of shotcrete in the crown and bench, lattice girders	Pipe umbrella, dewatering
3.3	Uncemented conglomerate	4" of shotcrete in the crown, bench, and invert, lattice girders	Pipe umbrella, dewatering, spiles

Support Class 2—Weathered Granite. Generally, Support Class 2 encompasses the range of ground conditions from slightly weathered granite that is blocky and seamy to highly weathered granite that is disintegrated. Ground support for this class ranges from systematic rock bolting with a flashcoat of shotcrete in the crown and bench to systematic bolting with a structural application of shotcrete in the crown and bench. It was anticipated that material in this class would be excavated using drill-and-blast methods with short round lengths of 4 to 6 ft to limit overbreak.

Support Class 3—Conglomerate. Generally, Support Class 3 encompasses the range of ground conditions from strongly cemented conglomerate to uncemented conglomerate, sand lenses, and mixed granitic and conglomerate face conditions. Ground support for this class includes shotcrete and lattice girder structural support with presupport measures including drain holes, spiling, self-drilling tube spiles, and pipe umbrellas as required. It was anticipated that material in this class would be excavated using an Inter Techmo Commerce (ITC) tunnel excavator.

The NATM approach required the presence of personnel on site who have experience with and knowledge of this method. The Joint Venture employed Albin Reinhart, a NATM engineer from BeMo who, in conjunction with the Joint Venture's engineers and superintendent, decided what support type was appropriate. He also helped to plan mining sequences and worked to increase mining efficiency and reduce cycle times. A technician from BeMo, Manfred Baumgartner, was on site as well. Mr. Baumgartner is experienced in NATM mining methods and equipment operation. He was on site to assist in training the local miners in such things as application of high performance shotcrete, accurate drilling, installation of pipe umbrellas, and operation of the ITC tunnel excavator.

Equipment

Personnel from the Joint Venture took several trips to Central Europe to investigate NATM tunneling equipment and methods. Particular site tours were planned to

Figure 6. ITC 112 with E3S boom

allow personnel to witness pipe umbrella drilling and operation of an ITC tunnel excavator. Neither pipe umbrellas nor ITC tunnel excavators are in common use in the United States at this time, but the Joint Venture thought that these tools were well suited to the potentially unstable conglomerate and mixed face conditions below the water table. Based on the observations made during these trips, the Joint Venture decided to use an ITC excavator to dig the conglomerate sections of Reach R-5. They also prepared to procure the equipment necessary to install pipe umbrellas in case ground conditions warranted their use. An ITC is shown in Figure 6.

A used ITC 112 was purchased and refurbished at the Traylor Bros. Inc. shop in Evansville, Ind. ITC supplied a new E3S boom, which had the capability of tilting side-to-side in order to efficiently dig the horseshoe tunnel shape. Additionally, the travel system was upgraded so the ITC could tram quickly from one heading to another. Other equipment purchased to excavate and support the tunnel included: an Atlas Copco Rocket Boomer 282 drill jumbo equipped with Atlas Copco COP1838ME hydraulic drills to drill blast holes as well as drill probe holes, drain holes, and install pipe umbrellas; two Wagner ST3.5 LHDs and one Atlas Copco ST3.5 LHD to load and haul muck from the drill-and-blast sections; and two Dux DT12 8 cy tunnel trucks to haul muck in the highly weathered granite, conglomerate, and mixed face sections where the ITC 112 tunnel excavator was expected to be used. The LHDs loaded excavated material into a heavy-duty muck box in the shaft bottom. The muck box was hoisted by a Liebherr 883 crane. A robotic shotcrete arm was purchased from Shotcrete Technologies and mounted on a New Holland LS185 skid steer loader. The skid steer towed a trailer that carried a Schwing B310 shotcrete pump as well as the accelerator dosing system. A 5 cy Normet Transmixer was used to transport shotcrete to the heading.

CONSTRUCTION CONDITIONS

Shaft Excavation

Shaft sinking operations began on October 10, 2005. Since the shaft was expected to progress through three anticipated ground types (conglomerate, weathered granite, and fresh granite) the Joint Venture anticipated that shaft excavation would be a good indication of how the ground would behave during tunneling, and would indicate the nature of the contact between the conglomerate and the granite.

The Slaughterhouse Shaft is 36 feet in diameter and 70 feet deep. Through the alluvium, conglomerate, and weathered granite, shaft support consisted of W6x 20 steel ribs on 5 foot centers with 2 inches of steel-fiber-reinforced shotcrete as lagging. Through the moderately weathered to fresh granite, support consisted of 6-foot-long rockbolts on a 5 foot pattern with 2 inches of plain shotcrete as a surface treatment.

The top 5 feet of the shaft was excavated through alluvium. The conglomerate, which extended to a depth of 35 feet, was excavated quite easily using a CAT 312 excavator. The 5-foot-high lifts stood vertically with no sign of raveling. A lift was typically not left open for longer than four hours. However, on isolated occasions, a lift was left open for roughly 12 hours with no sign of raveling. The groundwater at the time of shaft sinking was 10 feet below the ground surface. Excavation continued through the conglomerate below the water table without incident. Any troublesome groundwater flows were channeled by hoses or panning so as not to affect the shotcrete application.

However, several ground conditions were encountered that could be problematic if encountered during tunneling. Several weakly to moderately cemented sand lenses were encountered that presented a challenge to get shotcrete to adhere when below the water table. This was a minor problem on the shaft walls, but could be a much larger problem if encountered in the crown of the tunnel under much higher water heads. Also, a cluster of large boulders 2 to 8 feet in size were encountered close to the interface with the underlying weathered granite. In the shaft excavation, these boulders could be removed by the excavator, but in the tunnel they would likely need to be blasted. The weathered granite, extending to a depth of 60 feet, could be dug with an excavator, though with difficulty, so a hoe-ram was used until this method was no longer economical. The weathered granite stood with no problem, but it was very blocky, seamy, and friable and exhibited a higher permeability than the conglomerate. The remainder of the shaft through moderately to slightly weathered granite was excavated by drill-and-blast methods. Water inflow through the fresh granite appeared less than through the weathered granite above, and after several weeks most of the water inflow through the fresh granite ceased, while water continued to flow through the weathered granite. The total water inflow upon completion of the shaft excavation was on the order of 50 gpm.

The shaft sinking operations indicated that the transition zones from fresh granite to weathered granite to conglomerate would be marked by increasing water flows and increasingly friable and blocky material. Clusters of 2- to 8-foot boulders could be expected at the interface between the weathered granite and conglomerate, and fast raveling sand lenses could be encountered in the conglomerate. The conglomerate appeared to have good stand up time, though the water head in the shaft was less than would likely be encountered in the tunnel.

Tunnel Excavation

Tunneling began on December 16, 2005 with mining crews working two 10-hour shifts per day, six days per week. It was planned that there would be one mining crew and one fleet of equipment per shift, rather than a crew at each heading. The crew and equipment swung between the east heading and west heading.

Reach R-5 East. Reach R-5 East was on the critical path of the job, and was therefore the focus of the mining effort. Drill-and-blast operations began with an 8-foot round length in the granite. The first 100 feet of the east and west headings were mined using an enlarged section to provide space for parking and passing equipment underground. In the initial 46 feet of excavation, the granite was blocky and seamy and blasting operations led to loosening and separation of blocks in the crown. Because not all of the shotcrete equipment was on site, steel ribs and timber blocking were used

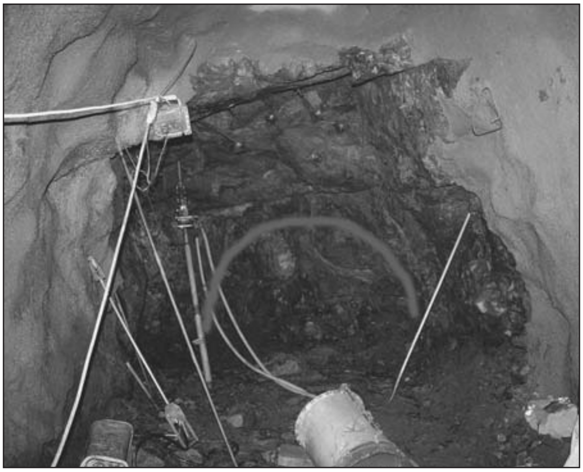

Figure 7. Excessive overbreak near rock-conglomerate interface

to support this section of tunnel. Ground conditions improved to the point where the ribs were no longer necessary and 6 foot Swellex rock dowels were adequate to support the rock. After 100 feet, the tunnel was necked down. It was taken from 16 feet, 6 inches wide by 14 feet tall to 10 feet, 6 inches wide by 11 feet, 2 inches tall. Drilling and blasting continued with 8-foot round lengths and rockbolt support for another 605 feet. The ground varied from slightly weathered granite with some spalling and loosening of blocks in the crown to fresh granite where no spalling was exhibited. When Reach R-5 East had advanced 605 feet, groundwater inflows began to increase, with several small flows from the face and sidewall. Up to this point, groundwater inflow had been limited to dripping in the crown and sidewall that lessened to nothing a week or so after the heading had advanced. A large block that fell out of the sidewall during blasting operations at this location is shown on Figure 7.

As the observed ground conditions became more adverse, the support classification was changed from 1.1 to 2.2 and the round length was shortened to 5 feet. Mining continued without incident for another 44 feet, at which point the first conglomerate was seen in the heading. The conglomerate was exposed in an approximately one foot square patch of the face near the crown. Though it appeared stable, there was a steady flow of water (estimated to be 15 gpm) dripping and streaming from the crown. The granite in the vicinity was weathered, but not disintegrated. Probe holes drilled in the heading did not show a significant weakness in the ground conditions, so it was decided to drill and shoot another round. The support classification was changed to 3.1 and the round length further shortened to 4 feet. Several more rounds were shot, fully exposing the conglomerate in the crown. There were no large boulders present and the ground exhibited good stand up time, with the heading once being left open for six hours with no raveling. The heading advanced 23 feet more with conglomerate in the crown until the face once again returned to rock. It was likely that the transition between rock and conglomerate was not far away, so mining continued with short rounds, though the support class was changed to 2.2.Conglomerate in the heading returned after approximately 46 feet of mining and the support class was again increased to 3.1 and the round length reduced to 4 feet. It was decided to continue blasting operations rather than to try to dig the conglomerate with the ITC tunnel excavator because, at the time, the conglomerate was difficult to dig and a majority of the

Figure 8. Mixed face condition

face consisted of granite. The proportion of conglomerate in the face continued to increase until on any given round it accounted for 45% to 55% of the face area, with the remaining face area being moderately weathered to slightly weathered granite. Figure 8 shows the mixed face condition, depicting three distinct layers of ground: weathered granite on the bottom, boulder-sized conglomerate in the middle, and cobble-sized conglomerate near the crown.

This roughly half-and-half mixed face condition continued for approximately 725 feet, after which the granite interface dipped down and conglomerate accounted for the full face area. An attempt was made to use the ITC 112 excavator to mine the conglomerate, but it was unable to do much more than scratch the face, and so blasting operations were continued. The inability of the excavator to dig the conglomerate was attributed to the density and cementation of the matrix and the tightly packed nature of the clasts within the matrix. After it became apparent that the conglomerate was relatively stable, the round length was increased to 5 feet with favorable results. Overbreak was limited and the conglomerate rarely raveled. One notable exception was a weakly cemented sand lens encountered in the crown for a length of approximately 20 feet. The sand was slow raveling and continuously dripped water, which resulted in difficulties related to shotcrete adhesion. This problem was remedied by drilling and installing 10-foot-long rebar spiles in advance of the excavation.

To date, excavation has continued, using drill-and-blast methods through the granite, mixed face, and conglomerate areas. The nested boulders encountered along the transition zone between granite and conglomerate during shaft excavation have only been observed in the tunnel in localized areas. The boulders were not as large as those encountered during the shaft excavation and there was enough supporting matrix to hold the boulders in place during blasting.

Groundwater inflow proved to be a good indication of when highly weathered granite and conglomerate was ahead of the face and the transition zones yielded most of the water inflows into this reach. Probe holes were required to be advanced a minimum of 20 feet ahead of the face at all times. These probe holes also acted as drain holes. Typically, groundwater inflows through the probe holes were on the order of 0 to 5 gpm, with probe holes in the transition zones producing a flow on the order of 10 gpm. Generally, the flows diminished to a trickle over the course of several days. Based on piezometer readings along the tunnel alignment, groundwater levels have been drawn down by the tunnel excavation ahead of the tunnel face and this drawdown has tended to improve tunnel stability. Drawdown was typically on the order of 25 to

50 feet and as high as 60 feet in the vicinity of the shaft. At the eastern end of the reach, drawdown was less, possibly as a result of this section of the tunnel being entirely within the conglomerate, which exhibited lower permeability values than the granitic rock.

To date, neither the ITC 112 excavator and tunnel trucks nor the pipe umbrellas have been used. The length of tunnel where full face conglomerate conditions have been present has been relatively short, and in the areas were the conglomerate was full face, it was too strong to be excavated with the ITC 112. Generally, the ground has had stand up time sufficient to allow installation of the initial tunnel support without the need for presupport. Pipe umbrellas have not been installed to date, and drilled spiling was necessary only for a short distance.

Excavation rates have averaged 7.6 feet per day, with the best daily advance being 24 feet. At the time of writing, Reach R-5 East was 92% complete.

Reach R-5 West. Reach R-5 West was not on the critical path of the job, since it was half the length of Reach R-5 East. It was planned that this heading would be mined when equipment and personnel were not being used in the East heading, such as during mucking operations.

The initial 100-foot-long enlarged section was mined with 8-foot rounds and rock bolt support. The tunnel was then necked down to a section 13 feet, 10 inches wide by 13 feet, 10 inches tall. Soon after necking down, the rock became moderately to highly weathered, and blasting operations led to significant loosening and separation of blocks in the crown and sidewall. The round length was shortened to 6 feet and the support classification changed to 2.1, which included 3 inches of shotcrete and 6 foot Swellex rock bolts on a 5 foot pattern. Mining continued in this manner, though it was anticipated that conglomerate could be encountered at any time. However, the buried conglomerate valley that was indicated in the geological profile was not encountered and after approximately 640 feet of mining, the granitic rock became much stronger. The support classification was reduced to 1.3 and the round length increased to 10 feet. Mining has continued to the present time in slightly weathered to fresh granite with little to no groundwater inflow. At the time of this writing, 1,527 feet of the 1,787-foot design length had been mined (86% complete).

Excavation rates have averaged 5.8 feet per day with the best daily advance being 22 feet.

CONCLUSIONS

Although the investigation program performed during the design phase provided a good indication of the nature of the conglomerate and granite that would be encountered in Reach R-5, accurately identifying the exact location and nature of the contact proved difficult. This can be attributed to the distance between the boreholes, the inability to use geophysics along the entire length of the reach, and the variability of the contact. The nature of the contact proved to be more favorable than expected for several reasons. First, the groundwater inflow was less than anticipated with heading inflows in the mixed face condition typically only about 2 to 3 gpm at the face. The standup time of the conglomerate in the mixed face zone was also better than anticipated. This was likely due to the very dense nature of the matrix and the drawdown of the groundwater ahead of the tunnel through the use of probe/drain holes. Finally, the very large boulders (6 to 8 feet in maximum dimension) encountered at the contact within the shaft were not encountered at the contact in the tunnel. Approximately 150 boulders larger than 2 feet were encountered in the reach, but most of these boulders were between 2 and 3 feet in maximum dimension. These boulders were typically located at the contact but did not impact the construction since the reach was constructed entirely by drill-and-blast methods.

The decision to require excavation of Reach R-5 by drill-and-blast or hand mining methods proved to be the correct decision given the highly variable ground conditions and the long section of the reach that encountered mixed face conditions. The decision by the contractor to use a NATM approach also proved to be a good decision given the adaptability of this approach to variable ground conditions. This approach allowed steady progress to be made through the mixed face ground and rapid progress in the granitic rock sections of tunnel. The use of the ITC 112 tunnel excavator was not effective in the conglomerate. The bucket of the excavator could not excavate the conglomerate even in the uncemented to weakly cemented conglomerate because the bucket was too wide to impact only the matrix without encountering the very strong clasts. The clasts in this formation are very tightly packed and require a pick type excavation tool to excavate the matrix around the clasts.

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