Chapter 86

RIVERSIDE BADLANDS TUNNEL, INLAND FEEDER PROJECT: THE CHALLENGES BETWEEN CONCEPT AND COMPLETION

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ABSTRACT

The Riverside Badlands Tunnel is a 13 km (8 mile) long segment of the Inland Feeder Project. This 3.65 m (12 ft) finished diameter water tunnel presented many challenges that had to be overcome to take the project from concept to reality, not the least of which were the diverse ground conditions. Construction of the tunnel was carried out by a single tunnel boring machine (TBM) in one tunnel drive. The project is considered a success due to the accurate baseline established for the ground conditions; the approaches used to mitigate adverse conditions; and the appropriate use of TBM excavation methods, which achieved rapid advance rates despite the challenging ground conditions.

INTRODUCTION

The Metropolitan Water District (MWD) of Southern California is constructing the Inland Feeder Project, which involves over 88 km (55 miles) of pipelines and tunnels to convey 31 m^3/sec (1,100 cfs) of raw water from the State of California's facilities at Devil Canyon, near San Bernardino to MWD's new Diamond Valley Reservoir, near Hemet. The Riverside Badlands Tunnel is a 13 km (8 mile) long segment of the Inland Feeder. The tunnel is located about 100 km (65 miles) east of downtown Los Angeles. It follows a north-south alignment from Redlands, in San Bernardino County, to just south of State Route 60, in Riverside County (Figure 1) and traverses the Crafton Hills and San Timoteo Badlands at a depth ranging from about 15 to 260 m (50 to 850 ft). A rural area of dissected hills known as "the Badlands" overlies a portion of the tunnel alignment. Most of the construction work was staged at the Gilman Portal located at the south end of the tunnel and the Opal Portal, at the north end, was used as an exit

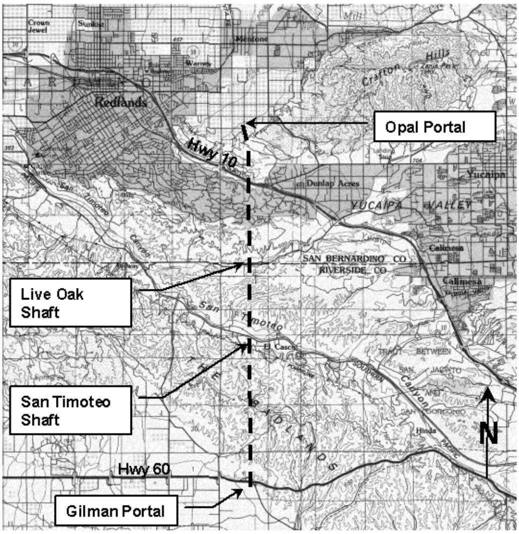

Figure 1. Tunnel alignment

portal to remove the TBM and place backfill around the pipe installed in the tunnel as a final lining.

Design of this 3.65 m (12 ft) diameter tunnel presented many challenges that had to be addressed in order to take the project from concept to reality. These challenges included: diverse ground conditions consisting of weak sedimentary rocks; strong, fractured metamorphic rocks; and alluvium, all of which were below the groundwater table; developing a cost effective tunnel design for the wide range of ground conditions; mitigating potential construction risks; and preparing a Contract that would allow flexibility for the contractor and also fairly allocate the risk between MWD and the contractor. This paper examines how these challenges were successfully addressed during design and construction of this project.

DESIGN CONSIDERATIONS

Design evaluations for the project focused on a several key issues: accurately characterizing the ground and groundwater conditions; identifying appropriate tunnel excavation methods; developing initial tunnel support and final lining designs; determining requirements for portal and shaft excavations; and developing a cost effective contract package that included suitable risk management provisions. A detailed discussion of all of these topics is beyond the scope of this paper, however, some of the more critical issues are briefly discussed in the following paragraphs.

Anticipated Ground Conditions

Fundamental to the design approach adopted for this project was the completion of a thorough geotechnical investigation program to accurately characterize the ground conditions along the tunnel alignment. This program was described previously (see Redd et al., 1997 and DMJM/WCC, 1997). The results of these investigations indicated that three distinct geologic units would be encountered in the tunnel in the following

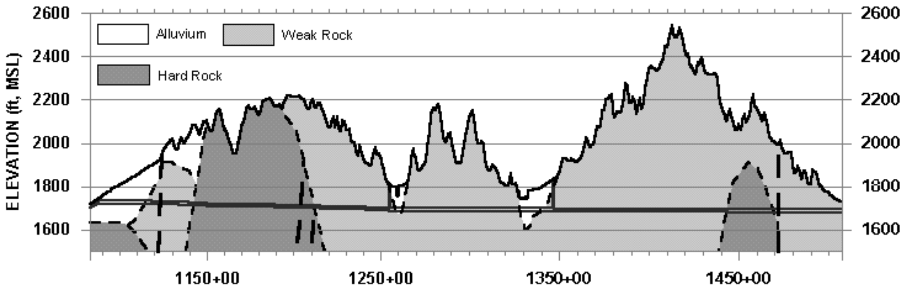

Figure 2. Geologic profile along tunnel

proportions: 10 percent soft ground (alluvium); 66 percent weak sedimentary rock (San Timoteo Formation); and 24 percent strong but variably fractured and sheared hard rock (metamorphic rocks). Several fault zones were also identified that crossed the tunnel alignment. The alluvium typically consists of dense to very dense silty and gravelly sands with local silt and clay layers. The San Timoteo Formation is a weak sedimentary formation that varies in strength from about 0.7 to 13.8 MPa (100 to 2,000 psi), except where the formation is uncemented and its strength is negligible. The metamorphic rocks are stronger, exhibiting strength values generally in the range of about 35 to 175 MPa (5,000 to 25,000 psi). Except for limited areas near the portals, approximately 90% of the tunnel is below the groundwater level with levels that range up to 100 m (330 ft) above the tunnel invert. Figure 2 is a geologic profile that shows the distribution of the geologic units along the tunnel. Several alternative tunnel profiles were evaluated during design that offered more uniform geology, however, these profiles were determined to be less desirable due to cost, constructability, and operational disadvantages.

The tunnel alignment was divided into ten reaches that were established based on the geologic units expected in the tunnel. These reaches are summarized in Table 1. Anticipated ground conditions included: raveling, running, and flowing ground in the alluvium; raveling, squeezing, and flowing ground in the San Timoteo Formation; and moderately jointed, blocky and seamy, and crushed rock in the metamorphic rocks. A more detailed discussion of the anticipated ground conditions is provided in Redd et al. (1997) and in the Geotechnical Design Summary Report [GDSR] (DMJM/WCC, 1997).

Tunnel Design Approach

Some of the important considerations that were addressed during design included:

- Need for positive groundwater control measures to prevent flowing ground in the alluvium.
- Potential for overstressed conditions in the weak San Timoteo Formation.
- Strong, variably fractured and sheared metamorphic rocks
- Highly fractured, crushed metamorphic rock and fault gouge in the Banning Fault zone (and other faults) under hydrostatic heads up to 100 m (330 ft).
- Uncemented zones in the San Timoteo Formation which could flow.
- Initial ground support requirements in the expected raveling, running, flowing, highly fractured, and crushed ground with low stand up time.
- Design of a watertight final lining for the tunnel to withstand the internal water pressures and external ground water pressures.

Table 1. Summary of geologic reaches for tunnel

Reach	Length (m)	Geologic Unit	Primary Soil/Rock Types	Natural Groundwater Head Range (m)
1	762 (2,500 ft)	Alluvium	Clean, silty, and gravelly sand	0
2	823 (2,700 ft)	San Timoteo Formation	Sandstone, conglomerate	0 to 24 (0 to 80 ft)
3	2,164 (7,100 ft)	Metamorphic Rocks	Gneiss	24 to 100 (80 to 330 ft)
4	1,372 (4,500 ft)	San Timoteo Formation	Sandstone, conglomerate	18 to 95 (60 to 310 ft)
5	152 (500 ft)	Alluvium	Clean and silty sand, some silt and clay beds	15 to 20 (50 to 65 ft)
6	2,012 (6,600 ft)	San Timoteo Formation	Sandstone, conglomerate, siltstone/claystone	15 to 20 (50 to 65 ft)
7	335 (1,100 ft)	Alluvium	Clean and silty/clayey sand, some silt and clay beds	14 to 20 (45 to 65 ft)
8	2,988 (9,800 ft)	San Timoteo Formation	Sandstone, siltstone/claystone, conglomerate	20 to 85 (65 to 280 ft)
9	945 (3,100 ft)	Metamorphic Rocks	Gneiss	46 to 55 (150 to 180 ft)
10	1,159 (3,800 ft)	San Timoteo Formation	Sandstone, siltstone/claystone	0 to 64 (0 to 210 ft)

Table 2. Feasible tunnel excavation methods

Reaches	Geologic Unit	Drill-and-Blast	Roadheader	TBM	Soft Ground Shield
1,5,7	Alluvium			X	X
2,4,6,8	San Timoteo Formation		X	X	
3,9	Metamorphic Rocks	X		X	

In addition, it was considered important to develop the Contract Documents in a way that would promote cost effective tunnel construction while also managing MWD's risks.

Tunnel Excavation Methods. Several excavation methods were determined to be feasible for the project, depending on the strength and character of the ground (Table 2). In order to provide flexibility and allow the use of different excavation methods in the various tunnel reaches, two intermediate shaft sites were made available, at the contractor's option. These 36 and 45 m (120 and 150 ft) deep shafts were located in Live Oak and San Timoteo Canyons, respectively, near the third points of the tunnel (Figure 1). This gave the contractor the ability to mine the tunnel using up to four headings (i.e., both portals and the two shafts).

Final Tunnel Lining. Due to water quality concerns, it was decided that a watertight lining was required to prevent groundwater infiltration into the tunnel. The static hydraulic grade line results in design hydrostatic pressures corresponding to about 58 to 73 m (190 to 240 ft) of head. In order to encourage competitive bids, designs for both welded steel pipe and reinforced concrete cylinder pipe were developed. Low density cellular concrete (LDCC) was specified as a backfill material around the pipe to reduce the risk of pipe flotation; facilitate the backfilling long sections of pipe; and provide corrosion protection for the pipe.

Contracting Approach. The contracting approach developed for the project allowed the contractor flexibility where possible, subject to certain limitations. Some of the specific requirements that had to be complied with included:

- Positive groundwater control in the alluvium reaches.
- Drilling of probe holes and pre-excavation grouting in certain defined intervals of the tunnel.
- Shielded TBM's were required due to the low strength of the San Timoteo Formation
- Mining operations limited at the Opal Portal to day shift only.

The amount of pre-excavation grouting required was uncertain and this work was paid for on a force-account basis to minimize the risk to both the owner and contractor. Other risk management provisions that were incorporated into the Contract included a GDSR, Disputes Review Board, and Escrow Bid Documents. The time for completion was increased to about 60 months to allow the contractor the flexibility to excavate the tunnel from one heading or multiple headings.

CONSTRUCTION PHASE

The project was bid in 1998 and the Contract awarded to a joint venture of Shank/ Balfour Beatty (SBB) for $113 million, which included a $5 million allowance for probe drilling and pre-excavation grouting. Construction began in October of 1998 with the excavation of the Gilman Portal and dewatering work at the two intermediate shafts. Tunnel excavation was carried out from November 1999 through July 2001.

Tunnel Construction Approach

The main tunnel staging area was established at the Gilman Portal and all tunneling operations and the majority of the pipe installation activities were carried out from this site. The two optional intermediate shafts, at San Timoteo and Live Oak Canyons, were used for ventilation, access during tunneling, and access to place the LDCC backfill. The entire tunnel was mined with the same shielded TBM designed to handle soft ground, weak rock, and hard rock. Precast concrete segments, 8 inches thick, were installed for initial support. The 4-segment ring was expanded with hydraulic jacks as it was pushed out of the tail shield and screw jacks were used to secure the expanded segment rings.

TBM Description. The TBM was a fully shielded machine designed and assembled by SBB (Figure 3). Hitachi Zosen manufactured the TBM body and tail shield. The hydraulically driven cutterhead was configured with 43 cm (17 in) diameter disc cutters and the machine was advanced with thrust jacks bearing against the precast concrete segment supports. Muck was removed from the plenum with a 76 cm (30 in) diameter screw conveyor. Key machine details are provided in Table 3.

TBM Progress Rates. SBB normally employed two mining shifts and a single maintenance shift 5 days per week. The overall average advance rate for the tunnel was about 30 m/day (99 ft/day). As indicated in Table 4, the advance rates are even higher if non-productive days, for grouting and drilling drain holes ahead of the TBM, are discounted. Making this adjustment increases the average advance rate to about 43 m/day (141 ft/day). Advance rates in Reaches 1, 5, and 6 were particularly impressive averaging over 60 m/day (200 ft/day) [Table 4]. Figure 4 shows the tunnel

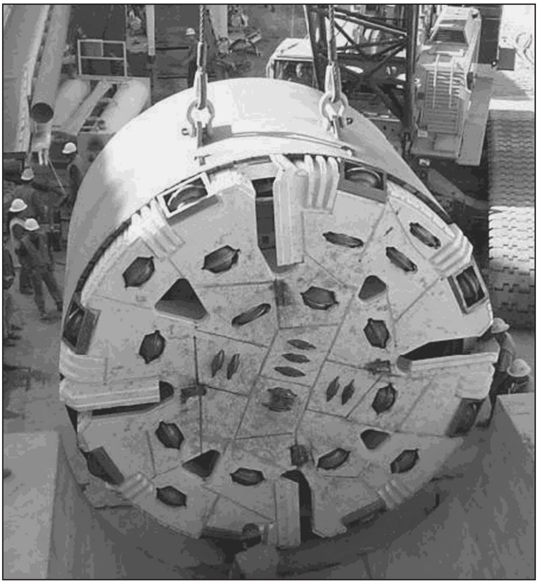

Figure 3. Shielded TBM used to excavate tunnel

Table 3. TBM design details

TBM Diameter	4.8 m (15.9 ft)
Total Horsepower	930 kW (1,250 Hp)
No. of Thrust Jacks	12
Total Thrust Force	16,900 kN (3,800,000 lbs)
Cutterhead Torque	1,176,300 m-kN (867,000 ft-lbs)
Cutterhead Speed	0 to 8 rpm
No. and Size of Cutters	32–43 cm (17 in)

progress graphically. The best day and best week (5 days) were 83 and 387 m (272 and 1,270 ft), respectively.

Pre-excavation Grouting. Probe drilling ahead of the TBM and pre-excavation grouting provisions were included in the Contract to control large, potential groundwater inflows associated with the expected fault zones. Pre-excavation grouting was also provided to control flowing ground conditions in uncemented portions of the San Timoteo Formation. Table 5 compares the estimated and actual grouting quantities. It should be noted that drain holes and dewatering were used, in lieu of grouting in Reaches 2 and 4, which decreased the amount of grouting performed during construction.

Groundwater Inflows. Groundwater inflows into the tunnel were estimated in the GDSR for the tunnel reaches (Table 1). Total cumulative inflows were estimated to be 168 L/sec (2,650 gpm), assuming that pre-excavation grouting, as discussed above, would be used to reduce inflows associated with fault zones and flowing ground. Figure 5 compares the estimated and actual groundwater inflows into the tunnel.

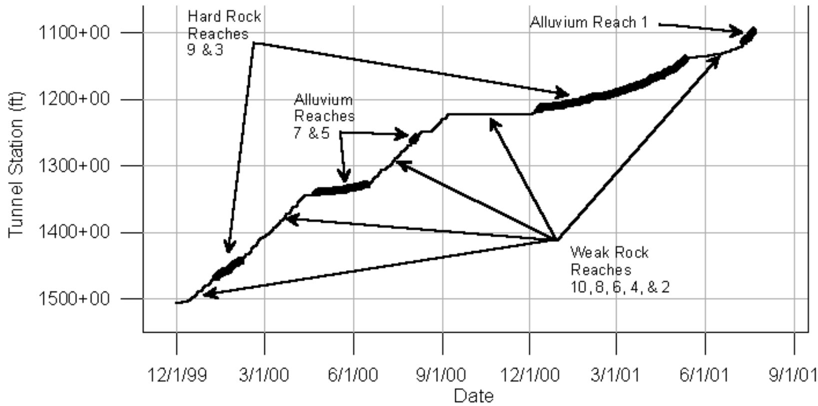

Figure 4. Tunnel excavation progress

Table 4. Average TBM advance rates

Reach	Formation	Overall Average Advance Rate (m/day)	Average Advance Rate, excluding grouting (m/day)	Comments
1	Alluvium	62 (203 ft/day)	—	No grouting req'd
2	San Timoteo Formation	19 (62 ft/day)	24.7 (81 ft/day)	Mined one shift per day at times
3	Metamorphic Rocks	21.6 (71 ft/day)	30.2 (99 ft/day)	
4	San Timoteo Formation	14 (46 ft/day)	38.4 (126 ft/day)	
5	Alluvium	62 (204 ft/day)	—	No grouting req'd
6	San Timoteo Formation	62 (203 ft/day)	—	No grouting req'd
7	Alluvium	11.6 (38 ft/day)	17.4 (57 ft/day)	Mined one shift per day
8	San Timoteo Formation	55 (181 ft/day)	—	No grouting req'd
9	Metamorphic Rocks	46.3 (152 ft/day)	—	No grouting req'd
10	San Timoteo Formation	41 (134 ft/day)	—	No grouting req'd

Table 5. Comparison of estimated and actual grouting quantities

Reach	Feature	Estimated Quantities			Actual Quantities		
		Cement (kg)	Microfine (kg)	Sodium Silicate (L)	Cement (kg)	Microfine (kg)	Sodium Silicate (L)
2	Reservoir Canyon Fault, Flowing ground	163,400 (360,000 lbs)	163,400 (360,000 lbs)	3,917,500 (1,035,000 gal)	26,700 (58,750 lbs)	108,100 (238,170 lbs)	591,000 (156,140 gal)
3	Banning Fault	817,200 (1,800,000 lbs)	817,200 (1,800,000 lbs)	—	1,060,600 (2,336,030 lbs)	383,400 (844,510 lbs)	0
4	Flowing ground	—	—	1,449,700 (383,000 gal)	0	0	210,600 (55,640 gal)
8	Flowing ground	—	—	870,600 (230,000 gal)	0	0	0
10	Fault D	272,400 (600,000 lbs)	272,400 (600,000 lbs)	—	0	0	0
Totals		1,253,000 (2,760,000 lbs)	1,253,000 (2,760,000 lbs)	6,237,700 (1,648,000 gal)	1,087,200 (2,394,780 lbs)	491,500 (1,082,680 lbs)	801,600 (211,780 gal)

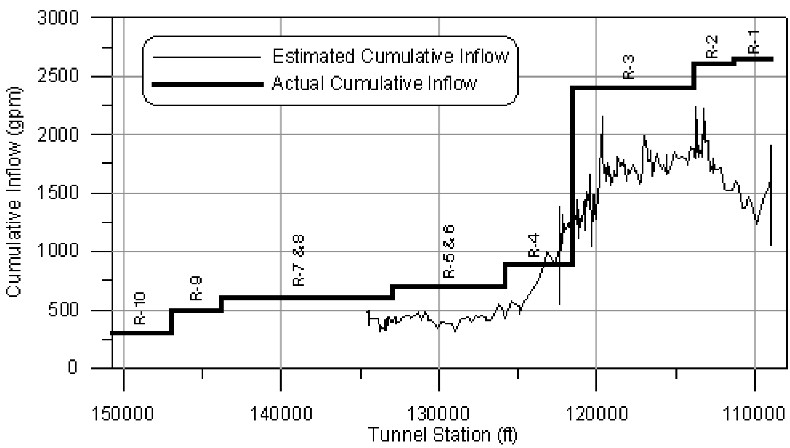

Figure 5. Comparison of estimated and actual groundwater inflows

Tunneling Challenges

For the most part ground conditions encountered in the tunnel were as described in the GDSR. However, difficult conditions were encountered creating challenges that had to be overcome.

Alluvial Valleys—San Timoteo and Live Oak Canyons. The tunnel had to cross two alluvial valleys at San Timoteo and Live Oak Canyons. The Contractor was required to design and implement appropriate groundwater control measures for mining through the saturated alluvium. Feasible approaches outlined in the GDSR included dewatering, use of an EPB tunneling machine, and jet grouting. Chemical grouting methods were considered to be only marginally applicable due to the cost and high fines content of the alluvium. SBB elected to dewater the alluvium and installed 23 dewatering wells in San Timoteo Canyon and 10 wells in Live Oak Canyon. The wells were typically spaced 15 m (50 ft) apart alternating on each side of tunnel centerline and were designed to extend 3 to 7.5 m (10 to 25 ft) below tunnel invert.

Dewatering started in San Timoteo Canyon (Reach 7) 8 weeks prior to the anticipated TBM arrival date. However, well yields were low and piezometer readings indicated that groundwater levels were not lowered sufficiently as they ranged from about 1.5 to 6 m (5 to 20 ft) above the tunnel crown when the TBM arrived at Reach 7. SBB considered that the ineffective dewatering was due to the ground having a lower permeability than expected, and decided that the ground could be controlled with the TBM by operating it in a partially pressurized mode (i.e. quasi-EPB) utilizing the screw conveyor. Unfortunately, the TBM was halted soon after entering the alluvium when silty sands flowed through the TBM and into the heading. At this point, it was obvious that tunneling could not proceed without a more positive means to control the flowing ground and SBB decided to chemically grout the rest of the alluvium in this tunnel reach. Drilling of vertical grout holes in a 3-hole pattern was initiated by as many as 5 drill rigs. Holes were drilled on 2.1 m (7 ft) centers, and chemical grout (sodium silicate) was injected through sleeve port grout pipes in several stages to treat the tunnel zone. Within ten days of initiating the grouting work, mining resumed and the grouting production allowed mining to proceed on a single shift basis in which an average of 18 m (60 ft) of tunnel was excavated per day.

While the chemical grouting operation in San Timoteo Canyon was successful, it was expensive and required complete surface access along the tunnel. Because similar ground conditions were anticipated ahead in Live Oak Canyon (Reach 5), and because the performance of SBB's dewatering system in Reach 5 had also indicated insufficient dewatering, there was concern that chemical grouting might also be required in this canyon. However, conflicts with existing residences and nearby water wells created difficulties for a chemical grouting approach. In addition, experience gained from the installation of a new water well for one of the residents suggested that the permeability might be higher than originally anticipated in this canyon. Recognizing the constraints to grouting, the actual performance of SBB's dewatering system, and the apparent higher permeability of the alluvium, SBB was directed to install two additional wells extending some 24 m (80 ft) below tunnel invert and into the San Timoteo Formation. These deeper wells produced an average flow of 14 L/sec (225 gpm) each and quickly lowered the groundwater level in the narrow canyon. By the time the TBM arrived at Reach 5, the groundwater level had been lowered to below the tunnel invert. As a result, mining proceeded through the alluvium in Reach 5 without incident at an average rate of about 60 m/day (200 ft/day) [Table 4].

Reach 4—San Timoteo Formation. North of Live Oak Canyon, in Reach 4, the groundwater level in the San Timoteo Formation gradually rises from about 15 m (50 ft) above the tunnel crown to over 60 m (200 ft) at a location several thousand feet north of the canyon. South of Live Oak Canyon, in Reach 6, the San Timoteo Formation was excellent for tunneling, as the TBM cut the ground easily but the ground was strong enough to have good stand up time and had sufficient silt and clay fines to prevent water problems. As anticipated, the formation became less cemented, weaker, and sandier as the tunnel proceeded north. Eventually the weaker, more pervious ground in combination with the higher groundwater levels led to significant problems about 1 km (3,300 ft) north of Live Oak Canyon where flowing ground with groundwater inflows in excess of 25 L/sec (400 gpm) halted the TBM. The water inflows decreased to about 5 to 6 L/sec (80 to 100 gpm), however, mining could not proceed in such unstable ground conditions.

The GDSR anticipated flowing ground being encountered and provided for the use of chemical grout (sodium silicate) to control this behavior. SBB planned to install sleeve port pipes for grouting using the lost point drilling method. Before this could be done, it was necessary to first stabilize the face and ground around the machine. This was achieved by chemical grouting through short pipes driven into the face and though holes cut in the shield. After completing this initial grouting, sleeve port grout pipes 9 m (30 ft) long were installed ahead of the TBM and chemical grout injected. Then the head was cleared of cobbles that had collected in the buckets and the head was turned. Mining recommenced but before a full 1.2 m (4 ft) shove could be completed the ground flowed into the tunnel and mining had to be stopped. This same chemical grouting process was repeated several times without success over the next 10 weeks, probably because the grout was not penetrating far enough into the formation to stabilize enough ground around the tunnel perimeter.

Considering this situation, MWD investigated the feasibility of installing a deep well from the ground surface in this area. The landowner was agreeable and dewatering analyses indicated that a well installed to a depth of about 150 m (500 ft) would be required to draw the groundwater level down to near the tunnel invert. MWD directed SBB to install a deep well located about 107 m (350 ft) ahead of the tunnel heading. In addition, drain holes 45 m (150 ft) long were drilled ahead of the TBM and a pump was installed in a well drilled in the invert of the tunnel.

The deep well was very effective, producing a flow rate of approximately 27 L/sec (425 gpm), and the drain holes yielded flows of about 6 L/sec (100 gpm) each. The combined result of these dewatering measures was an immediate improvement in conditions at the tunnel heading, and mining operations resumed. A second deep well was also installed approximately 150 m (500 ft) north of the first well to ensure that the remainder of the reach could be successfully mined. After a total delay of nearly 12 weeks, mining continued at a rate of 27 m/day (90 ft/day) to Reach 3.

Potential flowing ground conditions were also expected in the San Timoteo Formation in Reach 2. Because of the effectiveness of the dewatering wells in Reach 4 and the difficulty in grouting from the tunnel, it was decided to use the dewatering approach for Reach 2. Five wells were installed and they proved to be very effective in controlling the flowing ground and Reach 2 was mined without incident.

Final Lining

The Contract allowed the contactor to install a final lining of either reinforced concrete cylinder pipe or welded steel pipe. SBB selected the steel pipe option and elected to fabricate the pipe in 18 m (60 ft) sections with lap welded joints. The tunnel was prepared for the pipe laying operation and particular attention was given to installing a panning system that allowed water to be drained to the invert while ensuring that the LDCC would not infiltrate and plug the drains. Once proper drainage was established, the steel pipes were installed in the tunnel using a special pipe carrier designed by SBB. The pipe was transported and installed at a rate of about 120 m (400 ft) or 7 sections per day. After installing and welding the pipe sections, stulls were placed in the pipe 3 m (10 ft) apart to prepare for the LDCC backfill operation. The LDCC backfill, with a design strength of 2.75 MPa (400 psi), was placed in five lifts. Any voids remaining outside the pipe were contact grouted with a neat cement mix. A 2 cm (¾ in) thick field-applied mortar lining completed the pipe installation.

DISCUSSION AND CONCLUSIONS

Water started flowing through the completed tunnel in December 2002. To-date the total construction cost is about 7% above the $113 million bid price, but still substantially below the Engineer's Estimate. The project was also completed approximately one year ahead of schedule. Although there were some significant challenges during the tunnel excavation work, the ability of the parties involved to work together to solve these problems has resulted in an extremely successful project. Other key factors that contributed to the success of the project were the accurate baseline for anticipated ground conditions; Contract Documents that offered bidders flexibility in a number of areas; and the proactive mitigation of adverse ground conditions. The project is an excellent example of the use of a shielded TBM to handle extremely diverse ground conditions. Overall advance rates achieved by this TBM are impressive considering the variable ground conditions. Special measures such as probing and grouting ahead of the TBM and, in particular, deep dewatering wells were demonstrated to be effective for controlling adverse ground conditions. Another aspect demonstrated by this project is the advantage of working from a portal. The Gilman Portal site proved to be ideal, supporting very efficient mining and muck disposal operations and also allowing long pipe sections to be installed in the tunnel, significantly reducing the amount of field welding required.

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