NATM Excavation and Support Design and Construction of the Caldecott Fourth Bore

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ABSTRACT: The two-lane, 1,036 m long (3,399 ft) Caldecott Fourth Bore opened to traffic in November 2013 and along with the original three Caldecott bores provides a key transportation link between Alameda and Contra Costa counties. Seven cross passages connect the new Fourth Bore to the existing Third Bore. This paper describes the design of the initial ground support and final lining for the tunnel. The paper also documents the construction of the tunnel, including the daily support selection process, organization of the construction support team, examples of predicted versus observed ground behaviors, contractual considerations regarding support selection criteria, and the management of community impacts.

PROJECT DESCRIPTION
The original Caldecott Tunnel consist of three bores along State Route 24 (SR 24) through the Berkeley Hills in Oakland, California. The California Department of Transportation (Caltrans) and the Contra Costa Transportation Authority (CCTA) proposed construction of a Fourth Bore to provide two additional traffic lanes to address congestion on SR 24 near the original three Caldecott Tunnels. The horseshoe-shaped Fourth Bore is 1,036 m long (3,399 ft), 15.2 m wide (50 ft), and 9.7 m high (32 ft). The project included short sections of cut-and-cover tunnel at each portal, seven cross passages between the Fourth Bore and the original Third Bore, and a new Operations and Maintenance Control (OMC) building. The Fourth Bore provides two 3.6 m (11.8 ft) traffic lanes and two shoulder areas that are 3 m (9.8 ft) and 0.6 m (2 ft) wide, respectively (Figure 1). The tunnel includes a jet fan ventilation system, a wet standpipe fire protection system, and various operation and control systems, including closed circuit television (CCTV), heat and pollutant sensors, and traffic monitoring.

Ground Conditions
The geology along the alignment is characterized by Middle to Late Miocene-age marine and nonmarine sedimentary rocks, which strike northwest with high dip angles and are locally overturned. The western end of the alignment traverses marine shale and sandstone of the Sobrante Formation, which includes the First Shale, Portal Sandstone, and Shaley Sandstone members. The middle section of the alignment traverses chert, shale, and sandstone of the Claremont Formation, which consists of the Preliminary Chert, Second Sandstone, and Claremont Chert and Shale members (Page 1950). The eastern end of the alignment traverses nonmarine claystone, siltstone, sandstone, and conglomerate of the Orinda Formation. The limits of the major formations along the tunnel are shown in Figure 2. The Fourth Bore alignment encountered four major inactive faults, which occur at the contacts between the geologic units. These faults strike northwest, perpendicular to the tunnel alignment. In addition to the major faults, many other zones of weak ground were encountered, such as smaller faults, shears, and crushed zones. The active Hayward fault, located 1.4 km (0.9 mi) west of the project area, is the closest regional active fault. Additional details on the geologic conditions along the tunnel alignment are presented in Thapa et al. (2008a, 2009).

DESIGN
The following is a brief summary of the design of the Caldecott Fourth Bore.
Design of Initial Ground Support

The excavation and support design followed the principles of the New Austrian Tunnel Method (NATM), also commonly referred to as Sequential Excavation Method (SEM). Design drawings for the project included detailed requirements for the excavation sequence and initial ground support systems for the anticipated range of ground conditions including restrictions on advance length for each stage of excavation and the arrangement, dimensions, and capacity requirements for the support elements. The design included four major initial support systems, referred to as support categories (SC), SC I through SC IV, and three subvariations of the support categories, labeled with A and B. Table 1 summarizes the components by support categories, and Figure 3 presents a typical design drawing showing arrangement and installation requirements for the support elements for one of the major support categories. The design also included a toolbox of 20 additional support measures, consisting of shotcrete used as face sealing, initial lining, or temporary inverts, different types of rock dowels and spiles, lattice girders, face dowels, as well as probe and drain holes. The toolbox measures were used to augment the standard support category, if required by the encountered ground conditions.

Design of Final Lining

The final lining for the Caldecott Fourth Bore consists of cast-in-place reinforced concrete placed against a PVC sheet waterproofing geomembrane backed by a drainage geotextile. The waterproofing geomembrane extends only over the arch and sidewalls of the tunnel and drains into a drainage system located at invert level. The lining is 381 mm (15 in.)
Table 1. Summary of systematic support measures per support categories

<table>
<thead>
<tr>
<th>SC</th>
<th>Max. Advance Length</th>
<th>Systematic Presupport</th>
<th>Face Support (FRS=fiber rein. shotcrete)</th>
<th>Min. Shotcrete Thickness</th>
<th>Aver. Radial Dowel Spacing</th>
<th>Temporary Shotcrete Invert Arch</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>1.8 m ±5°–11”</td>
<td>None</td>
<td>Face dowels, sealing FRS, as required</td>
<td>~20 cm (8”)</td>
<td>1.8 m ±5°–11”</td>
<td>None</td>
</tr>
<tr>
<td>IB</td>
<td></td>
<td></td>
<td>Systematic face dowels, sealing FRS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IIA</td>
<td>1.4 m ±4°–7”</td>
<td>None</td>
<td>Face dowels, sealing FRS OR sloping core, sealing FRS</td>
<td>~25 cm (10”)</td>
<td>1.5 m ±4°–11”</td>
<td>None</td>
</tr>
<tr>
<td>IIB</td>
<td></td>
<td>Spiles</td>
<td>Sloping core, sealing FRS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IIIA</td>
<td>1.0 m ±3°–3”</td>
<td>Spiles</td>
<td>Sloping core, sealing FRS</td>
<td>~30 cm (12”)</td>
<td>1.2 m ±3°–11”</td>
<td>None</td>
</tr>
<tr>
<td>IIIB</td>
<td></td>
<td></td>
<td>Top heading and bench</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1.0 m ±3°–3”</td>
<td>Pipe arch canopy</td>
<td>Sloping core, sealing FRS</td>
<td>~30 cm (12”)</td>
<td>None</td>
<td>Top heading and bench</td>
</tr>
</tbody>
</table>

Figure 3. Example of support category requirements, typical excavation cross section for SC IIB

thick and includes two layers of reinforcing steel. The inner layer consists of 19 mm (No. 6) bars at 200 mm (7.9 in.) in the hoop direction and 13 mm (No. 4) bars at 200 mm (7.9 in.) in the longitudinal direction; the outer layer of steel consists of 16 mm (No. 5) bars at 400 mm (15.7 in.) in the hoop direction and 13 mm (No. 4) bars at 400 mm in the longitudinal direction. The design strength of the concrete is 35 MPa (5,000 psi).

The initial shotcrete lining and final concrete lining were designed as a combined support system, under the assumption that a portion of the ground load, initially carried by the initial support system, will be transferred to the final lining because of deterioration of the rock dowels and shotcrete comprising the initial support. Analyses indicate that approximately 50% of the load ground loads carried by the initial support system will be transferred to the final lining (Thapa et al. 2008b). However, in the design the final lining was conservatively assumed to carry two-thirds of the ground loads originally carried by the initial support system.

Extensive seismic analyses were performed to evaluate performance of the tunnel lining and ensure that the tunnel structure would meet Caltrans serviceability criteria for lifeline routes (Thapa et al. 2008a).
These analyses indicated that a single layer of reinforcing steel on the inside face of the lining would satisfy the seismic performance criteria. However, Caltrans decided to include a second layer of reinforcing steel to improve ductility during a seismic event (Thapa et al. 2013).

**Quantitative Risk Analysis**

A quantitative risk analysis was performed at several points during the design phase to evaluate and manage the risks to both project cost and schedule. Results of the risk studies were used to proactively plan risk mitigations and to help differentiate among design alternatives, and ultimately to establish the project budget and completion schedule. A series of facilitated workshops were attended by Caltrans design, construction, and legal personnel and members of the consultant design team, as well as external experts, focused first on identifying and quantifying all the project risks, and then on developing strategies to mitigate the most important risks.

The risks were grouped into five major categories: environmental, design, right-of-way, bid, and construction. Once the risks had been identified and quantitatively assessed, a custom probabilistic risk-based integrated cost and schedule model was built and used to evaluate the possible range in project cost and schedule, explicitly considering both: (1) the possible variation in the baseline cost and schedule; and (2) the various risks. One of the major risks identified for the project was a significant delay (and thereby cost) associated with either a challenge to the environmental documents or a legal action by one of the community groups opposed to the project. Based on accepted precedent for large infrastructure projects, the 80th percentile of mitigated cost and schedule was used for planning purposes. Identifying, quantifying, and then mitigating the risks allowed Caltrans and CCTA to establish and ultimately meet a realistic and stable budget and schedule for the project.

**CONSTRUCTION**

**Construction Milestones**

The contract was advertised to bidders by the Caltrans in May 2009 and was awarded to the low bidder, Tutor Saliba Corporation (TSC), on November 20, 2009. Tunnel construction was preceded by portal excavation and support, which began concurrently on the east and west sides of the alignment in May 2010. The Contractor elected to drive the top heading from both ends of the alignment concurrently to expedite the schedule. Approximately 80% of the top heading (800 m [2,625 ft]) was excavated from the East Portal, and the remaining 200 m (656 ft) were excavated from the West Portal. Break-in occurred in August 2010 at the East Portal by TSC, and in March 2011 at the West Portal by subcontractor FoxFire Constructors. Breakthrough of the top heading occurred at the end of November 2011 from the East Portal heading after tunnelling from the west side was completed to the breakthrough location roughly two weeks earlier.

Benching followed completion of the full top heading. TSC’s bench excavation sequence consisted of a center cut excavation followed by excavation of remaining side berms and installation of the tunnel sidewall support. TSC performed the center cut bench excavation working eastward from the breakthrough point for the majority of this reach. Foxfire excavated the full face of the bench from the West Portal towards the breakthrough point. Invert excavation and support followed benching, where required. Bench and invert excavation were completed in September 2012.

Final lining construction used a 15 m long (49 ft) form that was advanced uphill from the west to the east from April to October 2012. Typically, it took 8 to 10 hours to move, set, and place the concrete and another 8 to 10 hours for the concrete to set sufficiently to allow form removal, resulting in 4 to 5 form advances per week over a 6-day workweek.

Several life-safety systems were installed in the Fourth Bore and Third Bore, including linear heat detectors, smoke detectors systems, gas detection systems, message signs, fire suppression systems, jet fans. All of the systems are monitored and can be controlled at the control center located in the Operations and Maintenance Center (OMC), which also controls the systems for the three existing bores and it is planned to monitor all Bay Area tunnels from this location.

The tunnel was opened to traffic on November 16, 2013 (Figure 4).

**Support Selection Process and Organization of the Construction Team**

The Contract Documents described the design basis for the support categories and the criteria for selecting the appropriate support category based on the ground conditions and ground behaviors observed in the tunnel. Each support category was developed to support a defined ground condition that, along with the in situ conditions, resulted in certain ground behaviors. Defined ground behaviors included block failure, raveling, shallow shear failure, deep shear failure, slaking and softening, swelling, and crown instabilities due to low cover. (Thapa et al. 2008a,b, 2013). In addition, the design documents included the applicable toolbox support measures required for different observed or measured behaviors of the tunnel excavation.

The construction management team consisted of Caltrans personnel, augmented by Parsons...
Brinckerhoff and Gall Zeidler Consultants. Jacobs Associates as the designer provided the Design Representative during tunnel excavation and installation of the final lining. Gall Zeidler Consultants provided the NATM Engineer, who was in charge of the NATM tunnel-related technical construction management and led the team of engineers, geologists, and inspectors on-site.

Daily meetings were held during the mining phase between the Contractor’s and Engineer’s tunnel experts to select the appropriate standard support category and any required toolbox support measures based on observed ground conditions, observed support performance, and measured lining deformation. Encountered ground conditions and behaviors were mapped by both the Contractor’s and Engineer’s geologists on a daily basis during all phases of excavation of the tunnel for each face. Probe holes were instrumented using an automatic data logger that recorded feed pressure, torque, and advance rate, and this information was interpreted to predict the ground conditions ahead of the tunnel face. Convergence monitoring was carried out across the tunnel arch and bench walls at instrumentation stations spaced approximately 15 m (49 ft) apart that were typically monitored within 100 m (328 ft) of the tunnel heading. In one area, long-term convergences in the top heading foot area were observed additional rock dowels were installed and successfully controlled the ongoing convergence. However, in general the monitored movements stayed well below the warning levels defined by the design.

All the information described above was reviewed at daily meetings between the Contractor’s and the Engineer’s tunneling experts and provided the basis for a joint ground classification and support selection for each tunnel advance. The selected standard support categories and associated excavation were paid for on a per meter basis, whereas the toolbox support measures were paid for on a unit price basis.

**CONTRACT**

**Predicted Versus Observed Ground Behaviors and Support Requirements**

The encountered ground conditions along the alignment were generally consistent with the design prognosis, with the exception of two tunnel reaches that total 87 m (285 ft), or 9% of the alignment. These two reaches of differing site conditions occurred within the Second Sandstone between Tunnelmeter (TM) 241 and 322 (79 m [259 ft]) and within the Claremont Chert and Shale between TM 386 and 394 (8 m [26 ft]). In the Second Sandstone, the rock structure between TM 241 and 322 was blocky to massive, in contrast to the predicted blocky structure, and the intact rock strength was approximately 25% higher on average than indicated from strength tests performed during the design stage. The sandstone dikes in the Claremont Chert and Shale encountered in the tunnel between TM 386 and 394 exhibited a blocky to massive structure, in contrast to the predicted very blocky rock structure in the best rock mass in this formation. The Contractor and the Engineer negotiated a modified compensation for this differing site condition based on the item price for the original line item and documented effort.

**Quantity Deviations**

The major deviation from the design prognosis is the lesser quantity of SC III that was actually installed. While ground conditions anticipated to require SC III based on GSI, UCS data, and ground cover were encountered, SC II could be used in these reaches. This was because the strength of the fiber reinforced shotcrete as installed was higher than specified in the design. The higher than specified shotcrete strength
allowed for support selection of a thinner shotcrete lining, while still maintaining the required lining performance (Thapa et al. 2013). The predicted total quantity of SC III was 257 m (843 ft), compared to the installed quantity of 60 m (196 ft).

Another significant deviation from the design prognosis was the extent and payment for spiling in SC IIA and SC IIB. Spiling was an additional support measure in SC IIA, whereas SC IIB included systematic spiling (54 spiles total) over the entire arch (Table 1). The design intent was that SC IIB would be utilized where spiling was necessary around the majority of the arch and that SC IIA would be utilized where spiling was required over a limited portion of the arch. The Contractor’s interpretation of the contract was to apply the pay item for additional spiles applicable to SC IIA unless the full number of 54 spiles, as prescribed for SC IIB, was required. Negotiations between the Contractor and Engineer established a payment mechanism that compensated the Contractor for SC IIB when more than 37 spiles were required at a particular location and compensated the Contractor for SC IIA plus the unit price for the number of spiles when less than 37 spiles were required. This deviation from the design intent resulted in differences between the predicted support and as-installed support (Table 2).

**Table 2. Predicted versus installed support for Support Class II, including subtypes IIA and IIB**

<table>
<thead>
<tr>
<th>Support Category</th>
<th>Predicted Quantity</th>
<th>Installed Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>412 m</td>
<td>568 m</td>
</tr>
<tr>
<td>IIA</td>
<td>35 m</td>
<td>380 m</td>
</tr>
<tr>
<td>IIB</td>
<td>377 m</td>
<td>188 m</td>
</tr>
</tbody>
</table>

Contractual Considerations and Unit Price

A key advantage of NATM is the flexibility of the method to adapt to the observed ground conditions with suitable systematic and additional support measures. Support selection decisions were made by the on-site team in the daily meetings as described above. Based on this joint review and considering potential operational constraints, the group would decide on the support class and support measures required for the day’s advances.

The flexibility of the NATM tunneling method with the commensurate frequent variation in excavation sequence and support requirements can result in contractual challenges related to fair risk sharing between the Contractor and the Owner and equitable compensation mechanisms. One approach to addressing the issue would be to break all different elements of the excavation and support classes of the design into numerous separate unit price line items, for example, shotcrete, lattice girders, spiles, and rock bolts. Typically, only the line item for excavation is tied to a specific support category. The support measures, on the other hand, become independent from the support classes. ITA’s Working Group 19 addresses such an approach and provides design and contractual guidelines for the execution of NATM, referred to as Conventional Tunneling by the ITA (ITA 2009 and 2013). A detailed discussion of the different support measures is also provided in the Federal Highway Administration’s Design Manual (FHWA 2009).

The application of NATM in Austria and Germany typically allows selection of excavation sequence and initial support elements in combinations appropriate to variations in encountered ground behaviors, so as to achieve the most efficient tunnel support system possible. This approach often results in a highly variable excavation and support process that requires different pay items for each support element such that they can be combined as needed. Mostly, unexpected ground conditions do not become the basis for a differing site condition claim if the designed systematic and additional support measures are applied, even if they are modified from the standard support classes. However, using this approach can result in significant variations between predicted and actual quantities, and this quantity variation has to be appropriately addressed in the contract.

The Caldecott Tunnel used a detailed and prescriptive design of the excavation and support sequence, which was developed to minimize the number of support categories and pay items with the goal of simplifying the construction operations and avoiding an overly complex and cumbersome contractual payment process. Standard support categories were measured and paid on a per meter basis, with the pay item covering all associated excavation and support requirements. This approach was judged to be more conducive to promoting competitive and responsive bids. The payment approach for each support category was successful (except in the case of the spiling that is part of SC II, described above). Based on the divergence of the Contractor’s interpretation from the design intent, and the variability in the number of spiles required per advance, it may have been more advantageous to remove a prescriptive design for the spiling from systematic support measures and pay for the spiles as additional support (including time-dependent costs such as impacts on advance rates).
THIRD-PARTY INVOLVEMENT

California Division of Occupational Safety and Health Administration

After evaluating the information gathered during the ground investigation phase, the California Division of Occupational Safety and Health Administration (Cal/OSHA) classified the Caldecott Tunnel as “Gassy with Special Conditions.” This classification imposed stringent requirements on the Contractor with regard to equipment, operation, and health and safety precautions. During mining activities, the Contractor was required to measure and record gas readings every hour at the face of the main tunnel and the cross passages. The records were available at the site for review by Cal/OSHA engineers during their bimonthly visit. Additionally, the excavation equipment had to be fitted with a measuring device continuously measuring for traces of gas.

At the conclusion of the top heading excavation, and before the bench and invert excavation was completed, Caltrans requested that Cal/OSHA relax the classification to “Potentially Gassy with Special Conditions.” After reviewing all the records from the top heading excavation and finding that there were no significant traces of gas, Cal/OSHA reclassified the tunnel to “Potentially Gassy with Special Conditions.” This allowed the use of more standard equipment, without the stringent requirements imposed by a classification as gassy, allowing for expedited excavation.

Emergency Response Plan

A significant construction risk often overlooked is the integration of the electrical and mechanical systems. For road tunnels, NFPA Code 502 (NFPA 2011) requires preparation of an Emergency Response Plan (ERP). For the Caldecott Fourth Bore, the ERP was developed under the supervision of the office of the State Fire Marshall, the California Highway Patrol, and the Oakland and Orinda-Moraga Fire Departments. In compliance with the NFPA code, seven cross-passages were constructed between Bore 4 and the existing Bore 3.

Prior to the tunnel being opened to traffic, the emergency scenarios in the ERP were tested with the use of the tunnel safety-life systems. Experience gained at the Caldecott Fourth Bore project and other road tunnels recently completed in California reveals that integration of the system is complicated, difficult, and time consuming. Hardware and software issues occurred at any time during the integration process. Even though a particular system had passed during the individual testing, it could develop issues when integrated with other systems. In the Fourth Bore, there was the additional complication of integrating existing systems of the Third Bore with the newer systems in the Fourth Bore. Thus, sufficient schedule time was necessary for systems integration and testing, as well as continuous coordination with vendors, subcontractors, integrators, emergency responders and the operators.

Community Outreach

An extensive community outreach was initiated prior to construction and continued throughout to keep key stakeholders, taxpayers, and the motoring public well informed. A comprehensive strategic communications plan served as a blueprint for project-specific messaging and community outreach protocols, and helped to standardize communications among partner agencies, including Contra Costa Transportation Authority (CCTA), Caltrans, Metropolitan Transportation Commission (MTC), and Alameda County Transportation Commission (Alameda CTC). Prior to start of construction, CCTA and project partners launched a project website, www.caldecott-tunnel.org, which provided ongoing information. In addition, a full-time Public Information Officer provided regular updates to the many stakeholders and the public.

Blasting and Community Impact

The need for blasting and its potential impact on the nearby residents and structures were assessed in detail during the design phase. These assessments indicated that all encountered rock types along the tunnel alignment could be excavated by a large roadheader. However, in order to provide additional flexibility to the contractor in the event of encountering stronger, more massive rock than anticipated, blasting was permitted. Given the concerns of the public living in close proximity to the project, Caltrans required close controls on all blasting operations per the project specifications, including requirements for a 24-hour notice prior to blasting, prohibiting blasting during evening hours, submittal of detailed blasting plans, monitoring of ground vibrations and air overpressures, and strict limits on peak particle velocity and air overpressures at specified locations. As anticipated during the design phase, blasting was not required because of the utilization of a very powerful roadheader.

Noise Reduction

Managing noise impacts during construction on nearby residents was also a key consideration. The project plans included a detailed design for a sound wall adjacent to the West Portal to shield a large residential development from construction noise. In addition, the Contract Documents required the Contractor to prepare a detailed sound control plan. Monitoring was performed prior to construction to
measure ambient noise levels. The ambient levels were recorded by placing recording devices in close proximity to the construction area at locations designated by the specifications. During the construction period, the Contractor was required to continuously monitor and record ambient noise levels and compare them to the ambient baseline levels. In addition, the Contractor was required to install four monitoring and recording devices near the construction areas, with locations approved by the Engineer, and monitor for noise levels exceeding 86 dBA. If an event occurred that exceeded the noise levels, a notification was immediately sent to the Engineer, and the Contractor was required to determine the cause of the elevated sound level within 20 minutes of the occurrence. If the noise exceedance was caused by the Contractor’s activities, the Contractor was required to suspend operations and take measures to mitigate the sound.

CONCLUSION

The design and construction of the Caldecott Fourth Bore was based on the principles of the New Austrian Tunneling Method (NATM). The support systems as designed and implemented during construction were successful in supporting the tunnel opening, controlling ground behaviors, and limiting tunnel convergence to below the predicted thresholds. The NATM approach provided the required flexibility to adapt the support for the wide-span tunnel to the encountered weak and variable ground conditions. The experience with construction of the Fourth Bore indicates that the simplified contract structure minimizes the potential for misinterpretation of the contract as related to a multitude of support variations. With growing experience with NATM execution, it will be possible to develop designs with more flexibility that will require more refined contractual payment structures.

The successful completion of the Caldecott Fourth Bore on schedule and under budget demonstrates that large NATM tunneling is a cost-effective approach to tunnel construction.

ACKNOWLEDGMENTS

The authors acknowledge the major contribution of Dr. Bhaskar Thapa to the successful completion of the Caldecott Fourth Bore. He worked on the project through all phases, from the initial investigation to the completion of the final lining. Dr. Thapa passed away unexpectedly in June 2013, just four months prior to the opening of the Fourth Bore. The successful completion of this landmark project serves as a tribute to his hard work, dedication, and passion for tunnel design and construction. The high-quality analyses, reports, and construction documents that Dr. Thapa prepared will serve as models for future generations of tunnel engineers.

Dr. Bill Roberds with Golder Associates led the risk workshops and performed the risk analyses.

REFERENCES


