

# **NATM Strategies in the U.S.—Lessons Learned from the Initial Support Design for the Caldecott 4th Bore**

Bhaskar B. Thapa,<sup>1</sup> Thomas Marcher,<sup>2</sup> Michael T. McRae,<sup>1</sup> Max John,<sup>3</sup> Zuzana Skovajsova,<sup>2</sup> and Mahmood Momenzadeh<sup>4</sup>

<sup>1</sup>Jacobs Associates, San Francisco

<sup>2</sup>ILF Consultants, Austria

<sup>3</sup>Tunnel Consultant, Austria

<sup>4</sup>California Department of Transportation

## **ABSTRACT**

The design of the Caldecott 4th Bore, located along State Route 24 in Oakland, California, is based on the principles of the New Austrian Tunneling Method (NATM). Typical NATM initial support design practices used in Europe were adapted for this project to account for U.S. conditions and requirements, such as degree of experience with NATM construction, the prevailing contractual environment, and preferences for contractual simplicity. Key design features are: (1) support selection criteria based on ground behaviors and ground conditions; (2) a prescriptive design with allowance for support adjustments based on observations during construction; and (3) organization of support requirements into only four major support categories, while permitting some adjustment for variations in ground behaviors and conditions using a few subtypes and additional support measures.

## **INTRODUCTION**

### **Project Background**

The existing Caldecott tunnels 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) propose to address congestion on SR 24 near the existing three Caldecott tunnels by constructing a fourth bore that will provide two additional traffic lanes. The length of the proposed fourth bore is 1,036 m (3,399 ft). The project will include short sections of cut-and-cover tunnel at each portal, seven cross-passageway tunnels between the fourth bore and the existing third bore, and a new Operations and Control Building.

The fourth bore includes two 3.6-m (12-ft) traffic lanes and two shoulder areas that are 3-m and 0.6-m (10-ft and 2-ft) wide. The horseshoe-shaped mined tunnel is 15-m (50-ft) wide and 9.7-m (32-ft) high. A typical section of the tunnel is shown in 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) monitoring, heat and pollutant sensors, and traffic monitoring systems.

Details on ground conditions and initial support design have been described in previous papers (Thapa et al. 2007, 2008) and are not repeated here. This paper reviews general aspects of NATM design used on recent projects, identifies some key design issues regarding NATM practice in the U.S., and describes how these issues have been treated in the design for the 4th Bore.



**Beacon Hill.** The Beacon Hill Station and tunnels include one mile of twin tunnels, an underground station, portals, and ancillary works. Ground conditions consist of variable glacial soil deposits ranging from soft, water-bearing sands to stiff, slickensided clays (Phelps et al. 2005). A large number of geologic units have been grouped into five major ground types to reduce the complexity of the geologic profile.

The NATM (or Sequential Excavation Method, SEM) design of the station tunnels was based on a three-stage approach (Field et al. 2005) consisting of (1) a prescriptive design for excavation and support sequences, dimensions, and shotcrete support for each excavation element of the station complex; (2) prescriptive ground conditioning and presupport at critical locations; and (3) a “tool-box” of additional support measures to be used as required. Daily meetings between the contractor and engineer were used to confirm support requirements (Akai et al. 2007).

## **Europe**

**Strenger Tunnel, Austria.** The Strenger Tunnel consists of a twin two-lane road tunnel in Austria that was driven through highly squeezing ground, as described by John et al. (2005). Ground conditions consist of quartz phyllonites and quartzitic schists of low permeability, with a strike at an acute angle to the tunnel axis and steeply dipping. According to the Austrian Standard (ÖNORM B 2203), support categories are differentiated for the top heading, bench, and invert. Eight categories are defined for the top heading, six categories for the bench, and four for the invert. At each excavation stage, the ground behavior is evaluated and the applicable support category adopted. This allows for maximum flexibility with regard to changing ground conditions between the crown and invert. The project also utilized a sophisticated system for the adjustment of payment for support elements that accounts for the impact of support installation time on advance rates. Employing this remuneration system enabled payment for support elements on a unit-price basis.

## **NATM DESIGN ISSUES**

This section discusses some key considerations regarding NATM design that were identified as requiring adaptation to suit U.S. tunneling practices.

### **Experience with NATM Construction**

**United States.** Considering the size of the U.S tunneling industry, there have been relatively few tunnels constructed in the U.S using NATM. In addition to the Devil’s Slide and Beacon Hill projects, other recent NATM projects in the U.S. (reported in the 2005 and 2007 RETC Proceedings) include the Stanford Linear Accelerator (LINAC) Tunnel (Halim et al. 2007), Dulles Corridor Metrorail Project (Rudolf et al. 2007), a reach of the San Vicente Tunnel (Krulc et al. 2007), the Michigan Street Pedestrian Tunnel (Madsen et al. 2007), the Dulles International Airport People Mover (Frاندina 2005), and the San Diego Mission Valley East Extension (Field et al. 2005).

The limited experience with NATM in the U.S is important because NATM is an observational method that involves verification/finalization of excavation and support designs during construction, and effective application of the method requires experienced construction personnel within both the owner’s and contractor’s organizations. These personnel are required to observe ground conditions and behaviors and adjust support accordingly. Although the widely used (in the U.S.) ground classification scheme by Terzaghi (Proctor and White 1968) does consider some behavior modes, it is mainly focused on ground conditions. On the other hand, NATM ground classification considers a wide range of ground behaviors. The limited U.S. experience in working with ground behavior observations/evaluations, which are a key

part of NATM support selection/design verification, was considered a limitation to be accounted for in the design layout and preparation of the Caldecott 4th Bore contract documents.

**Europe.** In contrast to the U.S., numerous tunnel projects have been constructed throughout Europe using NATM and, therefore, there is a wealth of experience with both owners and contractors. This wealth of experience translates to well-trained miners and site supervisors with experience identifying key ground conditions and behaviors that allows immediate decisions at the face on support requirements. Workers are well acquainted with the procedures for handling and installing all support elements, which enables prompt switching of support categories with minimal impacts on productivity. Finally, complex regulations for measurements of bid items are standard as this procedure has been built upon for years. For example, in Austria each support element is remunerated by a separate pay item and all elements are clearly defined for each support category. Adjustments of support elements during construction are handled by payment for the actual number and type of elements installed. Impacts of support adjustment on advance rates are addressed by adjustment of contract support category advance rates established during bidding using evaluations of time consumed for installation of adjusted support elements. For instance, if additional dowels are to be installed, the advance rate will be reduced. This would be addressed by an adjustment for construction time and remuneration of costs.

### **Comparison of Contractual Practice**

Contracting for NATM tunnels in Europe allows optimization of construction to achieve cost and schedule efficiencies by placing the designer in the construction manager role to provide continued validation, back-analysis, and design adjustments (Field et al. 2005). In contrast, the U.S. practice tends to be oriented towards developing a set of clearly scoped contract documents for competitive bidding and does not allow the designer to fill the construction manager role. The risk to owners using the European NATM approach is accepted because differing site conditions are the responsibility of the owner in any case, and the owners are experienced in managing the risk by participating in the decision-making process at the face. By comparison, the risks to a U.S. owner entailed in using the European approach to NATM contradict the general risk management approach to construction projects that is prevalent in the U.S. Thus, it is necessary to adapt the European approach to NATM construction by simplifying and translating European NATM practice such that the bids are a meaningful basis for selecting the contractor and that the bid price can be fairly adjusted if conditions are different than anticipated.

In Europe it is practice for the NATM initial support design to be optimized for variations in ground behaviors so as to achieve the most efficient tunnel production system possible. This is accomplished by using a large number of support categories with each support category suited to a narrow range of ground behavior and providing bid items for the use of additional support measures as required. This approach is inconsistent with the general contractual practice in the U.S. of using only a few support categories that group a range of ground behaviors and provide a clear basis for bids. The Devil's Slide Tunnel is an example of the U.S practice on a recent U.S. NATM tunnel project. A similar approach was considered for the Caldecott Project so as to attract the largest number of bidders and promote competitive bidding.

### **CALDECOTT 4TH BORE NATM DESIGN FEATURES**

This section describes strategies used in the design of the 4th Bore NATM initial support to address NATM adaptation issues identified above.

#### **Site Investigation**

An extensive site investigation program involving over 1,245 m (4,100 ft) of borings, geological field mapping, in situ testing, and laboratory testing was undertaken to characterize materials along the

alignment, The borings cover over 90% of the alignment. Additionally, construction records from the existing three bores were reviewed in assessing ground conditions along the alignment. These data provided a detailed understanding of the range of ground conditions expected along the alignment. The site investigation information was evaluated to identify Rock Mass Types (RMTs), which are rock units with similar mechanical properties, and ground classes having similar excavation and support requirements (Thapa et al. 2007, 2008). Results of the site investigation indicate feasible excavation methods include use of a roadheader, excavator with cutter-head attachment, and drill-and-blast methods.

## Geotechnical Design

In order to address the NATM support selection criteria based on ground behaviors and also accommodate the typical U.S. practice of using ground conditions, the design defined ground classes, which are groups of RMTs having similar predominant behaviors in an unsupported opening (Thapa et al. 2007). Seven behaviors were defined in terms of failure modes and manifestations, as summarized in Table 1 and depicted on Figure 2. Support categories consisting of a set of excavation and support requirements were developed for each ground class on a one-to-one basis.

TABLE 1: Ground Behaviors *	
<i>Behavior</i>	<i>Description of Failure Modes and Manifestations in an Unsupported Tunnel</i>
Block failures	Discontinuity-controlled, gravity-induced failure of rock blocks that manifests as falling and sliding of blocks.
Raveling	Progressive, discontinuity-controlled failure of small rock blocks within the general rock mass at or near the excavation surface. Raveling is manifested as successive fallout of small rock blocks and can ultimately result in a significant overbreak.
Shallow shear failure	Shallow shear failures result from overstressing of the ground within 0.25D to 0.5D of the tunnel perimeter (D=tunnel diameter) and may be enhanced by the potential for discontinuity and gravity-controlled failure modes. Shallow shear failure is manifested by moderate inward movement of the tunnel perimeter, including invert heave, and possibly by movement of rock into the tunnel opening along discontinuities.
Deep shear failures	Deep-seated shear failures result from overstressing of the ground beyond 0.25D to 0.5D from the tunnel perimeter. Deep-seated shear failure manifests as large radial convergence of the tunnel perimeter, including invert heave.
Slaking/softening	Slaking is the deterioration and breakdown of intact rock upon exposure by excavation and manifests as slabbing of material from the crown and sidewalls. The severity of this behavior is assessed on the basis of slake durability tests performed according to ASTM Test Method 4644. Softening, which is dependent on wetting and exposure by excavation, is the reduction of intact rock strength at the invert or elsewhere and manifests as the development of a muddy or unstable invert or sloughing along segments of the tunnel perimeter elsewhere.
Swelling	Swelling occurs due to absorption of water by clay minerals in rock upon excavation-induced unloading. Swelling manifests as movement of the ground into the tunnel opening or additional tunnel support loading.
Crown instability due to low cover	Excessive crown geological overbreak and chimney-type failure will occur due to lack of confinement under low-cover reaches at portals. It manifests as block fallout and raveling above the crown.

\* Modified from Austrian Society for Geomechanics, 2004.

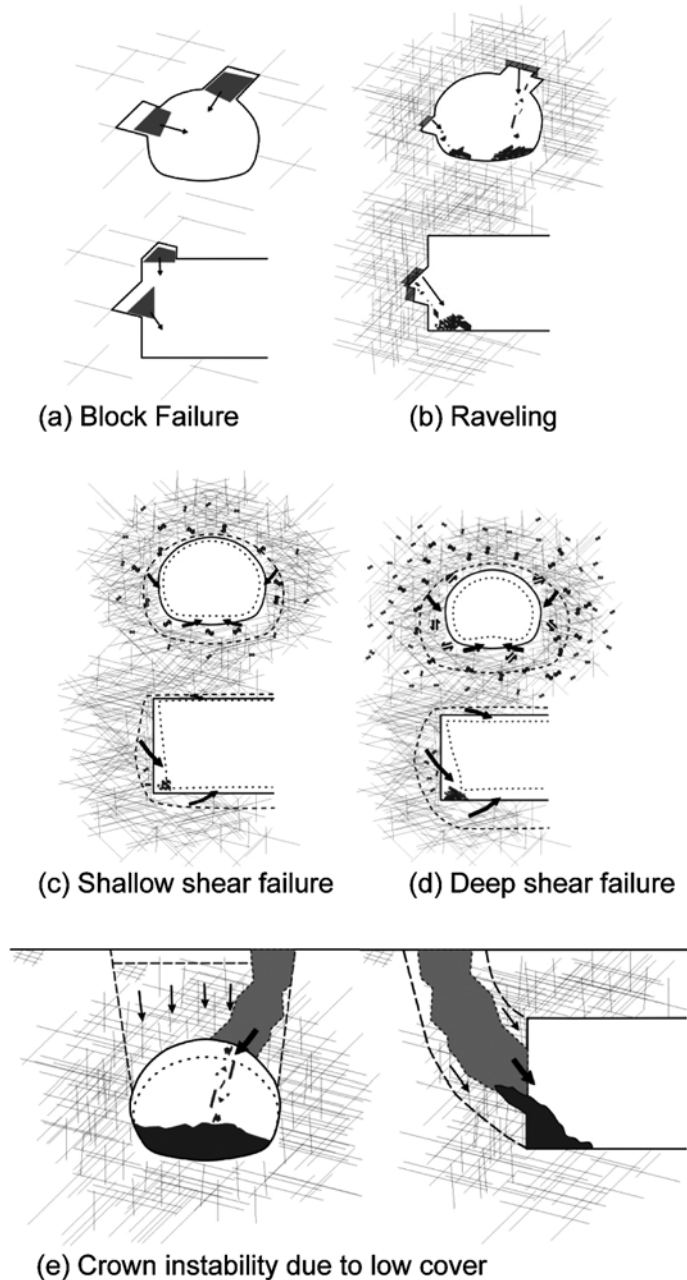


FIGURE 2. Ground behaviors

## Support Requirements

A prescriptive approach to the specification of the excavation and initial support requirements was adopted to implement NATM construction of the 4th Bore. Excavation and support requirements for each support category include overall excavation and construction sequence, restrictions on advance lengths, drift dimensions, arrangement and dimensions of support elements, as well as alternative schemes where applicable (Figures 3a, 3b and 3c). The construction sequence consists of a top heading, bench and invert excavation sequence. The design of the support system includes the following measures: fiber-reinforced shotcrete; drill and grout, as well as self-drilling rock dowels; lattice girders; invert arch; drill and grout, as well as self-drilling spiles, pipe canopy, face dowels, and a sloping core for face support.

In keeping with general tunneling practice in the U.S., it was decided to minimize the number of support categories on the 4th Bore to simplify the tunnel production operational requirements. The initial support design was organized into: (1) standard support consisting of four major support categories and three subtypes, each having a separate pay item; and (2) additional support elements on a unit-price basis (including time-dependent costs such as impacts on advance rates) to be used for local ground conditions/behaviors, as required. Table 2 summarizes the key support elements for the four major support categories, and Figure 3 shows the arrangement of support elements and support installation requirements for one of the support categories.

<i>Support Category</i>	<i>Max. Advance Length, m (ft)</i>	<i>Presupport</i>	<i>Face Support</i>	<i>Shotcrete Thickness, cm (in.)</i>	<i>Avg. Dowel Spacing, m (ft)</i>	<i>Invert Arch</i>
I	1.8 (6)	None	SC IA: face dowels/sealing fiber reinforced shotcrete (FRS) as required  SC IB: systematic face dowels/sealing FRS	20.3 (8)	1.8 m (6)	None
II	1.4 (4.5)	SC IIA: none SC IIB: spiles	Face dowels/sealing FRS or sloping core/sealing FRS	25.4 (10)	1.5 m (5)	None
III	1 (3.3)	Spiles	Sloping core/sealing FRS	30.5 (12)	1.2 m (4)	SC IIIA: none SC IIIB: top heading and bench
IV	1 (3.3)	Pipe canopy	Sloping core/sealing FRS	30.5 (12)	None	Top heading and bench

Additional support measures are supplementary to the standard support measures. These additional measures are required to address observed or measured local ground conditions or behaviors. They will be installed when measured convergence exceeds warning levels or when specific ground conditions or support system behaviors are observed, as defined in the contract documents. Estimated quantities of additional support measures included in the contract are based on an assessment of variations in ground conditions expected using the results of the site investigation program. Additional support elements include spiling, rock dowels, shotcrete, lattice girders, and an invert arch.

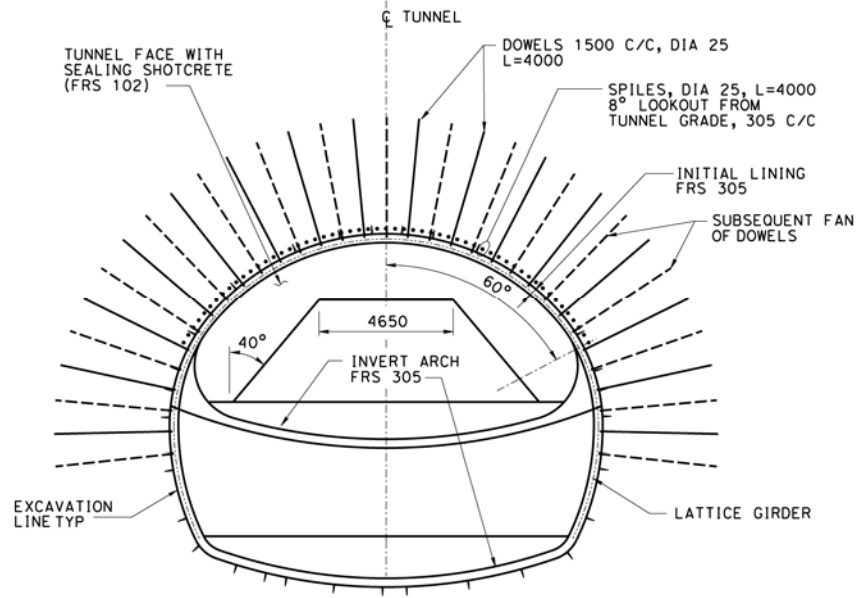


FIGURE 3a. Example of support category requirements, typical excavation cross section

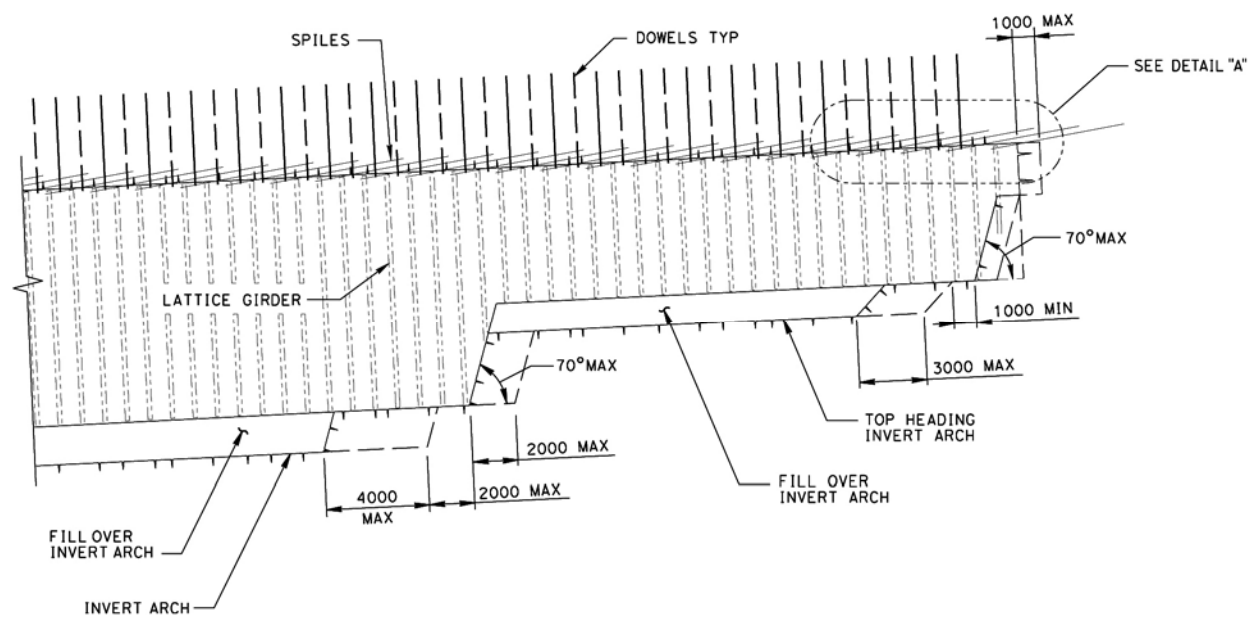


FIGURE 3b. Example of support category requirements, section

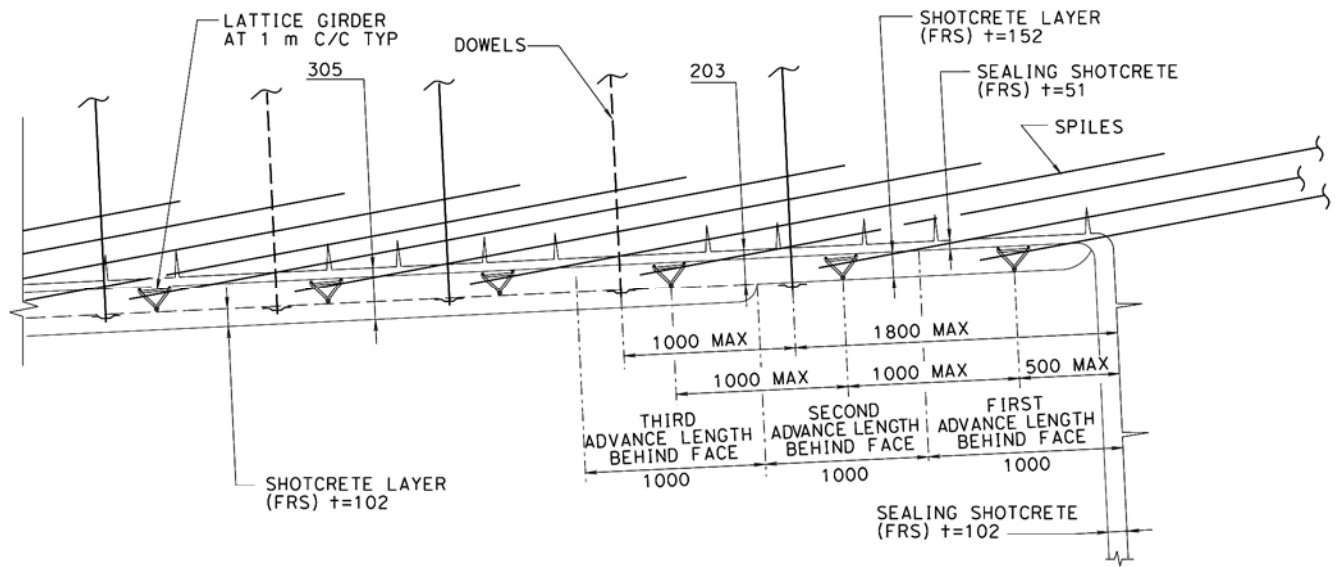


FIGURE 3c. Example of support category requirements, detail “A” of section

Numerical models were used to analyze the behavior of the support system during the excavation process, including evaluation of forces, moments and rotations in the shotcrete lining, and forces in the rock reinforcement support elements (Thapa et al. 2007, 2008). The design for the support categories was based on numerical calculations of typical sections along the alignment. The possible variation of support category application location, extent, and sequence from the design prognosis (Figure 4) is clearly stated on the contract drawings and Geotechnical Baseline Report (GBR) so as to clarify that the construction impact of such variations must be accounted for in the bids. The total quantities of support categories and the number of changes between support categories to be used for bidding purposes were stated in the contract documents. The “Variation In Quantities” Clause of the specifications allows for renegotiation of unit rates of support category payment should the bid quantities vary by more than 25%, or by a lineal meter threshold for items with a low estimated quantity.

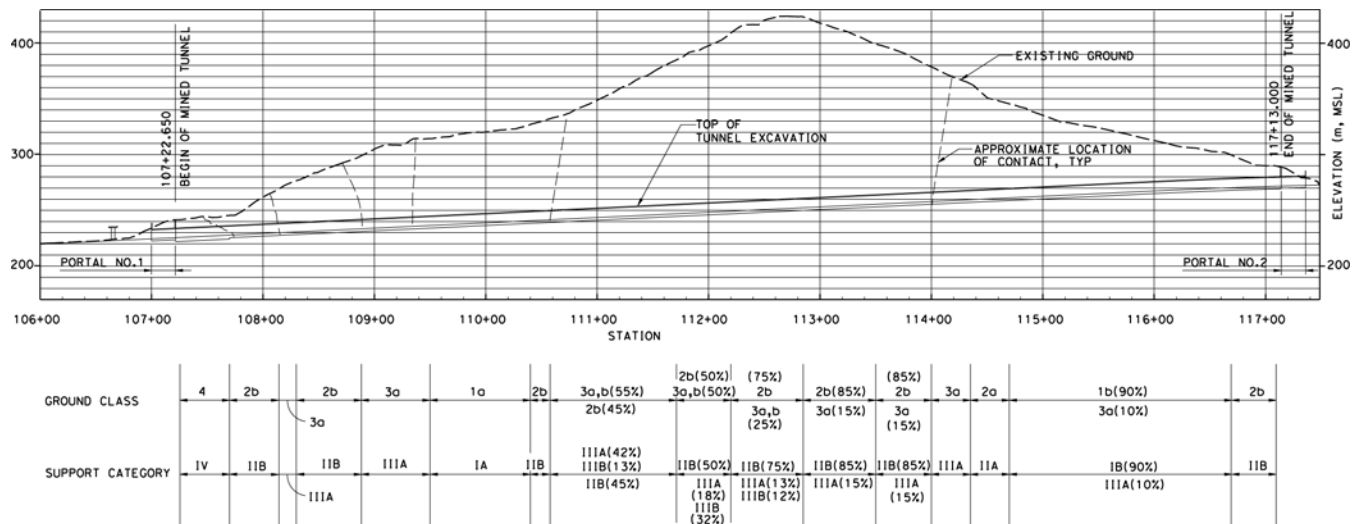


FIGURE 4. Design prognosis of ground classes and support categories along the alignment

## Support Selection Criteria

The definitions for each ground class, which are a key element of the support category selection criteria, were developed using consistent terminology based on the U.S. Bureau of Reclamation (USBR,1998) and Geological Strength Index (Marinos et al. 2005). Rock mass descriptions are summarized in the plans (see Figure 5) using the Geological Strength Index system and expanded upon in the GBR using the USBR terminology. Ground class behaviors also were defined consistently using the definitions shown in Table 1 and Figure 2. Expanded discussions of behaviors in the GBR clarify which behaviors will be directly observable and which ones will not, the locations and special conditions associated with specific behaviors, and the relations between ground behaviors and support elements required to control the behaviors. Criteria for application of additional support measures were defined in the plans in terms of local ground conditions and behaviors, including warning and alarm levels of tunnel convergence (Figure 6).

STANDARD SUPPORT APPLICATION CRITERIA				
GROUND CLASS	SUPPORT CATEGORY	PREDOMINANT ROCK MASS TYPES AND GSI DESCRIPTIONS	OBSERVED OR ANTICIPATED ROCK MASS BEHAVIOR	
			PREDOMINANT	SECONDARY
<b>2b</b>	<b>IIB</b>	Tsp: BLOCKY/DISTURBED/SEAMY ROCK MASS STRUCTURE AND POOR TO FAIR DISCONTINUITY SURFACE CONDITIONS	PREDOMINANT GROUND BEHAVIOR CONSISTS OF:  • DISCONTINUITY-CONTROLLED BLOCK FAILURES	SECONDARY BEHAVIORS INCLUDE:  • RAVELING • SHALLOW SHEAR FAILURE • SLAKING • SOFTENING • SWELLING
		Tss-1: BLOCKY/DISTURBED/SEAMY TO VERY BLOCKY ROCK MASS STRUCTURE AND POOR TO FAIR DISCONTINUITY SURFACE CONDITIONS		
		Tcs-2: BLOCKY/DISTURBED/SEAMY TO VERY BLOCKY ROCK MASS STRUCTURE AND FAIR DISCONTINUITY SURFACE CONDITIONS		
		Tc-1: VERY BLOCKY ROCK MASS STRUCTURE AND FAIR DISCONTINUITY SURFACE CONDITIONS		
		Tc-2: BLOCKY/DISTURBED/SEAMY ROCK MASS STRUCTURE AND FAIR DISCONTINUITY SURFACE CONDITIONS		
		Tc-3: VERY BLOCKY ROCK MASS STRUCTURE AND FAIR DISCONTINUITY SURFACE CONDITIONS		
		Tc-4a: DISINTEGRATED TO BLOCKY/DISTURBED/SEAMY ROCK MASS STRUCTURE AND FAIR DISCONTINUITY SURFACE CONDITIONS		
		Tc-4b: DISINTEGRATED TO BLOCKY/DISTURBED/SEAMY ROCK MASS STRUCTURE AND FAIR DISCONTINUITY SURFACE CONDITIONS		
		Tor-3: BLOCKY/DISTURBED/SEAMY ROCK MASS STRUCTURE AND POOR TO FAIR DISCONTINUITY SURFACE CONDITIONS		

FIGURE 5. Example of support category selection criteria

ADDITIONAL SUPPORT - APPLICATION CRITERIA AND MEASURES				CONTINGENCY MEASURES REQUIRED	
DISPLACEMENT WARNING LEVEL AND OBSERVATIONS OF SUPPORT PERFORMANCE	ADDITIONAL SUPPORT FOR WARNING LEVEL AND OBSERVATIONS OF SUPPORT PERFORMANCE	OBSERVED LOCAL ROCK MASS CONDITIONS AND ANTICIPATED BEHAVIORS REQUIRING ADDITIONAL SUPPORT	ADDITIONAL SUPPORT FOR OBSERVED CONDITIONS	ALARM LEVEL	OBSERVED CONDITIONS
RADIAL DISPLACEMENT: 50  CRACKS IN SHOTCRETE	ADDITIONAL FAST SETTING CEMENT GROUTED ROCK DOWELS.  APPLY ADDITIONAL FRS (+51) TO INITIAL LINING.	DISINTEGRATED ROCK MASS WITH POOR INTERLOCKING.  BEHAVIORS: RAVELING (FAST)	4000 LG GROUTED SPILES AND LATTICE GIRDERS AS REQUIRED.	RADIAL DISPLACEMENT: 70	CRACKS WITH OFFSET GREATER THAN 3 mm, OR WITH AN OPENING GREATER THAN 1.5 mm APPEAR IN SHOTCRETE
		DISCONTINUITIES FORM UNSTABLE BLOCK AT TUNNEL FACE (APPLIES TO SUPPORT CATEGORY IIB ALTERNATIVE 1)  BEHAVIORS: DISCONTINUITY CONTROLLED BLOCK FALURES	APPLY LOCAL FIBERGLASS FACE DOWELS (25 DIA, 6000 LG) AND FRS (+51) TO FACE AS REQUIRED.		
		PORTIONS OF SLOPING CORE EXHIBITS RAVELING/SHALLOW SHEAR FAILURE BEHAVIORS. (APPLIES TO SUPPORT CATEGORY IIB ALTERNATIVE 1)	APPLY FRS (+51) AND FIBERGLASS FACE DOWELS (25 DIA, 6000 LG) TO SLOPING CORE AS REQUIRED.		

FIGURE 6. Example of additional support application criteria

## Roles and Responsibilities

The roles and responsibilities for monitoring of the tunnel performance and support selection are detailed in the technical specifications. The contractor is required to collect monitoring bolt data within 6 hours after installation in the last excavation round, and provide data and interpretations to the engineer within 12 and 24 hours, respectively, after taking readings. The engineer’s role is to evaluate the information provided by the contractor in making independent assessments of support requirements. The contractor and engineer are to make independent assessments of support requirements and performance based on mapping of exposed excavation surfaces, probe drilling results, observations, and evaluations of ground behavior and the monitoring data. Daily meetings (or more as required) between the contractor and engineer are to be used to make decisions on excavation and support requirements. Decisions are as proposed by the contractor and as approved by the engineer.

## CONCLUSIONS

Several aspects of NATM practice in Europe were modified to suit U.S. tunneling practices in developing the design of the excavation and initial support for the Caldecott 4th Bore. The role of ground behavior in NATM support selection was clarified and integrated with the traditional ground condition criteria used for support selection in the U.S. A prescriptive design, including detailed criteria and procedures for construction decisions, was used to develop a biddable contract package while maintaining flexibility for the typical NATM practice of design verification and adjustment based on observations made during construction. Finally, the design was laid out to strike a balance between contractual simplicity and design optimization by minimizing the number of major support categories, subtype support categories, and use of additional support measures.

## REFERENCES

Akai, S., Murray, M., Redmond, S., Sage, R., Shetty, R., Skalla, G., and Varley, Z. 2007. Construction of the C710 Beacon Hill Station using SEM in Seattle—“Every chapter in the book.” In *2007 RETC Proc.*, Toronto, Ontario, Canada, June 10–13. Littleton, CO: SME.

Amini, M., John, M., Sander, H., and Wang, Y.N. 2005. Geotechnical design of Devil's Slide Tunnel. In *2005 RETC Proc.*, Seattle, WA, June 26. Littleton, CO: SME.

Austrian Society for Geomechanics. 2004. "Guideline for the geomechanical design of underground structures with conventional excavation." Draft English translation.

Field, D. P., Hawley, J., and Phelps, D. 2005. The North American Tunneling Method—Lessons learned. In *2005 RETC Proc.*, Seattle, WA, June 26. Littleton, CO: SME.

Frandina, F.P., Hirsch, D.R., Weeks, C.R., and Field, D.P. 2005. Design of shallow tunnels for Washington Dulles International Airport people mover. In *2005 RETC Proc.*, Seattle, WA, June 26. Littleton, CO: SME.

Halim, I., Vincent, F., and Taylor, J. 2007. NATM Design for Stanford LINAC Coherent Light Source Tunnels. In *2007 RETC Proc.*, Toronto, Ontario, Canada, June 10–13. Littleton, CO: SME.

John, M., Spöndlin, D., Ayadin, N., Huber, G., Westermayer, H., and Mattle, B. 2005. Means and methods for tunneling through highly squeezing ground: A case history of the Strenger Tunnel, Austria. In *2005 RETC Proc.*, Seattle, WA, June 26. Littleton, CO: SME.

Krulc, M. A., Murray, J.J., McRae, M.T., and Schuler, K.L. 2007. Construction of a mixed face reach through granitic rocks and conglomerate. In *2007 RETC Proc.*, Toronto, Ontario, Canada, June 10–13. Littleton, CO: SME.

Madsen, P.H., Younis, M.A., Gall, V. and Headland, P.J. 2007. NATM through clean sands—The Michigan Street experience. In *2007 RETC Proc.*, Toronto, Ontario, Canada, June 10–13. Littleton, CO: SME.

Marinos, V., Marinos, P., and Hoek, E. 2005. The Geological Strength Index: Applications and limitations. *Bull. Eng. Geol. Environ.* **64**, 55–65.

ÖNORM B 2203-1: *Underground Works. Part 1: Cyclic Driving*. Works contract, Issue 2001-12-01.

Phelps D.J., Gildner, J., and Tattersall, C. 2005. Design and risk management strategy for the Sound Transit Beacon Hill Station and tunnels. In *2005 RETC Proc.*, Seattle, WA, June 26. Littleton, CO: SME.

Proctor, R.V., and White, T.L. 1968. *Rock Tunneling with Steel Supports, with an "Introduction to Tunnel Geology" by Karl Terzaghi*. Youngstown, OH: Commercial Shearing and Stamping Company.

Rudolf, J., and Gall, V. 2007. The Dulles Corridor Metrorail Project—Extension to Dulles International Airport and its tunneling aspects. In *2007 RETC Proc.*, Toronto, Ontario, Canada, June 10–13. Littleton, CO: SME.

Thapa, B.B., McRae, M.T., and Van Greunen, J. 2007. Preliminary design of the Caldecott Fourth Bore. In *2007 RETC Proc.*, Toronto, Ontario, Canada, June 10–13. Littleton, CO: SME.

Thapa, B.B., Van Greunen, J., Sun, Y., McRae, M.T., and Law, H. 2008. Design analyses for a large-span tunnel in weak rock subject to strong seismic shaking. In *2008 NAT Proc.*, San Francisco, CA, June 8–11. Littleton: CO: SME.

USBR (U.S. Bureau of Reclamation). 1998. *Engineering Geology Field Manual*, 2nd Ed., U.S. Washington, D.C.: Government Printing Office.

## **ACKNOWLEDGMENTS**

The authors would like to acknowledge AMEC (Geomatrix Consultants) for its work on the site geology and Marlène Villeneuve of Jacobs Associates for her work on the ground behavior figures. The contents of this paper were reviewed by the State of California's Business, Transportation and Housing Agency; the California Department of Transportation; and the Contra Costa Transportation Authority. The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the State of California or the Contra Costa Transportation Authority. This paper does not constitute a standard, specification, or regulation.