Geotechnical and Design Challenges for TBM Selection on the ICE Tunnel

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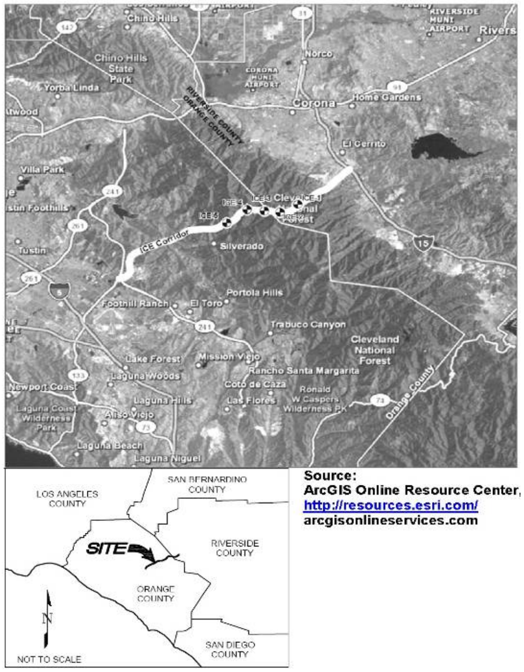
ABSTRACT

The Irvine-Corona Expressway (ICE) tunnels consist of two 16.0-m-diameter (52.5-ft) road tunnels and, potentially, one rail tunnel extending 17.4 km (11.5 miles) between Riverside and Orange counties in Southern California. The purpose of the tunnels is to relieve traffic congestion along the SR-91 corridor.

Among the geotechnical challenges are variable and poor quality ground conditions, including weak, highly fractured rock, numerous fault and shear zones, high groundwater pressures, potential for gassy ground conditions, and a corrosive groundwater environment. Other significant challenges include protection of sensitive groundwater resources in the Cleveland National Forest. This paper discusses some of the results of the feasibility study recently completed for the project with a focus on tunnel boring machine (TBM) selection.

INTRODUCTION

The Irvine-Corona Expressway (ICE) is a transportation corridor including tunnels and surface roads proposed between Interstate-15 near Cajalco Road in Corona and the interchange of the SR-133 and SR-241 toll roads in Irvine, California (See Figure 1). The tunnels evaluated in this study include highway and rail tunnels approximately 17.4 km (11.5 miles) long through the metamorphic and sedimentary rock formations of the Santa Ana Mountains separating Riverside and Orange counties. The ICE Tunnel Study considered highway and



Source:
ArcGIS Online Resource Center,
http://resources.esri.com/
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Figure 1. ICE Tunnels and Coreholes, Location Map

rail configurations relieving traffic congestion on the SR-91 through Santa Ana Canyon. According to California transportation authorities, traffic is projected to grow so much between now and 2030 that the SR-91 highway would have to expand from 12 lanes to 22 lanes in order to handle the increased demand. The highway tunnels, if constructed, are expected to remove roughly 60,000 to 70,000 average daily trips (ADT) from SR-91.

Funding for the ICE Tunnel feasibility evaluation was secured through the Safe, Accountable, Flexible, Efficient Transportation Equity Act—Legacy for Users (SAFETEA-LU). This paper summarizes both the geotechnical conditions to be encountered by the tunnels and the challenges posed to tunnel construction and tunnel boring machine (TBM) selection.

TUNNEL CONCEPTS CONSIDERED

Several tunnel concepts were evaluated, including a deep tunnel concept and a second concept that consists of a combination of surface roads and tunnels. The combined surface road/ tunnel concept is likely to present significant environmental challenges since the surface roads and associated construction activities would take place in the Cleveland National Forest and on nearby Irvine Ranch Conservancy land. Although this concept might be technically possible, it does not seem to be a viable approach at this time.

The deep tunnel concept considered four different tunnel configurations:

1. Twin-bore highway tunnels connected by emergency cross passages
2. A single two-lane reversible direction highway tunnel paired with a single track rail tunnel connected by emergency cross passages
3. Staged construction of twin-bore, two-lane highway tunnels paired with a single track rail tunnel connected by emergency cross passages, with the second highway tunnel being constructed at a later date
4. Three single-lane highway tunnels, two dedicated to one-way traffic and one reversible, all connected by emergency cross passages

This paper will focus on the third configuration, as shown in Figure 2, which includes twin-bore, two-lane highway tunnels (the second highway tunnel to be constructed at later date) and one rail tunnel, each with a total length of approximately 18.5 km (60,000 ft, or 11.5 miles). These tunnels would be connected to I-15 to the east and the SR-241/SR-133 interchange to the west by relatively short sections of surface highway. Each of the two or three tunnels would have two portals. The tunnel plan and profile are shown in Figures 1, 3a, and 3b.

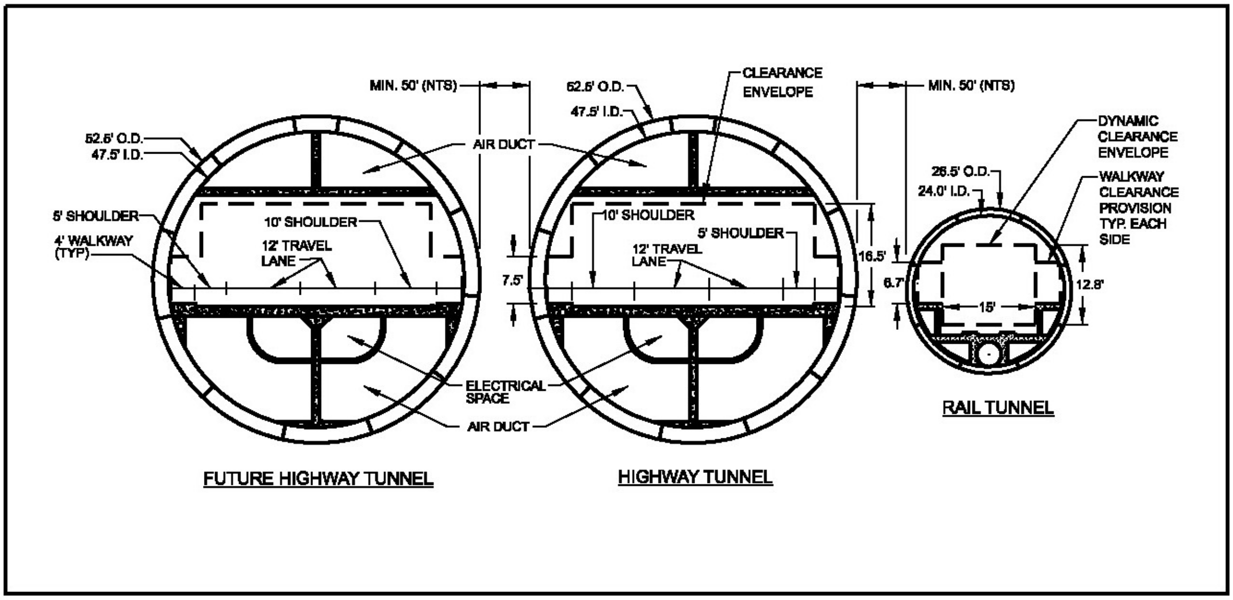

Figure 2. Tunnel Configuration

The twin-bore tunnels start at an approximate elevation of 204 m (670 ft) above mean sea level (msl) at the West Portal and reach a maximum elevation of 649 m (2,130 ft) msl at approximately Station 510+00; the tunnels end at an approximate elevation of 515 m (1,690 ft) msl at the East Portal. The tunnel grade varies along the alignment and ranges from 0.1% to 5.0% (although inclusion of a rail tunnel in the project will likely limit the maximum grade to 3%). The ground cover above the tunnels ranges from a minimum of 6.1 m (20 ft) at Station 25+00 to a maximum of 408 m (1,340 ft) at Station 440+00. The minimum tunnel cover under the major canyons and creeks is approximately 15.2 m (50 ft).

Tunnel size exceeds 15.2 m (50 ft) in diameter, based on Caltrans clearance requirements for a highway tunnel of this length. Assuming two 3.7-m-wide (12-ft) traffic lanes in each bore and 1.5 and 3 m (5 and 10 ft) wide shoulders plus two 1.2 m (4-ft) walkways, a finished tunnel diameter (ID) of approximately 14.5 m (47.5 ft) is required for the project (Kleinfelder 2009b). Clearances for the rail tunnel indicate that a finished tunnel diameter of 7.3 m (24 ft) is required for a single track tunnel. These preliminary clearances have been adopted for the feasibility study, and they will be revisited in more detailed design studies for the project.

REGIONAL GEOLOGY

The Santa Ana Mountains are the northern portion of the crystalline bedrock Peninsular Ranges that extend south into Mexico. The northeast side of the Santa Ana Mountains forms a steep scarp that rises from the Elsinore and Temescal valleys along the active Elsinore fault zone. The western side of the Santa Ana Mountains is less abrupt and slopes down to the Santa Ana Plain (see Figure 3a). The core of the Santa Ana Mountains consists of Mesozoic metasedimentary and igneous rocks that are flanked on the west by younger Late Cretaceous and Tertiary-aged clastic sedimentary rocks (see Figure 3b). The dip of strata in the eastern part of the Santa Ana Mountains is generally steep and to the east along the tunnel corridor (50 to 70 degrees) but is sometimes near vertical and locally overturned. The bedding dips of the western sedimentary strata are gentler, about 15 to 30 degrees, generally dipping to the west, although several anticlines and synclines have been mapped within the western strata (Schoellhamer et al. 1981).

The Santa Ana Mountains contain numerous faults and folds that generally trend northwest-southeast, parallel to the strike of the Tertiary sedimentary strata. The majority of the mapped faults demonstrate a down-to-the-west displacement (Schoellhamer et al. 1981), although the Elsinore fault, which is the dominant structural fault in the area, demonstrates secondary down-to-the-east displacement (i.e., thousands of feet). The predominant structural displacement along the Elsinore fault is right-lateral strike-slip displacement (i.e., tens of miles). The eastern tunnel portals have been strategically placed west of the Elsinore fault to avoid potential fault displacement across the tunnel.

SEISMICITY

The Elsinore fault forms the eastern boundary of the Santa Ana Mountains. At its northern end, the Elsinore fault splays into two branches, the Chino fault and the Whittier fault. The maximum magnitude of an earthquake on the Elsinore fault is estimated to be M7.1 (Cao et al. 2003). There has only been one large earthquake on the Elsinore fault during historical times: the earthquake of 1910, an M6 near Temescal Valley, which produced no known surface rupture (SCEDC 2008). During the field investigations of this study, the M5.4 Chino Hills earthquake occurred on July 29, 2008, on a suspected “blind thrust fault” beneath the Puente Hills 25.7 km (16 miles) north of the site.

FEASIBILITY-LEVEL FIELD INVESTIGATION RESULTS

The purpose of the feasibility-level field investigations was to evaluate geotechnical and hydrogeological conditions in the interior of the Santa Ana Mountains, where rock and groundwater conditions are least known. Therefore, the investigations focused on the eastern half of the ICE tunnel corridor, where high groundwater pressures and high overburden pressures are expected to define the most difficult design and construction challenges. The geologic setting and geotechnical condition of the sedimentary formations at the western end of the tunnel has been interpreted from the literature and other available geotechnical data.

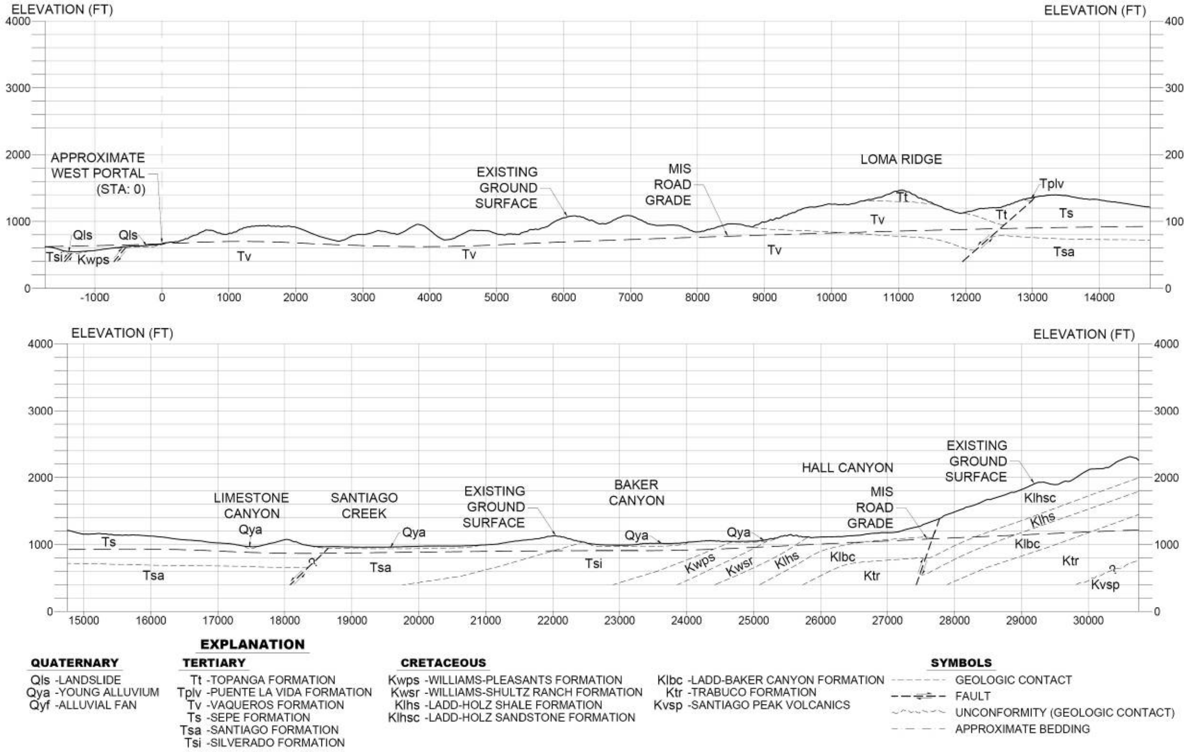

Figure 3a. West Profile

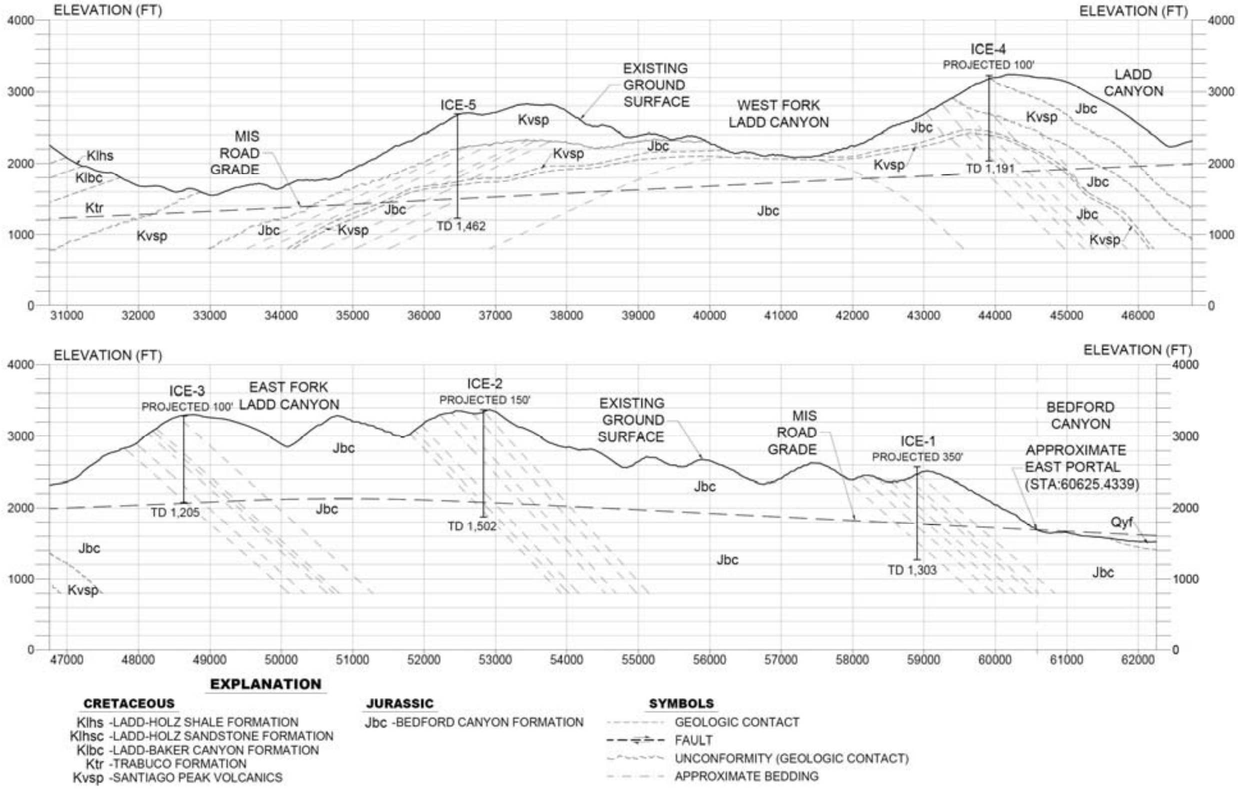

Figure 3b. East Profile

The field investigations involved five deep coreholes (ICE-1, ICE-2, ICE-3, ICE-4 and ICE-5) completed at select sites along the ICE corridor (see Figure 1). The geotechnical data collected include continuous rock core (2,057 m [6,750 ft]); in situ geophysical logs; in situ hydraulic testing; and laboratory test data on rock samples.

In ICE-1, ICE-2, and ICE-3, the rock mass is composed of the Bedford Canyon Formation (see Figure 3b), which is a sedimentary flysch deposit consisting of alternating sandstone, argillite, pebbly mudstone, pebble conglomerate, mudstone, and shales that have undergone low-grade metamorphism followed by extensive shearing. In ICE-4 and ICE-5, the Bedford Canyon Formation has been locally intruded by the Santiago Peak Volcanics, a suite of volcanic and shallow plutonic igneous rocks that consist of basalt, andesite, diorite, and volcaniclastics that have also undergone low-grade metamorphism (see Figure 3b).

Data from vibrating-wire piezometers installed in the coreholes indicate that groundwater pressures at the tunnel invert range from 0.7 to 2.2 MPa (6.7 to 21.3 bar) after a year of equilibration. These pressures are less than expected, as a constant hydrostatic pressure gradient from the shallowest groundwater elevation to tunnel depth would result in pressures of 3.4 MPa (33.3 bar). Lower pressures are advantageous for tunneling and tunnel lining design; however, peizometer readings may vary seasonally, and long-term monitoring is required to confirm these initial findings.

The RQD values for 2,057 m (6,750 ft) of core do not exhibit a strong dependency upon lithology or depth (see Figure 4). Observed trends in the RQD do change considerably with corehole location, however. For example, at ICE-1, ICE-2 and ICE-3, approximately 90% of the RQD values are less than Fair (RQD <50), compared with 44% and 37% of the RQD values from ICE-4 and ICE-5, respectively, being less than Fair. Over 42% of the RQD values are Poor (RQD <25), irrespective of lithology or location.

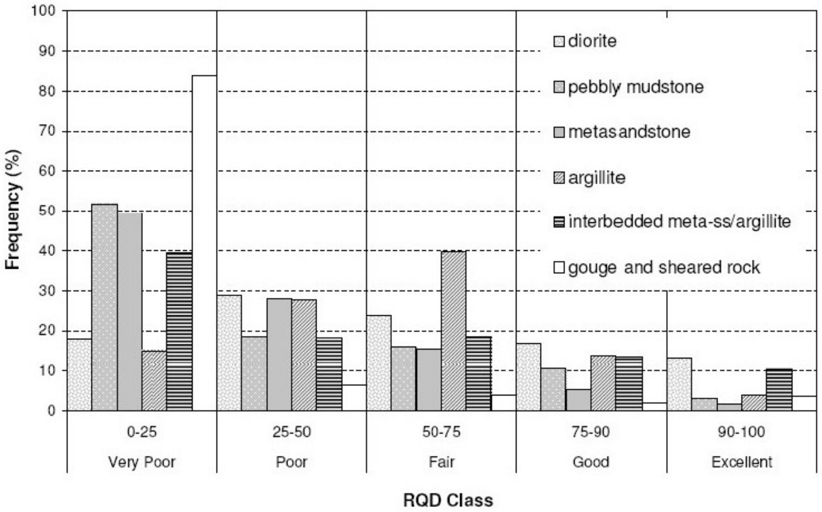

Figure 4. RQD vs. Rock Lithology

Data from laboratory tests (Unconfined Compression, Brazilian Tensile tests) and field tests (point load index) of rock core indicate a wide range of intact rock strengths for both the Bedford Canyon Formation (Jbc) and the Santiago Peak Volcanics (Kvsp). The Bedford Canyon metasandstone ranges from moderately strong to extremely strong (25 to >250 MPa [3,500 to >35,000 psi]). The interbedded metasandstone and argillite ranges from weak to very strong (5 to >100 MPa; 750 to >15,000 psi). Strengths of the pebbly mudstones of the Bedford Canyon Formation ranges from very weak to moderately strong (1 to 50 MPa [150 to 7,500 psi]). The intact strength of the Santiago Peak Volcanics (diorite) also ranges widely from moderately strong to very strong (25 to 250 MPa [3,500 to 35,000 psi]). No testing of the sedimentary formations in the West Tunnel Segment was conducted under this study, but formations are estimated to range from extremely weak (e.g., shales) to moderately strong (shales, sandstone, and conglomerate) based on general lithology and strength-test results on rock cores from nearby projects (i.e., Bowerman Landfill and SR-241 Toll Road).

Rock mass classification systems indicate generally poor rock conditions for tunneling in the Bedford Canyon Formation and the Santiago Peak Volcanics, as suggested by RMR, Q, and GSI indicators. From 9,315 calculated RMR values, the rock mass character can be described as Poor to Fair rock, with more than 85% of the RMR values within the ranges defined by these two categories ($21 < RMR < 60$) (see Figure 5). From 3,056 calculated Q values, nearly 84% of the Q values occur in the Extremely Poor to Very Poor ($0.004 < Q < 1$) rock mass classes (see Figure 5). Figure 6 illustrates RMR versus Q values for the rock within the tunnel envelope only (15.2 m [50 ft] envelope). Nearly 83% of the GSI values for the entire rock core are less than Fair ($GSI < 41$) (see Figure 5).

The in situ hydraulic conductivity testing (i.e., packer testing) indicates that effective hydraulic conductivities at the ICE Tunnel envelope depths are on the order of 2.5E-05 cm/sec (Corehole ICE-1 between 198.7 and 228.8 m [652.1 and 750.6 ft] beneath ground surface [bgs]) to 2.9E-08 cm/sec (Corehole ICE-5 at 328.5 to 352.9 m [1,077.9 to 1,157.9 ft] bgs). The data suggest low groundwater inflows during tunneling in the Bedford Canyon Formation and the Santiago Peak Volcanics, although localized higher inflows should be expected.

Groundwater Conditions

Potentially adverse geochemistry of the Bedford Canyon Formation includes an abundance of sulfides, including pyrite, marcasite, and chalcopyrite yielding hydrogen sulfide gas noticeable during field exploration. Additionally, field testing of water samples from two mountain springs yielded pH readings as low 2.8 and 3.5; however, the majority of readings are in the neutral pH range.

Geologic Profile

The ICE Tunnels have been subdivided into a West and East Tunnel Segments based upon the anticipated geologic and groundwater conditions (see Figures 3a and 3b).

West Tunnel Segment (Sta 000+00 to 322+00)

The West Segment of the ICE Tunnels is anticipated to be located in sedimentary rocks that consist of shale, sandstone, and conglomerate that are estimated to be extremely weak to moderately strong and under moderate hydrostatic pressure 0 to 0.5 MPa (0 to 5 bar), with most below 0.3 MPa (3 bar). The geologic and hydrogeologic conditions along the West Segment corridor are expected to be fairly uniform but with local shearing along bedding and at a few mapped fault zones. When tunneling through the West Segment, the ground is expected to be slow to fast raveling because many of these geologic formations are anticipated to be soft or weakly cemented. Some of the formations may exhibit soil-like behavior during tunneling, and flowing conditions could be encountered in isolated areas where the sedimentary formations are uncemented and the tunnel is below groundwater. The potential for groundwater inflows generally ranges from low to moderately low on the basis of the anticipated rock types.

According to published geologic maps (Schoellhamer et al. 1981) three fault traces have been identified. Squeezing ground conditions could be associated with these faults because the rock mass is weakened significantly. Also, groundwater inflows can be high in fault zones because of the increase in fracturing typically associated with fault activity.

East Tunnel Segment (Sta 322+00 to 602+25)

The East Segment runs through the core of the Santa Ana Mountains, and at tunnel depth is expected to encounter igneous and sedimentary to metasedimentary rocks under potential hydrostatic pressures up to 2.1 MPa (21 bar). Ground conditions are inherently variable in terms of lithology and composition. Some lithologies are extremely weak, while others have intact rock strengths that are extremely strong. Ground conditions are expected to range from massive to blocky and seamy to raveling. Potential squeezing conditions are expected in sheared and fault zones where the overburden is thick, and interbeds where the rock mass is predominantly argillite or pebbly mudstone.

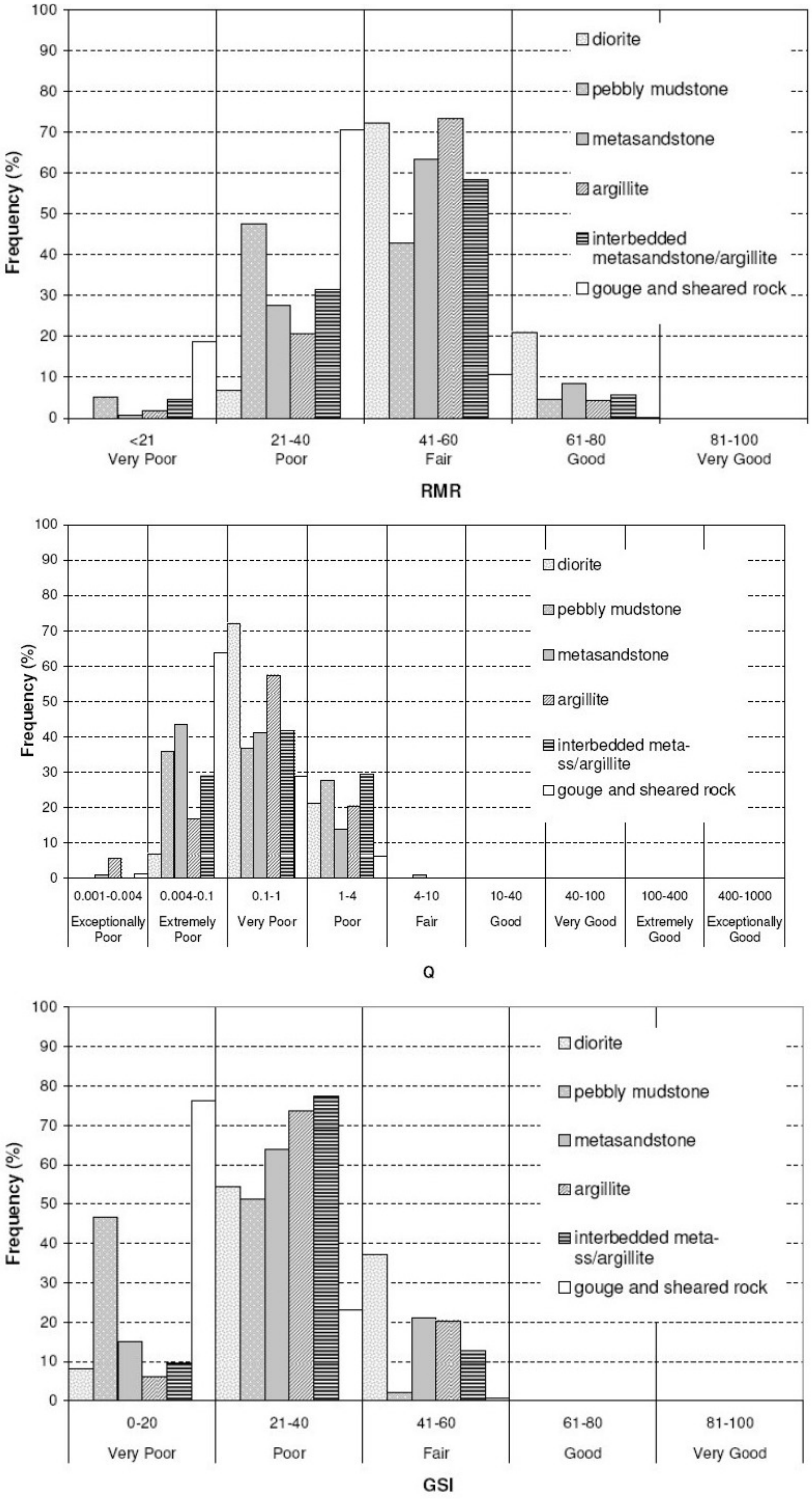

Figure 5. RMR, Q, and GSI by Lithology

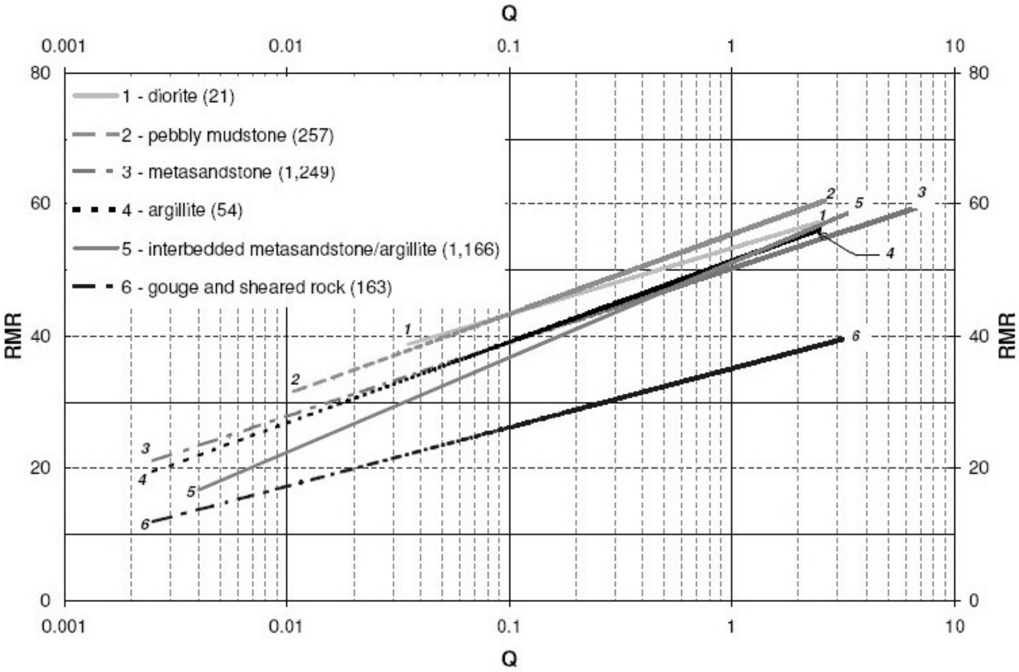

Figure 6. RMR vs. Q

PROJECT CONSTRUCTION CHALLENGES

The entire study area crosses a complex geologic zone with variable ground conditions ranging from sedimentary rock under relatively low groundwater pressures in the west to volcanic and metasedimentary rock under high groundwater pressures to the east. Potential design and construction challenges that are related to the geotechnical conditions include:

- Variable and difficult ground conditions
- High external water pressures
- Gassy ground
- Corrosive groundwater

Other significant design challenges include lining design and protection of groundwater resources.

Variable and Difficult Ground Conditions

Because of the potentially long tunnel lengths, a broad range of ground conditions may be encountered along the tunnel alignments. A particularly undesirable condition is a mixed face condition where the face is in both rock and soft ground or several materials of widely differing density and hardness. However, a given TBM will generally perform optimally in a relatively narrow range of ground conditions. If the rock has very high strength, the TBM may be designed for efficient mining of the strong rock, but will be less effective in mining poor quality rock. The opposite can also be true. For the ICE tunnels, the overall best performance may be achieved by tailoring the TBM to address the intensely fractured rock conditions that are currently estimated to comprise at least 53% of the alignment in the metamorphic terrain (approximately 9.7 km [6 miles]).

To overcome these challenging ground conditions and behaviors, the TBM should be designed with these considerations:

- The muck handling should be compatible with high water inflows and weak ground, and be able to efficiently collect the material under all conditions.
- The TBM should have exceptional thrust capacity to overcome high ground loads or muck-packing conditions.

- The cutterhead should be able to limit or control the flow of material through the head (both from the outside through the head or out of the head) and aid in maintaining face support under weak ground conditions.
- The TBM should be able to maintain line and grade in variable ground, including weak ground, and in curves.
- In squeezing ground conditions, special design provisions should be included, such as increasing the overcut, lubricating the TBM shield skin, reducing the TBM shield length, using a tapered shield, limiting TBM stops at critical stations, monitoring tunnel deformation and earth pressure, and having the ability to flush out material from the annulus back towards the cutterhead.

Technological advancements and additional practical experience with hybrid-style TBMs may eventually improve the performance of the TBM for the anticipated conditions of the ICE project.

High External Water Pressures

The maximum groundwater head is expected to be in excess of 2 MPa (20 bar). Excavating a tunnel under pressures of this magnitude presents health and safety hazards as well as challenges in designing a machine and initial lining to withstand the pressure. While tunneling under pressures of 0.4 MPa (4 bar) is routinely performed, pressures in excess of 0.5 MPa (5 bar) for this size of excavation will require state-of-the-art techniques. It should be noted that it would not be possible to operate a TBM with a closed, pressurized face under such high water pressure, as the machine could not be pushed forward against such pressure. The current concept is that the tunnels would be mined using a slurry TBM. Under this concept, in areas of lower groundwater pressure the heading area would be pressurized to control the potential water inflows and the primary lining would be erected and grouted in place within the rear of the TBM.

Recognizing that water inflow through some fractures, faults, and shear zones could potentially exceed the TBM's capacity to control water inflows, the TBMs will have to incorporate provisions to perform systematic probing (i.e., drilling ahead of the advancing TBM), and pre-excavation grouting ahead of the TBM. Systematic probing ahead of the tunnel face with probe holes will be required along the tunnel alignment where significant inflows may occur in order to mitigate the risk of encountering high flush flows that might exceed the water handling capacity of the TBM. Probing may also be used to detect areas of weak, unstable ground. When these conditions are found, TBM operation procedures may be modified or pretreatment may be warranted. Various methods can be employed to alter the operation of the TBM, such as closed or pressurized mode, to enhance its compatibility with unfavorable water or ground conditions. Pretreatment may include reducing the driving head through drainage of the groundwater to reduce impacts on the tunneling operations, or performing pre-excavation grouting ahead of the TBM. To sufficiently treat the problem areas ahead of the tunnel, the TBM will need to have a sufficient number of ports (openings) around the circumference of the machine to facilitate drilling grout holes ahead of the face. Alternative access ports through the TBM shield or concrete segments further back from the face facilitate treatment of the rock mass surrounding the TBM or immediately at or ahead of the tunnel face. Having an enhanced level of accessibility adds flexibility and options to the treatment of groundwater and ground behavior problems.

Interventions will need to be performed both routinely (planned interventions) and when the progress of the TBM is slower than expected (due to worn cutters). To access the cutterhead for maintenance while tunneling in closed mode, the interventions will need to be performed under free air, compressed air, or a mixed-gas environment.

In locations where interventions need to occur under high pressures (e.g., blocky and seamy and crushed rock , sheared or faulted ground with high permeability), compressed air and/or mixed gas may be required; however, for interventions under high head in rock, the rock should be stable enough for the performance of interventions in free-air. Additionally, ground improvement methods could be employed to reduce or eliminate the need for compressed air by making the surrounding ground more stable. Depending on the pressures expected, the TBM may need to be fitted with a decompression chamber.

Corrosive Groundwater

During the groundwater monitoring program water samples were chemically tested, and two spring/stream monitoring sites in the middle fork of Ladd Canyon exhibited pH levels of less than 5.5. The results of an acid generation potential test performed during the geotechnical investigation (Kleinfelder 2009a) indicated intrinsic buffering capacity in a composited, sulfide-rich core sample. The buffering capacity is attributable to the neutralizing action of calcite in the rock mass. Therefore, it is anticipated that water collected during the tunnel excavation will have acidic properties along certain portions of the alignment. The corrosion potential of such water should be considered with regards to the design, operation, and maintenance of the TBM; health and safety of the crew; and the design of the ground support systems within the tunnel.

Gassy Ground Conditions

Within the ICE tunnel corridor, the lignitic shales of the Silverado Formation (Tsi) are a potential source of methane gas (see Figure 3a). Methane (CH_4) is the most common gas that occurs within gassy ground, and it is both highly flammable and an asphyxiant. The lower explosive limit (LEL) of methane is 5% by volume, while the upper explosive limit (UEL) is 15% by volume (Kissell 2006). According to the California Code of Regulations (CCR), a methane concentration greater than 0.25% by volume near any surface within the tunnel would warrant a gassy ground classification.

The potential for hydrogen sulfide gas is inferred from several intervals of Santiago Peak Volcanics and Bedford Canyon Formation that contained abundant sulfide metals (i.e., pyrite), and from the strong sulfurous odor noted in the exploration boreholes (Kleinfelder 2009a). Hydrogen sulfide (H_2S) has a strong odor similar to rotten eggs and is both corrosive and toxic. Hydrogen sulfide gas is also combustible, but at concentrations that are much higher than the 0.1% concentration that is toxic (Doyle 2001).

On the basis of the findings from the ICE Geotechnical Report (Kleinfelder 2008), the ICE tunnel corridor will likely be classified as “gassy” or “potentially gassy” ground according to California Occupational Safety and Health Administration (Cal/OSHA) criteria because of the presence of methane and hydrogen sulfide. In these conditions, a slurry TBM would be advantageous since it operates in a “closed circuit,” minimizing workers’ exposure to gas underground. Also, a slurry TBM provides more safety for the expected high pressures, especially in cohesionless ground.

OTHER SIGNIFICANT DESIGN CONSIDERATION

Lining Design

The permanent tunnel lining will need to be watertight in order to avoid any long-term adverse impacts on groundwater levels in the Santa Ana Mountains. The proposed deep tunnels linking Riverside County to Orange County will be constructed using a TBM and will require the installation of a permanent watertight lining to control groundwater inflows into the tunnel. To achieve a watertight lining, a segmental precast concrete lining with gasketed joints will need to be used. Such linings were designed to withstand groundwater pressures up to almost 2.7 MPa (392 psi) for the Arrowhead Tunnels project near San Bernardino (Swartz et al. 2002). A two-pass lining would require an excavated diameter that exceeds the current state of the art design for TBMs.

Soil structure interaction methods were used to develop design concepts for the tunnel linings. The tunnel lining was analyzed at a section along the alignment corresponding to the highest water pressure (approximately 244 m [800 ft]), as well as squeezing ground loads. Lining analyses were performed for 762 mm (30 in.) and 914 mm (36 in.) segment thicknesses. Results of the tunnel lining analyses indicating anticipated lining thickness and concrete strength are summarized in Table 1.

Table 1. Results of Lining Analyses for Roadway Tunnels

Tunnel Reach	Groundwater Head	Concrete Strength	
		762 mm (30 in.) Thick Segment	**914 mm (36 in.) Thick Segment**
0+00 to 323+60	0 to 49 m (0 to 160 ft)	Class I Lining 41.3 to 55.2 MPa (6,000 to 8,000 psi)	Class I Lining 41.3 to 55.2 MPa (6,000 to 8,000 psi)
323+60 to 344+50	0 to 195 m (0 to 640 ft)	Class II Lining 55.2 to 96.5 MPa (8,000 to 14,000 psi)	
344+50 to 540+00	110 to 244 m (360 to 800 ft)	Class III Lining 96.5 to 117.2 MPa (14,000 to 17,000 psi)	Class II Lining 55.2 to 96.5 MPa (8,000 to 14,000 psi)
540+00 to 596+00	104 to 460 m (340 to 460 ft)	Class II Lining 55.2 to 96.5 MPa (8,000 to 14,000 psi)	Class I Lining 41.3 to 55.2 MPa (6,000 to 8,000 psi)
596+00 to 606+25	0 m (0 ft)	Class I Lining 41.3 to 55.2 MPa (6,000 to 8,000 psi)	

Local concrete suppliers indicate that precast concrete with 56- to 90-day unconfined compressive strengths ranging between 89.6 and 96.5 MPa (13,000 and 14,000 psi) are readily achievable and that 117.2 MPa (17,000 psi) is feasible with materials available in southern California. Strengths up to about 137.9 MPa (20,000 psi) are a possibility, but higher quality aggregates from sources outside California may be required. In addition to high-quality aggregates, other key factors in producing high strength concrete include a low water-cement ratio, high-quality cement, additives such as silica fume and super plasticizers to improve workability, and a very high degree of quality control. Premium costs are associated with these high strength concretes. Factoring in the cost of materials, additives, and an increased level of quality control, the cost of 117.2 to 137.9 MPa (17,000 to 20,000 psi) concrete is approximately three times the cost of 41.4 MPa (6,000 psi) concrete, and 96.5 MPa (14,000 psi) concrete is approximately twice as expensive as 41.4 MPa (6,000 psi) concrete.

Protection of Groundwater Resources

The majority of the ICE tunnel alignments will be located beneath the Cleveland National Forest and private lands adjacent to the western forest boundary. In addition, for the most part the proposed tunnels will be constructed beneath the groundwater table. As a result, the tunnels have the potential to drain groundwater from the rock mass, and perhaps adversely affect water resources available to the overlying land. The extent to which drainage may occur during construction will be dependent on the hydraulic conductivity of the rock mass, and also the construction methods used.

At tunnel depth, the rock mass generally is of low to very low hydraulic conductivity, and groundwater flow through the rock mass is generally expected to occur at a very slow rate. This condition is favorable in terms of limiting the potential effects that tunnel construction could have on water resources in the vicinity of the project. Fault, shear, or fracture zones that are present in the rock mass could introduce relatively high water flows into the tunnels, causing significant hazards and/or difficulty during construction. Considering the water head present at tunnel depths, uncontrolled inflows could potentially be in the range of thousands of gallons per minute (gpm).

Pre-excavation grouting is expected to be necessary for tunnel excavations along significant portions of the ICE corridor, in particular along the east portion of the corridor within the Bedford Canyon Formation, and possibly the Santiago Peak Volcanics, where water head in excess of 2 MPa (20 bar) is anticipated at some locations. For the West Segment of the ICE Tunnels, the maximum groundwater head is expected to be substantially less than for the East Segment. Therefore, pre-excavation grouting may not be necessary along this portion of the tunnel alignments if pressurized face TBMs are used that are compatible with the ground and groundwater conditions. The objectives of pre-excavation grouting include minimizing the effects of tunnel excavation on the groundwater resources in the project area to satisfy any special permit requirements, and reducing groundwater inflows into the tunnel to improve ground conditions and facilitate tunnel excavation.

Under the assumption that a TBM will be used to excavate the tunnels, inflows may come from the heading area and through the completed tunnel lining. Therefore, some short-term water ingress will inevitably occur during construction, although this is unlikely to have significant effect on surface groundwater levels, and it is expected that recharge would occur relatively quickly after the tunnel face has passed any given location.

PROJECT STATUS

Constructing the proposed ICE tunnels appears to be geotechnically feasible on the basis of the information collected to date for the project. Many engineering and construction challenges would be encountered, such as variable and difficult ground conditions, high groundwater pressures, and gassy ground conditions. In addition, lining design and protection of groundwater resources are significant concerns. Special design considerations and state-of-the-art practice would be required to overcome these challenges with respect to TBM selection and tunnel construction. Upon presentation of the feasibility evaluation findings, the Orange and Riverside transportation agencies will decide if the project should move forward with additional engineering and environmental investigations. Funding mechanisms for future work are not available at the present; however, public and private partnerships may be explored in 2010.

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