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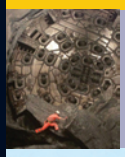

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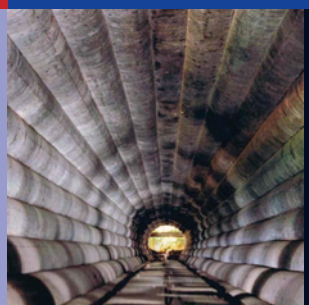

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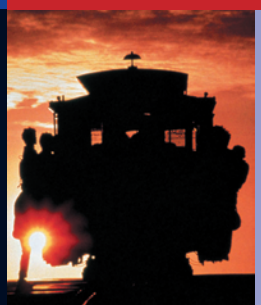

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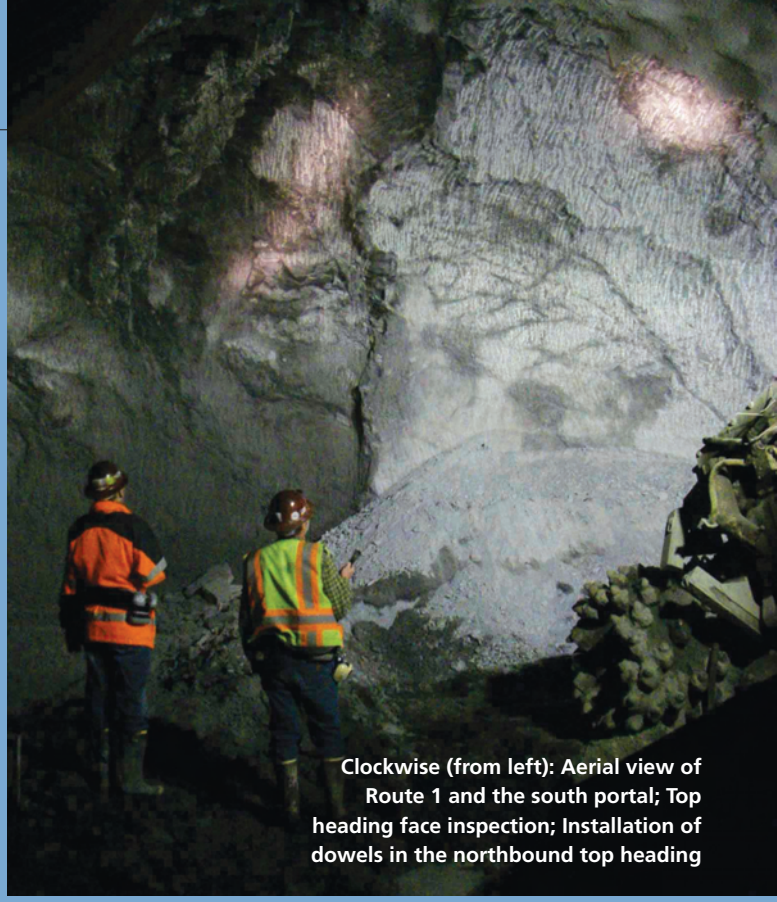


Clockwise (from left): Aerial view of Route 1 and the south portal; Top heading face inspection; Installation of dowels in the northbound top heading

The detail in the DEVIL'S SLIDE

Located on one of the world's most beautiful coastlines, the twin tube Devil's Slide Tunnel is California's first NATM highway tunnel. Dan Zerga, of NATM tunnel designer ILF Consultants, and Sebastian Kumpfmueller, of CM partner Dr Sauer Corp, discuss experiences gained during the design and construction management of the project

LAST OCTOBER, tunnel crews and members of the public alike celebrated as Kiewit broke through on the 4,100ft (1250m) long Devil's Slide twin tube tunnels, in San Mateo County, California. Once complete, the tunnels and two new 1000ft (300m) long bridges will steer California's famous scenic Highway 1 route away from a perilous section of coastline, which is eroding due to harsh winds and the powerful Pacific Ocean. Dubbed by the contractor as "The Best Tunnel Job in America" there is little doubt that the dreamlike ocean scenery of this area is hard to beat. However, when it comes to rock-falls, Devil's Slide is more of a nightmare. On several occasions, landslide damage has been so severe that the road has been closed for long periods while extensive repairs were undertaken. For decades local residents fought for a permanent solution to the problem and ultimately, in 1996, a tunnel bypass was selected.

Project overview

The northbound and southbound Devil's Slide tunnels, which are 4,133ft (1.26km) and 4,035ft (1.23km) long, respectively, pass under the San Pedro Mountain at depths of 650ft (200m). The two 30ft (9m) wide x 22ft (6.8m) high horseshoe shaped openings each house a single traffic lane, plus an emergency shoulder, and are connected every 400ft (120m) via nine 16.5ft (5m) wide x 60ft (18m) long pedestrian cross-passages. A tenth, cen-

trally located, 20ft (6m) wide cross-passage is also provided for access/egress of emergency vehicles. There are two mined equipment chambers situated between the tunnels, at the south portal and at the center of the alignment, with a third cut & cover equipment chamber located between the north portals.

The California Department of Transportation (Caltrans) awarded construction of the project – the state's first highway tunnel since the third bore of the Caldecott Tunnel opened in 1964 – to Kiewit Infrastructure West on January 3, 2007, at a bid price of $273 million. Due to the complex and highly variable ground conditions along the alignment, the New Austrian Tunneling Method (NATM) was specified for construction. As this was the first time a California highway tunnel had been designed using the NATM method, American and European tunnel engineers led a coordinated team design effort.

HNTB was the prime and was responsible for the final lining design including mechanical and electrical systems. Subconsultant ILF Consultants was responsible for NATM design of the initial lining and ground support, geohydrology, drainage systems and waterproofing. Kiewit employed Gall Zeidler Consultants to provide specialist NATM construction support. While a joint venture of URS and Dr G Sauer Corporation (DSC) was selected to perform tunnel excavation inspection and scheduling for Caltrans. ILF had a geotechnical engineer on site during construction to assure that the design was properly implemented.

Excavation of the tunnels commenced from the southern portals in November 2007. Depending on encountered ground conditions, two 120-ton Voest Alpine ATM105 roadheaders, a twin-boom Sandvik Axera drilling jumbo and a Terex TE210 excavator, were employed to mine the tunnels in a concurrent top heading, bench and invert sequence. Average advances of 32ft/week (9.8m) were achieved in the northbound tunnel with a best day of 19ft (6m) and week of 75ft (23m). The southbound tunnel had a best day of 22ft (7m), week of 75ft (22m) and averaged 31.5ft/week (9.6m). Excavation progressed ahead of finishing works, which include a drained waterproofing system incorporating a 2mm thick Sikaplan sheet waterproofing membrane installed by Wisko America, and a 13.7in (350mm) cast-in-place concrete lining with two layers of rebar reinforcement. This final lining is cast using custom Ceresola reinforcement gantries and arch forms that facilitate ongoing construction traffic within the tunnel. At the time of writing, these lining works were roughly 68% complete in the northbound tunnel and 66% complete in the southbound tunnel. Installation of mechanical instrumentation and other operational systems had also begun in areas where the final lining was already in place.

Geology

Ground conditions along the Devil's Slide alignment are divided into three distinct geological zones, separated by three inactive faults (Figure 1): The 'South Block' is predominantly massive quartz diorite, locally grading to granodiorite, with irregular quartz and felsic dikes; the 'Central Block' comprises thick interbedded layers of massive marine sandstone, conglomerate, and clay-siltstone; while the 'North Block' consists of thin bedded interlayered fine-grained marine sandstone and clay-siltstone, with lenses of sandy conglomerate. The North Block is disturbed by a wide shear zone consisting of steeply south-dipping planar zones of fault gouge.

Fault A, in the South Block, is an internal feature within the granitic rock and dips at a shallow angle to the north. Fault B dips moderately to the north near the center of the tunnel, where the overburden is greatest, and forms the boundary between the crystalline bedrock and the overlying sedimentary rocks. While the steeply dipping Fault C separates the Central Block from the North Block.

Aside from the portal areas, the groundwater table lies above the tunnel. However, the groundwater level disconnects by about 330ft (100m) in the vicinity of Fault B, indicating the fault acts as a groundwater drain. Major groundwater migration paths include fractured fault zones and contact surfaces between different formations and different materials within the formations.

During initial investigations, a horizontal borehole drilled from the north portal through the shear zone resulted in a significant increase of water inflow, from 0.5 to 2 gallons/sec (2 to 8 liters/sec), where the borehole intersected Fault C; indicating this fault behaves as a groundwater barrier.

Lining design

Rock mass characteristics of the geology along the alignment[1] were grouped based on factors such as lithology, properties of intact rock and rock discontinuities. For each of the 10 rock mass categories defined for the project, rock mass parameters – such as compressive strength and deformability – were derived. The boundary conditions of the tunnel excavation were then evaluated to determine rock mass behavior, including potential failure mechanisms. Among the parameters considered were the virgin (primary) stress field, groundwater conditions, orientation of the tunnel opening in relation to the rock mass structure and the dimensions/geometry of the excavation opening.

Fig 2: Geotechnical design flowchart

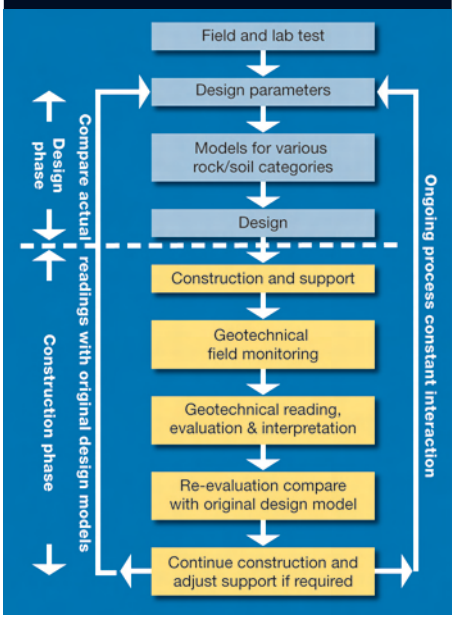


Fig 1: Longitudinal cross section with geological conditions and core hole locations; the vertical white lines indicate where analyses were conducted for the three models used for the geohydrology study

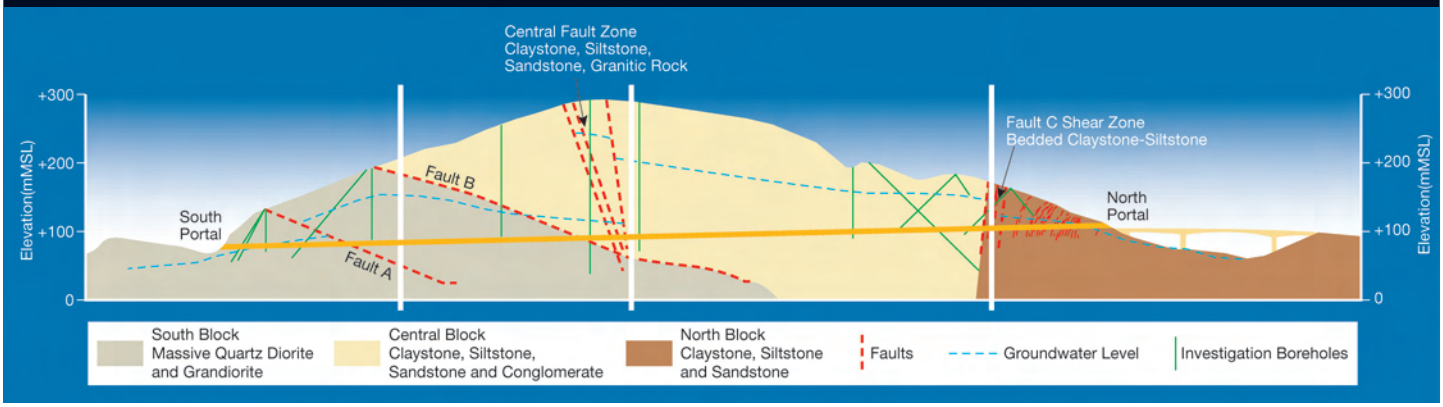


Table 1: Toolbox Items for top heading excavation

Support Category	Typical Advance	Initial Lining Thickness	Length of Rock Dowels	Spacing of Lattice Girders	Spiles and Canopy	Length of Face Dowels	Face Flash Thickness
I	2.2m	100mm	3.6m	n/a	n/a	n/a	n/a
II	1.6m	200mm	4m	1.6m	n/a	n/a	n/a
III	1.2m	250mm	6m & 4m	1.2m	4m	n/a	n/a
IV	1.0m	300mm	6m & 4m	1m	4m	n/a	50mm
V	1.0m	300mm	4m	1m	Canopy pipes	9m	100mm

Failure mechanisms were separated into the following failure modes: Failure of rock blocks; fracturing induced by stresses and/or discontinuities; progressive failure induced by stresses; failure induced ahead of tunnel face; and failure of tunnel face (face stability). Depending on the potential failure mode, key block theory, Finite Element (FE) and slope stability models, were then used to analyze and define five individual support categories for the tunnels (Table 1). For cases of potential rock mass failure, initial lining deformations were calculated for each of the relevant support categories. Expected lining deformations, tolerances for initial lining deformation and construction tolerances were all defined.

A geotechnical monitoring program was devised to ensure verification of the designed support categories during construction. This included monitoring and observation of the behavior of the excavation opening by surveying predefined deformation points; measurement of the rock mass behavior via extensometer; rock dowel performance through measurement devices attached to special dowels; and stress measurement in the shotcrete lining and/or at the interface between the rock mass and the shotcrete lining using pressure cells.

The intent of NATM is to activate the strength of the ground and combine it with the initial support to form a ring-like structure around the perimeter of the tunnel excavation. Rock loading on the initial support system results in deformation of the integrated excavation/lining structure. Tunnel deformations are continually monitored and compared with pre-determined warning levels, thus providing continual verification of analysis results and the opportunity to adjust support measures as required in the field.

It was assumed that the initial lining support will deteriorate over time. The initial support loading, as determined by analysis, was then directly applied to the final lining resulting in a conservative design. The dimensions of the final lining were mainly dictated by the rock and seismic loads. However, fire, traffic and utility loads as well as loads from temperature changes were also considered.

Seismicity was a key factor in design since the project is relatively close to the San Andreas Fault and earthquakes are quite common within the region. For this reason, there are no expansion joints in the final lining and steel reinforcement is continuous along the full length of the tunnels. Additional reinforcement is also installed at all intersections in order to transfer the longitudinal forces from the tunnel lining into the adjacent profiles. Two layers of rebar reinforcement are required for the full length of both tunnels.

Fig 3a: Possible Hazards: Type 1 Failure of Rock Blocks

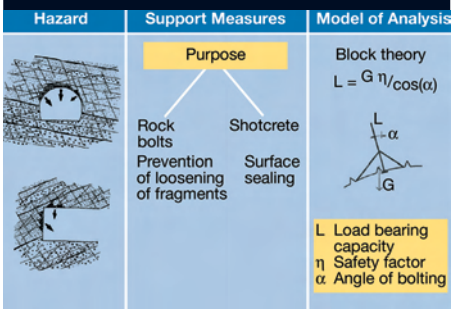


Fig 3b: Possible Hazards: Type 2 Fracturing induced by stresses and/or discontinuities (loosening pressure)

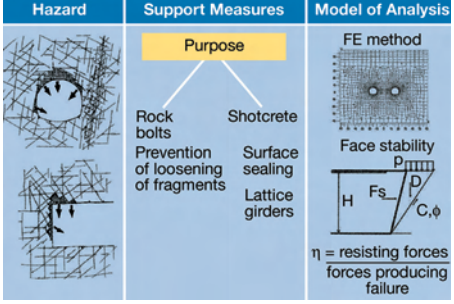


Fig 3c: Possible Hazards: Type 3 Progressive failure induced by stresses

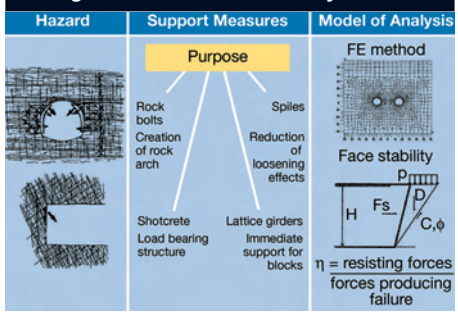
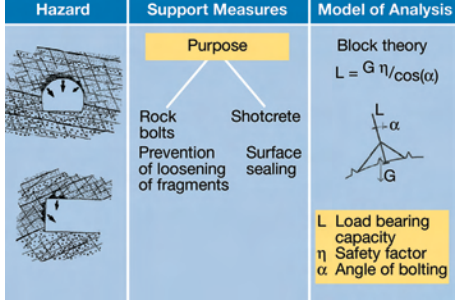


Fig 3d: Possible Hazards: Type 4 Progressive failure induced by stresses ahead of the face



Fiber reinforced shotcrete

The contract specifications for the Devil's Slide Tunnels called for a fiber reinforced initial shotcrete lining but left the use of steel or synthetic fibers to the discretion of the contractor. In this case Kiewit opted to use BarChip54 structural synthetic fibers[2]. A batch plant for shotcrete production was set up on-site, near the south portal, which was of great benefit to the project and is highly recommended to avoid delivery and/or quality problems.

Each excavation advance received an initial flashcrete layer, which was applied to seal the exposed rock and protect miners. The first 150mm (3.9in) layer of shotcrete was applied after the lattice girders were placed. Before the second and final layer was applied, three excavation rounds from the face, rock dowels and other pre-support measures were installed. In CAT I a single layer of shotcrete was applied on bare rock after the rock dowels were installed (Table 2).

Proper curing of the shotcrete and failed toughness tests caused a number of problems at the start of the project. However, thanks to the onsite batch plant – which allowed immediate adjustment of the shotcrete mix – and the contractor's quality management team, who did a great job and pushed for a quick solution, these issues were soon solved. Improving the water temperature at the batch plant and revising dosing programs on the Meyco Potenza shotcrete robot, as well as increasing the fiber content of the shotcrete mix, from 5kg/m^3 to 7kg/m^3, proved necessary adaptations and guaranteed a shotcrete quality throughout the project that far exceeded the contract requirements. In addition to compressive strength testing, the shotcrete

Table 2 : Summary of shotcrete application

Category	Total mm	Flash mm	1st layer mm	2nd layer mm
I	100	0	0	100
II	200	25	150	25
III	250	50	150	50
IV	300	100	150	50
V	300	100	150	50

Right: Successful three-piece break for Round Determinate Panel (RDP) test

Opposite page top: Completing the invert in the northbound tunnel

was required to meet ASTM 1550 Round Determinate Panel (RDP) test requirements[3]. These tests had to be conducted for every 100m³ of material used in the lining. RDP tests are being implemented on more and more projects to test flexural toughness of fiber reinforced concrete. One reason Kiewit chose synthetic fibers over steel fibers was to meet the specified requirement for RDP values in excess of 320 Joules at 40mm deflection at an age of seven days. The RDP testing was carried out at an on-site facility, erected close to the portal, which included a fully air-conditioned curing room to provide a controlled environment for panel production and storage. In order to achieve best results it also proved necessary to have a single individual responsible for the panels from production to testing.

Instrumentation & monitoring

Convergence arrays with optical targets, pressure cells and extensometers were used in combination to monitor rock behavior and deformations during excavation[4]. While data collection from pressure cells mainly assisted design validation and back analysis, the convergence arrays and extensometers were vital instruments for daily excavation and support decisions and for verifying the stability of the structure. Rod-type borehole extensometers with hydraulic bladder anchor and vibrating wire transducer were incorporated at four monitoring sections along the alignment of each tube. These sections were adjacent to the south and center equipment chambers, at the start of the North Block where the weakest ground was expected and near the north portal with the lowest overburden.

The intervals of convergence arrays were determined in the design, based on the ground support categories, but were modified on-site if deemed necessary. A set number of readings were performed daily in the vicinity of ongoing excavation works. Once a week, the NATM team determined the appropriate frequency for the rest of the monitoring sections, which could be daily, weekly or monthly. As per the contract documents, instrumentation warning and alarm levels were defined and established for each ground support category. When instrument readings exceeded warning levels, additional excavation support measures had to be installed and the frequency of monitoring doubled until movements stabilized. If readings exceeded alarm levels, excavation and all associated activities at that location had to be suspended until the contractor proposed measures to stop further movements. Stability of initial shotcrete lining was defined as closure measurement of <0.5mm/day for 10 consecutive days.

Discussion of monitoring data was part of the daily meeting and incorporated in all decisions. Through observation of the ground, for example, it was agreed classification of some locations should be amended from CAT II to CAT III. Convergence results also had a major influence in the elimination of the initial lining invert in these same Category III areas. At the time of placing the inverts, convergence readings indicated the structure, with all the installed support measures and lining in place, was fully stable. All parties therefore agreed invert installation was unnecessary, which resulted in time, cost and material savings.

During excavations, convergence readings were generally less than predicted. Only one section, in the northbound bore between TM 500 and 600, were warning and alarm levels exceeded. The contractor halted excavation works and had the owner evaluate the situation before continuing. Luckily, the convergence only resulted in high deformations and cracks in the initial shotcrete lining, rather than failure or collapse. Following back analyses and additional support measures, the ground was stabilized and excavation continued. A major shear between two ground formations running parallel between the bores is the most likely reason for the unexpected event.

Notable changes

NATM meetings (attended by owner, contractor, construction management and designer) included the review of geologic parameters and monitoring data on a round by round basis. During the course of excavation, the owner agreed to several notable changes in order to avoid additional costs and/or delays. One such change came about due to the high inflows of water encountered during initial geologic probe drilling. A dewatering system was requested for the North Block, comprising three horizontal dewatering drain holes drilled into the fault from the north portal area. One hole drained by gravity, while the other two were slightly inclined and equipped with pumps. In total, more than 10 million gallons of water was drained in order to keep both tunnel headings dry during excavation through the difficult shear zone.

Another change was in relation to cross-passage #8. While nine of the cross-passages are designed for pedestrian use, cross-passage #6 at TM 700 is wider to allow access/egress of emergency vehicles once the tunnels are operational. During excavation the contractor utilized this cross-passage to move construction equipment between the two bores, which allowed concurrent operations such as final lining or invert arch construction, while maintaining excavation activities that required mucking out. When excavation expectedly slowed in the North Block's poorer rock conditions, subsequent final lining operations were expected to catch up and would have come to a halt at cross-passage #6, which had to stay accessible for excavation traffic. Instead, it was decided cross-passage #8 at TM 950 should be expanded to permit the contractor to continue moving vehicles between tunnels. This cross-passage will be backfilled later and restored to its original size.

Another change related to the North Equipment Chamber. The excavation and support of the northbound tunnel in the North Block was designed on the assumption that total backfill of the portal cut & cover structure would be completed. This backfill was to provide support of the vertical wall where the North Equipment Chamber is located, which extends about 165ft (50m) back from the end of the northbound tunnel. However, the top heading excavations in both bores reached the North Block before backfill was in place and potential delays became a concern.

In order to progress the excavation, Caltrans requested that ILF and DSC provide alternatives for continuation of the northbound bore

Table 3: Equipment use per category

Northbound tunnel equipment use				Southbound tunnel equipment use			
	D&B	Roadheader	Excavator		D&B	Roadheader	Excavator
CAT I (273.5m)	79%	21%		CAT I (237.3m)	89%	11%	
CAT II (597.5m)		99%	1%	CAT I (237.3m)	7%	90%	3%
CAT III (249.5m)		48%	52%	CAT III (245.3m)		20%	80%
CAT IV (86.5m)		30%	70%	CAT IV (43.9m)			100%
CAT V (55.0m)			100%	CAT V (28.6.0m)		10%	90%

Table 4: Average top teading production rates

	Northbound Tunnel		Southbound Tunnel	
	Baseline [m/day]	Actual [m/day]	Baseline [m/day]	Actual [m/day]
CAT I	3.57	1.62	3.56	2.43
CAT II	2.86	1.90	2.83	2.37
CAT III	1.99	1.38	1.40	1.40
CAT IV	0.91	1.58	0.91	1.33
CAT V	0.69	1.13	0.69	1.20

Installation of dowels in the northbound top heading

without the backfill support of the cut wall. Several analyses were performed to determine what additional support measures would be required. The pillar between the tunnel and the wall was about 10ft (3m) wide, in the worst ground conditions (CAT V), therefore longer rock dowels and canopy pipe umbrellas were adopted. Soil nails, providing wall support, had to be cut as excavation advanced and sequence modifications were also made. In addition, the monitoring program inside and outside the tunnel was intensified. Due to these changes, breakthrough was achieved without complication or delay.

The excavation sequence for North Block bench and invert excavation was also amended. Prior to starting bench and invert excavation of the 600ft (180m) long North Block section, Kiewit requested a change of excavation sequence to improve work efficiency. This included bench excavation over the entire length of the North Block without invert installation following behind. The invert would then be installed from the north portal going south after the bench was completed. Original contract drawings called for invert installation at 30ft (10m) in CAT III and 20ft (6m) in CAT IV & V behind the bench face and placement of a protective material over the newly installed invert to enable the next round of bench excavation.

Back analyses of top heading parameters and convergence readings indicated the change in sequence would not result in excessive deformations or loadings of the lining and that the tunnel would be stable without immediate application of the invert. However, if the newly defined settlement warning level was triggered, it was agreed that Kiewit would immediately revert to placement of the initial invert, as per original drawings. All in all, both contractor and owner benefited, as the new sequence did not require the invert protection layer and time saved on schedule.

Production rates

Production rates within the baseline schedule were for a seven-day week with concurrent benching behind the top heading excavation. During the course of the project Kiewit changed this construction sequence, advancing the top heading without simultaneous bench excavation on a five- to six-day week schedule. Actual production rates shown in Table 4 do not include downtimes, which included but were not limited to equipment breakdown and maintenance, shutdowns due to ventilation moves and non-working days.

Conclusions

During design and prior to excavation ILF and DSC held numerous workshops and training sessions to further enhance team members' knowledge of NATM excavation and support principles, as well as inspection and documentation procedures. Maintaining detailed and continuous documentation, including daily meeting minutes and excavation/support progress sheets, as well as geological mapping of the face, has been a vital tool during the project; and has played a significant role during negotiations, discussions and the decision-making processes for excavation and lining operations. This documentation will also remain valuable in resolving payment issues or claim negotiations.

As the first NATM highway tunnel to be built in California, the Devil's Slide Tunnel challenged all parties involved. European NATM experience had to be modified in order to conform to US conditions and standards; and Caltrans' staff and Kiewit's crews had to overcome numerous on-site difficulties – including exhaustive evaluations, complex decisions and challenging ground conditions. Nevertheless, all parties involved rose to the challenge, producing a high quality end result.

Last year, the project received the 2010 "Outstanding Environmental & Engineering Project Award" from the Association of Environmental & Engineering Geologists. When open to traffic, in 2012, the Devil's Slide tunnels will greatly improve this problematic stretch of Route 1 to the benefit of locals, commuters and visitors alike.

REFERENCES

1. Geotechnical Baseline Report. Devil's Slide Tunnel Project for California Department of Transportation, prepared by: HNTB Corp, ILF Consultants & Earth Mechanics. October 14, 2005.
2. PH Madsen, JB Decker, K Zeidler, V Gall & TM O'Brien, 2009. "Experience with synthetic fiber reinforced initial shotcrete lining at the Devil's Slide Tunnel Project." Spritzbeton-Tagung 2009.
3. JB Decker, PH Madsen & V Gall, 2010. "Examination of Shotcrete Liner at Devil's Slide Tunnel utilizing ASTM 1550 field test results and back analysis." 44th US Rock Mechanics Symposium & 5th US-Canada Rock Mechanics Symposium, Salt Lake City.
4. JB Decker& PH Madsen, 2009. "Utilizing Convergence Reading to Determine Stability and Support Category in NATM Tunneling at the Devil's Slide Tunnel." 43th US Rock Mechanics Symposium & 4th US-Canada Rock Mechanics Symposium, Asheville.