began in 2007, and the tunnels opened to traffic on March 26, 2013, when they were officially named the Tom Lantos Tunnels, in honor of the late U.S. Senator who secured emergency federal funding for the project. Marking the first highway tunnels constructed in California since 1964, the twin tunnels are 9m wide by 6.8m high and 1.3km long. Contract bids for the project were opened in Sacramento on November 14, 2006. Kiewit Pacific submitted the winning bid of $272,366,000 with a 1,500-day construction schedule.

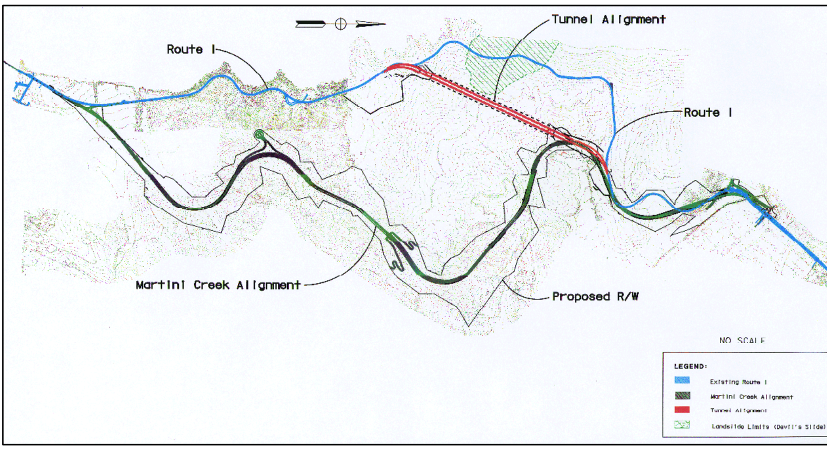

Figure 1. Tunnel alignment

PROJECT DESCRIPTION

The Tom Lantos Tunnels at Devil's Slide consist of a separated two-lane road, one lane in each direction, which passes through twin tunnels and over twin bridges and then connects with the existing non-separated, two-lane road at each end. The length of the entire project is approximate 1,900 meters, made up of four major project sections and moving from south to north:

1) The Operations and Maintenance Center (OMC) area, the 250m-long south approach roadways, including the South Rock Cut (tall tie-back retaining walls), extends to the tunnels' South Portals.

2) The twin tunnels are 1,310m long and extend to the North Portals near the south abutments of the twin bridges.

3) Twin segmental concrete box girder bridges are 275m and 300m long, respectively, and span the Shamrock Ranch valley.

4) North approach roadways then rejoin the existing highway.

The tunnels include the following features:

- Cut-and-cover portals
- Two 4ft emergency and maintenance walkways on either side
- Single 12ft traffic lane with an 8ft right shoulder and 2ft left shoulder

- 10 cross-passages for emergency egress
- Three equipment chambers
- State-of-the-art safety and communications system
- State-of-the-art fire detection and suppression system
- Carbon monoxide and nitrogen oxide detection system
- Electronic message signs displaying safety/advisory information
- Eight pairs of jet fans for ventilation
- High-quality lighting
- Operations control system
- Off-site operations and maintenance center
- Design that can withstand a 7.5 magnitude seismic event
- Bicycle accessibility

INNOVATIONS

The Tom Lantos Tunnels at Devil's Slide project employed several innovations.

State's first use of NATM. The length of the tunnels and the challenging ground conditions did not lend themselves to a tunnel boring machine technique. Instead, Caltrans chose to use the New Austrian Tunneling Method (NATM), a sequential excavation and support tunnel-mining technique. The tunnels are the first to be built in California using the NATM. This flexible, adaptable method relies on observation of ground behavior during excavation, which facilitated unprecedented in-field team collaboration. Based on instrumentation and monitoring of the rock deformation, geologists and engineers adjusted the rock supports "on the fly." This allowed the tunnel to be constructed safely, timely, and at a reasonable cost.

NATM incorporates the strength of the surrounding rock during construction and uses a double-shell support system. The system consists of an initial lining of sprayed fiber-reinforced shotcrete, rockbolts, and lattice girders. Once a section was excavated, crews installed lattice girders and then quickly applied an initial 6in. layer of shotcrete. The shotcrete included structural synthetic fiber to meet specified deflection requirements, a novel approach in the United States. The final lining, designed to accommodate seismic forces, was constructed from reinforced concrete. It was applied after rock dowels and other pre-support measures were implemented. The initial support and final lining are separated by a waterproofing and tunnel drainage system.

Tunnel excavation was accomplished using top heading, bench, and invert. Both tubes were excavated 60ft apart and simultaneously, beginning at the southern portals. Each time crews encountered a different rock type, they had to swap out an entire set of machinery. To improve excavation efficiency, the bench was excavated the full length of the reach prior to the installation of the invert.

Unprecedented in-field collaboration. The flexible, adaptable NATM relies on observation of ground behavior during excavation, which facilitated unprecedented in-field team collaboration. Specifically, engineers in the field—representing the owner, the designer, and the contractor—observed, with geologists, the excavation as it happened and made modifications to the construction process "on the fly" based on the observed behaviors of the ground and rock. This allowed the tunnel to be constructed safely, timely, and at a reasonable cost.

Shotcrete lining with structural synthetic fiber, unique in the U.S. NATM incorporates the strength of the surrounding rock during construction and uses two types of support: an initial lining and a final lining. The initial shotcrete lining included structural synthetic fiber to meet specified deflection requirements, a novel approach in the United States. The final lining was made of traditional, cast-in-place reinforced concrete.

3-D modeling. In addition to two-dimensional numerical models of tunnel cross-sections, the project team prepared 3-D structural analysis models for a typical cross-passage and the transition of the tunnel to the north portal. Construction of the 10 cross-passages, which connect the two tubes, changes the rock stress field that impacts both tubes; therefore, to assess the impact of constructing the cross-passages on the stresses in the rock and, subsequently, the stresses in the tunnel liner, 3-D numerical modeling was required.

TECHNICAL CHALLENGES

The Tom Lantos Tunnels at Devil's Slide were constructed in one of the most complex settings in California. The location presented four major technical challenges:

Technical Challenge 1: Variable rock formations. As part of a geotechnical baseline report, the project team collected rock data during the early stages of the design process by drilling many borings (up to 2,130m core length with horizontal bore up to 350m in length) along the proposed alignment. Laboratory tests performed on the rock cores provided engineers with the data necessary to identify and categorize 10 rock types that would be encountered during excavation.

The alignment contained highly-deformed Mesozoic granitic rock overlain by a series of thrust sheets, consisting of granitic rock and late-Cretaceous and early-Tertiary-age clastic sedimentary rock. The variety of rock was intermitted with hard and soft zones and consisted of blocky and seamy ground, squeezing rock and raveling ground. During the tunnel excavation, when tunnel excavation crews encountered softer soil types, they used articulated arms for digging. For harder rock, a 130-ton Voest Alpine ATM105 roadheader with rotating spike cylinders took over. Each time crews encountered a different rock type, they had to swap out an entire set of machinery. For the toughest areas, they drilled holes and used explosives.

Technical Challenge 2: High seismic zone. Because the tunnels lie along the active San Andreas Fault and four inactive fault lines, the subsurface structures comply with some of the toughest seismic criteria in the world. First, they had to withstand a 7.5–8.0 magnitude earthquake, the maximum movement geologists estimated for this arm of the San Andreas Fault. (The U.S. Geological Survey Working Group on California

Earthquake Probabilities has estimated a 21% probability of a strong earthquake—magnitude 6.7 or greater—occurring on the peninsula section of the San Andreas Fault within the next 30 years.)

Designed to accommodate seismic forces and allow for potential movements, the final lining of the tunnels eliminated expansion joints and consisted of two layers of reinforcement. The design team recommended two layers for the following reasons:

1) Key block loading occurs over much of the tunnels' length, which generally results in tensile stresses at the outside (rock) face of the final lining. Reinforcing steel was added to resist these tensile stresses. The design considered that the initial support would deteriorate over time and the final lining would be required to support all rock loadings, including key block loading.

2) Some areas of the tunnel produced unsymmetrical rock loadings. This loading necessitated two layers of reinforcement at these areas and areas of discontinuity, such as the tunnel and cross-passage junctions.

3) Final lining distortions from seismic ground displacements frequently caused tension stresses at the outside lining face under some combinations of lining self-weight and geostatic loading.

After a design seismic event, the tunnels are to remain serviceable and have experienced only "repairable" damage. "Serviceable" is defined as providing immediate access to emergency vehicles and full access to normal traffic almost immediately. "Repairable damage" is defined as allowing moderate inelastic response of the tunnel concrete liner and portals to occur. Concrete cracking, reinforcement yielding, and some spalling of cover concrete over the reinforcement is expected at this level. However, there will be no structural failure and damage will be limited to permit restoration of the structure (essentially the tunnel's pre-earthquake condition) without replacing any portion of the lining or portals. Damage will be repairable within 90 days and only by requiring lane closures during off-peak traffic periods.

Technical Challenge 3: Mixed ground conditions. The groundwater table lies above the tunnel alignment, and original projections showed that excessive amounts of groundwater were anticipated during construction. The construction sequence, starting from the south portal working north at a 2 percent slope, allowed the groundwater/formation water to flow by gravity to the south portal. Groundwater flows into the tunnel through the rock dowel boreholes and relief holes in the shotcrete lining, as well as through weep holes located near the longitudinal drain pipes. Dewatering ahead, using horizontal drainage holes drilled through the excavation face, was essential in areas of expected high water ingress. In the north block, crews encountered excessive water flow from a fault acting as a drain, collecting groundwater from the rock mass. To eliminate the water, three horizontal dewatering drain holes were drilled through the fault. One hole drained by gravity; the other two were inclined slightly and equipped with pumps. More than 10 million gallons of water were drained to keep the tunnel headings dry.

Technical Challenge 4: Environmentally-sensitive area. As if the rock formations, seismic activity, and ground conditions were not challenge enough, federallyprotected Peregrine falcons nested near the construction site, and California's endangered red-legged frogs were found living in the Shamrock Valley wetland area. The alignment of the tunnels was carefully chosen to respect these environmental concerns. To protect the endangered frog habitat, no equipment was allowed to enter the wetland area. Crews cordoned the area with frog fences and conducted extensive wetland monitoring to ensure the frogs' safety. To minimize the project's impact and to connect the north portal to SR 1 without disrupting the wetland area, twin balanced, cantilever, cast-in-place segmental concrete box girder bridges were constructed. They are the first bridges of their kind in California.

PROJECT RISK

Top risks specific to this project were local environmental concerns, potential contractor claims, and the unknown. Following were the strategies for mitigating each one.

Local environmental concerns. Knowing public opposition killed plans for a six-lane inland bypass, the local communities were proactively involved and regulatory permitting agencies were consulted in very early in the design and permitting process. Over the course of two years, numerous meetings were held with stakeholders to discuss aesthetics and other project elements. Through extensive collaboration, the context-sensitive design was developed that respects the community's concerns and is considerate of the world-class natural setting. These collaborative efforts led to a project that minimizes physical impacts to the existing pristine landscape by protecting vegetation, drainage courses, wetlands, existing landforms and open space. The project advanced with unprecedented community support.

Potential contractor claims. Caltrans desired to have a comprehensive bid package to lessen the likelihood of potential contractor claims, change orders, and cost increases. To mitigate those risks, world known tunnel expertise was retained to help to prepare plans, specifications and estimates for construction.

Unknown risks. World-known tunnel expertise was sought and peer review panels were held, identifying every possible risk that might encounter before, during, and after the project. These brainstorms resulted in an exhaustive risk register that groups the risks according to category: technical risks, external risks, organizational risks, project management risks, environmental risks, right-of-way risks, and construction risks. Each risk was then ranked according to the likelihood of occurrence, conditions that could trigger each event, outlined mitigation strategies, and the cost of impact to both schedule and budget, and oversight of each register entry was assigned to specific team members. Monthly and quarterly meetings were hold to review the status of each risk and update the register.

SUCCESSFUL COMPLETION

A+B contracting. Caltrans led the project as a design-bid-build job in 2006 under a cost-plus time bidding structure known as A+B contracting. Under this method, the time to complete the project (B) is assigned a monetary value and combined with the contract items-based bid (A). The bidder with the lowest overall combined bid (A+B) is awarded the contract.

Extensive public involvement. The project team had two objectives: establish a permanent connection between Pacifica and Half Moon Bay and meet environmental and local expectations. An extensive public involvement campaign was conducted that gathered residents' perspectives on everything from how the portals would look to how many lanes each bore would contain.

As a result of Caltrans' public outreach effort, its relationship with the residents of Pacifica and Half Moon Bay is much better than at the project's onset when residents, protective of their bucolic community, were skeptical of the project's ability to be sensitive to the environment. The same people who attended public hearings 13 years earlier also attended the ribbon-cutting ceremony and expressed how pleased they were with the tunnels' design, how well they blend with the surrounding mountainside, and the respect for the environment.

High aesthetic value. Public input on how the tunnels would relate to their surroundings was vital to the project's success. To solicit opinions, Caltrans created an Aesthetics Committee that participated in a two-phased process to address key aesthetic issues that would impact the tunnels' designs. Committee members included two representatives from the Pacifica City Council, two non-participating representatives from the Half Moon Bay City Council, two representatives from the Midcoast Community Council, one representative from the San Mateo County Board of Supervisors, Caltrans staff, and consultants.

The committee met bimonthly from August 2001 to March 2003. Its goal was to develop project concepts that conform to the context of the Devil's Slide environment; minimize physical impacts to existing landscape elements, including vegetation, drainage courses, and wetlands; and minimize visual impacts to existing landforms and open spaces. The Aesthetics Committee documented its recommendations in a report and presented the information to its constituents at the end of each phase.

Tunnel portals were designed to meet context-sensitive aesthetic and safety requirements and were approved by both the California Coastal Commission and local commissions. Each end of the tunnels is different. The north portals' architectural texture matches the north mountain terrain, and the south portals blend with the south mountain terrain. In total, 20 different design concepts were created before the Coastal Commission approved what exists today.

Each tunnel has a vertical clearance of 15.5ft. The portal entrances have a 22-degree vertical skew, and the north portal entrances have a 57-degree horizontal skew. Each entrance has a bull nose composed of up to 21 different elliptical shapes gradually transforming from one end to the other. The skews and the elliptical shapes required complicated 3-D modeling for fabricating forms and rebar and installing the forms and rebar. Faux boulders crafted by the artist who designed Disneyland's Indiana Jones ride were strategically and safely positioned over the portal entrances.

In addition to their aesthetic function, the boulders act as deflective shields, protecting vehicles from rock slides. Rock bolting and permanent steel mesh netting also provide rockfall protection at the south portals.

Caltrans permanently closed the dangerous stretch of roadway after the tunnels opened. It now is a pedestrian and bicycle trail, offering some of the most spectacular vistas in the United States

CONCLUSIONS

The new $439 million Tom Lantos Tunnels are among the safest in the nation, meeting every requirement of the National Fire Protection Association's 502 Code and the Americans with Disabilities Act.

This project is an excellent example of an engineering team's commitment to identifying and evaluating all aspects of a project and developing a solution through a cooperative partnership with all involved parties and agencies. The work conducted was geologic and geotechnical site characterization, portal stability analysis, geohydrologic modeling, and soil structure interaction for the tunnel support system loads. It also included the design of the tunnel lining and portal; initial ground support using the New Austrian Tunnel Method construction; final lining design, including seismic analyses; soil-nail retaining walls; ventilation design using jet fans; and electrical, lighting, and systems monitoring design.

The constructed project has significantly improved safety on the infamous coastal stretch of California's State Highway 1 and provided a structure that fits aesthetically with the area.

ACKNOWLEDGMENTS

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A Study of Nonlinear Time History Analysis vs. Current Codes Analysis Procedure of Comparing Linear Dynamic Demand with Nonlinear Static Capacity for Ordinary Standard Bridge

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ABSTRACT

Nonlinear time history analysis is known simulating a structure behavior under severe earthquake more proper than other methods. However for simplicity, most of bridges in category of Ordinary Standard Bridge (OSB) are being analyzed by a combined procedure which consists of a linear ARS analysis for earthquake response (demand) and a static nonlinear pushover for ultimate displacement (capacity) per guideline of many transportation agencies worldwide. The demand and capacity are then compared to determine the safety of the bridge. For single degree freedom (SDF) system this procedure has been proven an effective method with satisfactory accuracy. For bridges in the category of OSB but with noticeable characteristics of MDF (multi-degree of freedom) system, large discrepancies between deformation patterns from linear analysis and nonlinear pushover are often observed by engineers, so the accuracy of conclusion from this procedure is questioned. To explore nonlinear dynamic behavior of these bridges and investigate the adequacy of the popular combined linear with nonlinear analysis procedure, a series bridges within category of OSB ranging from slight to severe mass and stiffness unbalance were analyzed. The analysis methods used for each bridge include linear and nonlinear time history analysis, linear ARS analysis and nonlinear static pushover. To ensure valid results comparison, a ground acceleration time history is used for both linear and nonlinear time history analysis, its frequency domain ARS curve is used for ARS analysis. Selected bridges model, ground acceleration and analysis methods, procedures, results, comparison, discussion, conclusions and suggestions are all presented in the paper.

INTRODUCTION

Due to the complicity and time consuming of bridge nonlinear time history analysis, most of bridges in OSB category are currently designed based on a simplified seismic analysis procedure which consists of a linear ARS analysis for earthquake response (demand) and a static nonlinear pushover for ultimate displacement (capacity) per guideline of many transportation agencies worldwide. The demand from elastic analysis is compared to the capacity from nonlinear analysis to determine the safety of the bridge. This simplified procedure is an extended application of a proven method for single degree freedom (SDF) system. The accuracy of this simplified procedure is often questioned when engineers are working on the bridge which possesses characteristics of MDF (multi-degree of freedom) system even they do belong to category of OSB, because noticeable discrepancies between deform pattern from linear analysis and nonlinear pushover are observed. To explore nonlinear dynamic behavior of these bridges and investigate the adequacy of the combined linear with nonlinear analysis procedure, a series bridges within category of OSB ranging from symmetric, slight to severe mass and stiffness unbalance are analyzed. The analysis methods used for each bridge include linear and nonlinear time history analysis, linear ARS analysis and nonlinear static pushover. A selected ground acceleration time history is used for both linear and nonlinear time history analysis, its frequency domain ARS curve is used for ARS analysis. Two single column models subjected to earthquake inputs of different strengths are also analyzed to show how well the aforementioned simplified procedure works for SDF system and how it is changed in MDF system. This paper presents the investigation analysis which includes selected bridges model, ground acceleration, analysis methods, procedures, results, comparison, discussion, conclusions and suggestions.

SAMPLE STRUCTURES AND ANALYSIS MODELS

Analyzed Bridges and Systems. The investigation and analysis include total four bridge structures and two single columns, namely Bridge-1, Bridge-2, Bridge-3, Bridge-4, Column-A and Column-B. All bridges and columns are concrete structures. The table below listed the geometry and type of the analyzed bridges.

Table 1. Geometry Data and Type of the Analyzed Bridges

Name	# of Span	Bridge Length (ft)	Bridge Width (ft)	Span Length (ft)	Skewed Angle (degree)	Column Length	Superstructure type	Substructure type
Bridge-1	3	202.30	27'-8"	60.53	A1: 0	-	Concrete precast P/S I-Girder with CIP Deck	5'-0' column on pile group, fix-fix joints. Seat type abutment
				81.24	Bnts: 0	B2: 26'-5"		
				60.53	A4: 0	B3: 27'-1"		
Bridge-2	3	202.30	27'-8"	60.53	A1: 45	-	Concrete precast P/S I-Girder with CIP Deck	5'-0' column on pile group, fix-fix joints. Seat type abutment
				81.24	Bnts: 45	B2: 26'-5"		
				60.53	A4: 45	B3: 27'-1"		
Bridge-3	3	214.70	33'-3"	70.00	A1: 19	-	Concrete precast P/S I-Girder with CIP Deck	5'-0' column on pile group, fix-fix joints. Seat type abutment
				82.00	Bnts: 19	B2: 26'-0"		
				62.70	A4: -23	B3: 26'-0"		
Bridge-4	6	540.78	42' at Abut-1 and taped to 15'	67.54	-	-	Concrete precast P/S I-Girder with CIP Deck	6'-0" column on 8'-0" CIDH pile shaft. Seat type abutment
				97.92	-	B2: 64'-3"		
				97.92	-	B3: 67'-3"		
				97.80	A1: 25.05	B4: 70'-2"		
				105.73	Bnts: 25.05	B5: 72'-5"		
				73.88	A7: 25.05	B6: 74'-8"		

Note: A1 is Abutment 1, B2 is Bent 2, and so on.

It can be seen from the above table that Bridge-1 is a symmetric structure system. The skewed angle and un-uniformity increased from Bridge-2 to Bridge-3 and Bridge-4 is the most irregular one among all four bridges.

Column-A and Column-B both are 5'-0" diameter reinforced concrete cantilevered columns with a clear depth of 21'-6". Column-A supports a concentrated weight of 600 kips at top of the column to represent superstructure while Column-B supports 750 kips. Both columns represent SDF systems with different natural frequency due to difference of the supporting mass.

The computer models of all the analyzed bridges are shown below in Figure 1 through Figure 4.

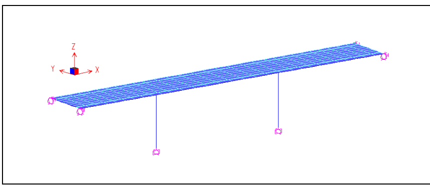

Figure 1. Computer Model of Bridge-1

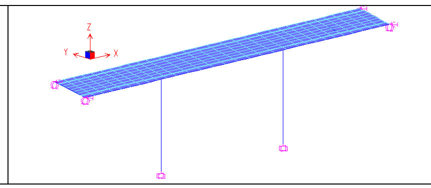

Figure 2. Computer Model of Bridge-2

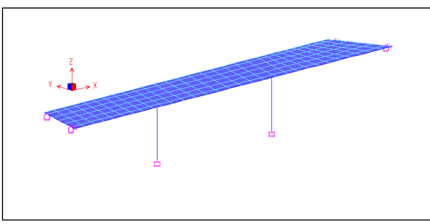

Figure 3. Computer Model of Bridge-3

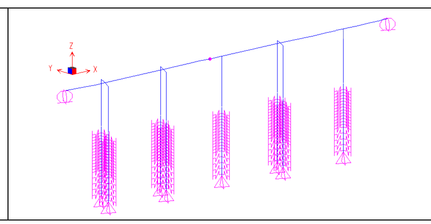

Figure 4. Computer Model of Bridge-4

Ground Motions. Imperial Valley earthquake record IMPVALL/H-E07239 with 5% damping and 0.463g PGA recorded on October 1979 is selected as seismic excitation for the study. The 30 seconds acceleration record is used in both linear elastic time history analysis and nonlinear time history analysis. The frequency domain ARS curve of the record is also used for ARS analysis of all bridge models for obtaining demand displacements as specified in most of the bridge seismic design guidelines. Kobe earthquake record of year 1995, KOBE/KJM000 with 5% damping and 0.821g PGA is also applied as input to some models for both linear and nonlinear analysis to see the sensitivity of the structure to different ground motions and to have better universality of the conclusions drawn from the study. The ground motions are from PEER (Pacific Earthquake Engineering Research Center) with headquarters at University of California, Berkeley.

To investigate bridge seismic response in different post yielding stages, Imperial Valley earthquake record is multiplied by a series of constants to create several seismic excitations with different strengths. In order to clearly identify the structural 3-D response effect, single direction seismic input is used in each analysis