CHARACTERIZING THE LOS ANGELES AQUEDUCT CROSSING OF THE SAN ANDREAS FAULT FOR IMPROVED EARTHQUAKE RESILIENCE

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ABSTRACT

The five-mile-long Elizabeth Tunnel, which crosses the San Andreas fault (SAF) zone near Lake Hughes, California, is part of the Los Angeles Aqueduct (LAA) that delivers water from Owens Valley to the City of Los Angeles. Geologic characterization of the Elizabeth Tunnel alignment is focused on developing a better understanding of fault displacement hazards at the SAF crossing to support design of both short- and long-term strategies to increase the earthquake resilience of the City’s water supply system. The results of this study define a fault zone that is wider and more complex at the surface than at tunnel depth. A 750-ft transect of deep, angled core borings, located ~ 100 ft west of, and parallel to the tunnel alignment, penetrated a wide zone (>550 ft) of fault-damaged granitic and gneissic rocks containing a few thick fault zones that can be correlated confidently between borings as well as a multitude of very thin faults and shears throughout the rock mass. Fault rocks are predominantly defined as coherent cataclasites and ultracataclasites, as opposed to incoherent clay gouge, even at this relatively shallow sampling depth. Integrating geomorphic, geologic, petrographic, and geophysical data defines a steeply south-dipping SAF that splays upward and increases in complexity toward the surface, and provides the basis for engineering design considerations at this critical SAF crossing.

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ABSTRACT

The five-mile-long Elizabeth Tunnel, which crosses the San Andreas fault (SAF) zone near Lake Hughes, California, is part of the Los Angeles Aqueduct (LAA) that delivers water from Owens Valley to the City of Los Angeles. Geologic characterization of the Elizabeth Tunnel alignment is focused on developing a better understanding of fault displacement hazards at the SAF crossing to support design of both short- and long-term strategies to increase the earthquake resilience of the City’s water supply system. The results of this study define a fault zone that is wider and more complex at the surface than at tunnel depth. A 750-ft transect of deep, angled core borings, located ~ 100 ft west of, and parallel to the tunnel alignment, penetrated a wide zone (>550 ft) of fault-damaged granitic and gneissic rocks containing a few thick fault zones that can be correlated confidently between borings as well as a multitude of very thin faults and shears throughout the rock mass. Fault rocks are predominantly defined as coherent cataclasites and ultracataclasites, as opposed to incoherent clay gouge, even at this relatively shallow sampling depth. Integrating geomorphic, geologic, petrographic, and geophysical data defines a steeply south-dipping SAF that splays upward and increases in complexity toward the surface, and provides the basis for engineering design considerations at this critical SAF crossing.

Introduction

The Los Angeles Department of Water and Power (LADWP) is evaluating both short-term and long-term mitigation measures to improve the resiliency of Elizabeth Tunnel, which will be subject to fault displacement in the next rupture along the Mojave portion of the San Andreas fault (SAF). Elizabeth Tunnel is a 5-mile-long tunnel of the Los Angeles Aqueduct (LAA) that delivers water

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from the Owens Valley to the City of Los Angeles (Fig. 1). The concrete-lined tunnel was constructed between 1907 and 1912 with a cross-sectional dimension (H x W) of approximately 11 x 9 ft. The tunnel was excavated through granitic and gneissic rocks and the tunnel invert lies about 300 ft below the ground surface at the fault crossing. In this region, the SAF has a geologic slip rate of ~1.2 in/yr (30 mm/yr) and has an average interval between ground-rupturing earthquakes of ~120 years [1].

A short-term mitigation measure that has been studied by LADWP involves installing a high-density polyethylene (HDPE) pipe inside the existing tunnel. The HDPE pipe is intended to survive a modest fault displacement or tunnel roof collapse and improve the likelihood for delivering a portion of the water supply following an earthquake [2]. Given the tunnel width of about only 9 ft, there is limited capacity for the tunnel and the internal HDPE pipe to survive displacements much greater than 9 ft unless this slip is broadly distributed along the tunnel. Based on offset geomorphic features along the northern and southern Mojave sections of the SAF [3, 4], the Elizabeth Tunnel fault crossing location likely experienced on the order of 16 ft of right-lateral displacement in the 1857 M~7.8 Fort Tejon earthquake. For a M7.8 rupture, two fault displacement prediction equations (one for all slip types [5] and one for strike-slip faults [6]), yield mean displacements of 11.8 to 12.5 ft, with 84th percentile displacements of 28.6 to 30.5 ft. The strong likelihood of future large SAF displacements that exceed the tunnel width requires that LADWP also consider long-term, more expensive alternatives to fully address the significant fault displacement hazard. Therefore, it is essential to geologically characterize the Elizabeth Tunnel’s SAF crossing to evaluate and optimize design options and improve the resiliency of the tunnel and the ability of the LAA to provide water supply to Los Angeles following the next SAF surface rupture.

Figure 1. Location of the Los Angeles Aqueduct (LAA) and the Elizabeth Tunnel crossing of the San Andreas fault (SAF) in (A) regional map and (B) more detailed map of the fault crossing near Munz and Hughes Lakes.

Geologic Setting

The LAA and Elizabeth Tunnel cross the Mojave south section of the SAF. From the north portal on the Antelope Valley floor, the 5-mi-long tunnel extends southward beneath the higher
topography of Portal Ridge, the San Andreas Rift Valley and the Sierra Pelona, an individual range within the larger Transverse Ranges (Fig. 1). Geologic maps indicate that north of the SAF, the tunnel was advanced through Late Cretaceous granodiorite beneath Portal Ridge, and south of the fault, the tunnel primarily penetrates early Cretaceous to Proterozoic quartzofeldspathic gneiss and amphibolite gneiss as well as Late Cretaceous quartz diorite within the Sierra Pelona [7, 8].

The rift valley is a long, narrow valley that marks the location of the dextral, strike-slip SAF and separates the higher topography of Portal Ridge and the Sierra Pelona. At the SAF crossing, the valley is approximately 1,300 ft wide, but narrows to as little as 400 ft between bedrock ridges about 700 ft west of the tunnel. Presently, there is no large axial valley stream or wash flowing through the rift valley. Sediment input to the valley largely consists of alluvial fans emanating from small and moderate catchments draining the flanks of Portal Ridge and the Sierra Pelona. Alluvial fan deposits typically consist of sand and silt with minor gravel. Finer-grained lacustrine deposits of silt and clay are associated with depocenters (closed basins) within the valley, such as Munz and Hughes Lakes, as well as the larger Elizabeth Lake located ~1.5 mi east of Fig. 1B. Based on several radiocarbon dates obtained from core samples in the alluvium, the basal alluvial deposits are about 10,000 years old north of the SAF and 15,000-18,000 years old south of the SAF, where they reach a maximum observed thickness of about 140 ft.

Methods

The methods employed to characterize the geology of the fault crossing include both surface and subsurface data and analyses. The surface efforts, which spanned the entire length of Elizabeth Tunnel [9], utilized historic air photos and topographic maps, acquisition and interpretation of lidar data, compilation of previous mapping, field reconnaissance mapping, and geomorphic analyses. The initial report [9] also summarized the paleoseismic information on the SAF and included a probabilistic fault hazard displacement analysis (PFDHA) to quantify the fault displacement hazard. The subsurface data collection in later work focused exclusively on the SAF crossing and included: (1) transects of CPTs and hollow stem auger core borings to map the buried bedrock surface, (2) a transect of deep (400 to 550 ft) angle core borings across the fault zone and adjacent to the tunnel, (3) downhole geophysical surveys, and (4) more than 50 petrographic analyses of rock core samples to quantify the degree of damage from faulting and to develop a consistent fault rock classification to aid in mapping faults through bedrock. Radiocarbon dating was completed on material in the alluvium.

Subsurface Exploration

The exploration program was designed to aid in the mapping of the fault zone in both map view and in cross section. Seven transects of CPTs and borings (Fig. 2) were located across the fault zone in order to map anomalous or abrupt changes in the top of rock elevation and/or abrupt facies changes between closely spaced explorations that may suggest the presence of faulting. Contouring of the buried bedrock surface further aided in mapping faults that vertically displace the bedrock surface along linear trends (Fig. 2).
Figure 2. Map of SAF crossing showing CPT and boring transects (T1 through T8), contours on buried bedrock surface (top of rock), and surficial scarps interpreted from 1928 and 1948 historical air photos on lidar basemap. Faults F1a and F1b (darker shading) represent the principal fault strands at the alluvium/bedrock interface and these two strands merge with depth before intersecting the tunnel. Cross section of transect 7 (T7) is shown in Figure 3. Black triangles represent CPTs that were used to define buried bedrock surface and gray triangles represent CPTs that were interpreted to have met refusal within the alluvium and were not used in the construction of the bedrock contours.

Transect 7, located about 100 ft west of the tunnel, included seven northeast-plunging angle core borings designed to map the fault zone in cross section (Figs 2 and 3). The spacing, depths, and inclination (~55-65°) of these rock core borings were laid out to provide maximum coverage of the anticipated fault zone adjacent to the tunnel. The northward inclined angle borings extend to a maximum vertical depth of about 460 ft, up to 175 ft below the tunnel invert, and provide coverage beneath the west end of Munz Lake (Fig. 3). These borings acquired nearly 2,500 ft of 2.4-inch diameter rock core with a ~95% core recovery. At the completion of each boring, project team geologists reviewed the entire core, and following the entire drilling phase, core from all borings were laid out side by side at full-core review to correlate faults between borings.
A suite of downhole geophysical surveys was performed in the angle core borings. These surveys included long and short resistivity, single point resistance, spontaneous-potential (SP), natural gamma, acoustic televiewer, and suspension logging to obtain in situ measurements of Vs and Vp. The most useful geophysical information came from the resistivity surveys, which yielded prominent resistivity lows corresponding to most of the significant cataclasite zones.

Brittle fault slip and deformation produce fault rock textures by mechanically reducing the grain size of the parent rock. Petrographic analyses were performed on more than 50 core samples from the angled borings to help define the finer fault rock textures in accordance with Sibson’s textural classification of cohesive fault rocks [10] that was slightly modified to include foliated cataclasites as products of brittle deformation [11]. The three most intensely deformed fault rock textures include:

- Ultracataclasite: matrix comprises 90 to 100 percent of the rock
- Cataclasite: matrix comprises 50 to 90 percent of the rock
- Protocataclasite: matrix comprises 10 to 50 percent of the rock

The matrix is defined as particles finer than 0.004 in (0.1 mm), which are generally not visible to the unaided eye. The petrographic analyses, which included microscopic thin section analysis, were essential for establishing guidance in macroscopically classifying the remainder of the core into the following categories (in order of decreasing deformation): ultracataclasite, cataclasite, protocataclasite, fault damaged rock, and weathered/decomposed intact rock. The distribution and thickness of ultracataclasites and cataclasites, which are used to help define mappable faults within the bedrock, are shown in Fig. 3. A core photograph of cataclasite and ultracataclasite from a principal fault strand (F1a) are shown in Fig. 4.

Fault Model

In developing a fault model of the SAF crossing, we include observations and interpretation of all available surface and subsurface data. Some of this information, such as scarps and tonal lineaments at the ground surface and faults interpreted in the subsurface between CPTs and borings, provides constraints on the fault zone in map view. Other information from the transect of angle core borings and downhole geophysical logs provide constraints on the dip, width, and complexity of the fault zone in cross section view and at tunnel depth. Integrating this information provides a three-dimensional model of the fault zone.

Faults in map view (Fig. 2) were mapped based on (1) geomorphic expression and tonal lineaments from historic photographs, (2) apparent scarps in buried bedrock surface, (3) abrupt facies variations in the CPT, and (4) faults penetrated by angle core borings in transect 7. The SAF exhibits a locally complex geometry at the fault crossing (Fig. 2). West of the tunnel, between T3 and T1, the fault zone is defined by a simple and relatively narrow, prominent north-side-down step in the buried bedrock surface that corresponds to a north-side-down scarp in historical air photos. The scarp is best expressed west of T4A and becomes more diffuse to the east due to increased fault complexity and man-made modification of the ground surface. Excavation of the eastern portion of Munz Lakes had occurred prior to the 1928 air photos and the man-made islands in the lake (Fig. 2) were constructed between 1928 and 1932.
East of T4A and T4B, the fault zone widens with additional faults that appear to deform the buried bedrock surface (Fig. 2). At T2, the fault zone is comprised of several strands over a width of ~200 ft. At T7 and the tunnel, the most prominent faults are F1a and F1b, which exhibit significant south-side-down separation in the bedrock surface. The northernmost step in the bedrock surface appears to diminish in height to the east (F1b to F3) and largely dies out by T7 (Fig. 2).

Faults in cross section (Fig. 3) were mapped based on (1) the most prominent and thickest zones of cataclasite, (2) low resistivity values, which consistently corresponded to cataclasite observed in the core, (3) steps in the buried bedrock surface, and (4) abrupt facies changes between closely spaced CPTs. Given the base of the alluvium is less than 18,000 years old, the latter two criteria imply a Holocene age and therefore a high confidence for slip in future ruptures. Faults recognized within bedrock that do not correlate with vertical separations of bedrock surface or displacement higher in the alluvial section, however, may not represent active strands. The buried bedrock surface in Fig. 3 was drawn by linear interpolation between the elevation data points representing CPT refusal depths or top of bedrock observations in core borings. Closely-spaced data points along T7 define two significant steps in the bedrock surface that correspond to faults F1a and F1b and also correlate with two similar, but significantly larger steps that are present along T2 (Fig. 2). In boring AC-4, F1b is expressed as banded and sheared alluvium directly above the bedrock contact, indicating that the contact is faulted.

The most prominent fault encountered is F1, and based on the width and intensity of deformation observed in the rock core, it appears to have accommodated the greatest amount of cumulative slip. At the depth of the tunnel, principal fault F1 dips 80-85° to the south (Fig. 3). About 20 ft above the tunnel, boring AC-1 drilled through 12 ft of cataclasite associated with fault F1. Considering the fault dip, the width of fault F1 is estimated to be nearly 7 ft thick. Displacement may be focused on much thinner ultracataclasite bands (slip surfaces) within the ~7-ft-wide cataclasite. It is assumed that the majority of future displacement will occur on this fault, which exhibits the greatest degree of cataclasis and brecciation of the original rock mass, produces the largest steps in the bedrock surface, and is observed as topographic lineaments in the historic air photos (Fig. 3). Based on the thickness and degree of cataclas, and the associated low resistivity signature, the second most prominent fault is F2. This fault dips 70-80° to the south and crosses the tunnel 30-35 ft south of fault F1.

The rock mass explored by angle core borings contained thin seams of cataclasite over the entire, ~550-ft horizontal distance explored. Secondary slip may occur on faults F2 and F3, as well as other lesser, undefined faults beneath the valley floor. The absence of geomorphic or topographic lineaments in the crystalline bedrock ridges and slopes on the north and south side of the valley preclude the occurrence of repeated, significant secondary displacement beyond the valley margin in the bedrock terrain. Therefore, most secondary displacements will be limited to within the valley alluvium and within a few hundred feet of the principal fault F1.
Figure 3. Preliminary cross section along transect T7 illustrating the San Andreas fault zone and the Elizabeth Tunnel. Thick, dashed red lines represent the most significant faults based on thick, well-developed cataclasites, low resistivity zones, and apparent vertical separation of the buried bedrock surface. Fault F1 represents the principal SAF strand, which bifurcates upward to displace the buried bedrock surface on faults F1a, F1b, and possibly F1c. F2 is based on zones of low resistivity and cataclasites and the topology of the bedrock surface.

Figure 4. Photograph of core sample from fault F1a in AC-2 at a depth of 215.5 to 217.5 ft. Sample taken from an 11-ft-thick interval comprised of predominantly foliated cataclasite.
cataclasite with thinner zones of ultracataclasite.

Conclusions

The Elizabeth Tunnel crosses the SAF in a location where the fault appears to rapidly change geometry both along strike and down-dip to the tunnel, which lies about 300 ft below the ground surface. Subsurface exploration combined with geomorphic observations have attempted to define the fault zone at the ground surface, the buried bedrock surface, and at the depth of the tunnel. The fault zone appears most complex and wide near the surface and narrows with depth to the tunnel (Fig. 3). Principal fault F1 is defined as a ~6-ft-wide cataclasite dipping steeply south (80-85°) at the tunnel depth. The majority of fault displacement in future earthquakes is likely to occur within the tunnel on fault F1 based on the coincidence of the fault with recent deformation indicated by the alluvial contact and the aerial photos. A second fault (F2) intersects the tunnel within 30-35 ft of fault F1 and also dips steeply south (70-80°). Minor secondary displacements may occur on some of the many thin cataclastic shear bands observed throughout the entire zone of fault damaged rock penetrated by the angle core borings. Secondary displacements will likely be limited to the narrow rift valley and not extend into the bedrock slopes to the north and south, based on the absence of topographic lineaments in the bedrock.

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