State of California
DEPARTMENT OF TRANSPORTATION

Business, Transportation and Housing Agency

Memorandum

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To: MR. TOM OSTROM
Supervising Bridge Engineer
Office of Earthquake Engineering

Date: August 19, 2013

Attention: Mark Yashinsky

File: 04-MRN-1 PM 22.81
59-93034-N
EFIS# 0000001016-N
Olema Creek Bridge 27-0020

PROFESSIONAL GEOLOGIST
ANNA SOJOURNER
CERTIFIED ENGINEERING GEOLOGIST
No. 2562
Exp. 12/31/13
STATE OF CALIFORNIA

From: ANNA SOJOURNER
Engineering Geologist
Office of Geotechnical Design - West
Geotechnical Services
Division of Engineering Services

CHRISTOPHER FISDEN
Chief, Branch B
Office of Geotechnical Design - West
Geotechnical Services
Division of Engineering Services

Subject: Preliminary Evaluation of Fault Rupture Potential for Bridge 27-0020 on Olema Creek, Marin County

SUMMARY

Caltrans bridge 27-0020 lies approximately 3.5 miles south of Olema, Marin County (MRN-1-22.81; Figure 1). The bridge lies within the Alquist-Priolo Earthquake Fault Zone (EFZ) of the 1906 trace of the northern San Andreas fault (Figure 2). The bridge lies approximately 8.2 meters (27 feet) from the nearest mapped active fault strand and approximately 227 meters (745 feet) from the 1906 trace.

The 1906 trace of the San Andreas fault is capable of very large displacements, but the probability of off-fault displacements decreases rapidly with increasing distance from the fault. We do not expect significant offset associated with the 1906 trace within the bridge footprint. However, the Eastern Boundary fault, part of the San Andreas system that may have slipped in 1906, lies just 8.2 meters from the bridge. The activity and rate of slip on the Eastern Boundary fault are not well-known. The combined hazard for off-fault displacements within the bridge site is 0.4 m (1.3 feet) deterministically and 0.3 m (1 foot) probabilistically. Vertical displacement of approximately 10% of the horizontal value, or up to 0.04 m (0.13 feet), should be assumed to occur with the horizontal displacements.

Per Memo to Designers (MTD) 20-8, either the larger of the deterministic and probabilistic values or a site-specific value should be used for design. If the existing bridge can tolerate 0.4 m (1.3 feet) roughly perpendicular to the bridge alignment, then no additional work is recommended at this time. If this deterministic value is not acceptable, I recommend the use of the probabilistic value (0.3 m or 1 foot), also per MTD 20-8, which states that given sufficient

reason, a lower probabilistic value may be used with permission from the Office of Earthquake Engineering. If both values are too large, we can discuss conducting site-specific studies to locate potential faults near the bridge footprint. **Please respond to this preliminary evaluation with a request for no further work, in which case the design value will be 0.4 m (1.3 feet), permission to use the probabilistic value of 0.3 m (1 foot), or a request for site-specific studies. A final memo will be issued following your response.**

INTRODUCTION

This evaluation was prepared as part of a statewide evaluation of fault rupture potential at Caltrans bridges. Caltrans policies regarding fault rupture at bridges are described in Memo to Designers 20-10. Caltrans requires a fault rupture evaluation if a bridge is located within an Alquist-Priolo Earthquake Fault Zone or within 1,000 feet of an un-zoned fault 15,000 years or younger in age.

Bridge 27-0020 (MP 22.81) was built in 1928. It is a 3-span slab bridge on reinforced concrete pile bents with reinforced concrete abutments.

The bridge lies east of the 1906 trace of the San Andreas fault, near the Eastern Boundary fault, a smaller fault within the San Andreas fault zone (Figure 2). The 1906 trace is the most active fault within the zone. The bridge lies within a few meters of the active Eastern Boundary fault. The style and rate of offset on the Eastern Boundary fault are not well known, but it is considered to be active and it may have ruptured in 1906 (Knudsen, 2002).

This evaluation consisted of literature, air photo, and LiDAR review, discussions with experts, a site visit, and deterministic and probabilistic calculations of potential off-fault displacements within the bridge footprint.

LITERATURE, AIR PHOTO, LiDAR, AND FIELD REVIEW

Galloway (1977)

Galloway (1977) first mapped the Eastern and Western Boundary faults of the San Andreas fault zone as graben-bounding faults. These basin-bounding faults are considered Quaternary-active but are not known definitively to have ruptured in the 1906 earthquake.

Berquist (1978)

Bergquist (1978) noted that some 1906 subsidence of Bolinas Lagoon had occurred east of the 1906 trace, possibly on the Eastern Boundary fault (p. 46). Estimates of 5.8 to 17.9 m of tectonic subsidence in early to middle Holocene deposits in Bolinas Lagoon yield an

approximate vertical offset rate of 1-3 mm/year, if the slip occurred wholly on the Eastern Boundary fault.

Hall, Hay, and Cotton (1986)

Hall et al. (1986) mapped the area near the bridge in detail (2 foot contour interval) as part of a study of the 1906 trace of the fault and of the work done on the fault immediately after the 1906 earthquake. Their map did not include the bridge site or the Eastern Boundary fault, but confirms that the USGS mapping at this site is reasonably accurate.

Niemi and Hall (1992)

Niemi and Hall (1992) excavated multiple trenches on the 1906 trace of the fault at the Vedanta Wind Gap site near Olema, approximately 2.4 miles (3.9 kilometers) northwest of Bridge 27-0020 (Figure 1). They matched buried segments of a late Holocene stream channel to find the slip rate for the northern San Andreas of 24±3 mm/year. A maximum coseismic displacement of 4.9 to 5.5 meters was calculated. This empirical measurement is incorporated into the probabilistic calculations for offset at the bridge.

Grove, et al. (1995)

The Olema Creek Formation is a Pleistocene sedimentary sequence that occurs between the Eastern Boundary fault and the 1906 trace, between the southern edge of Tomales Bay and Five Brooks (Figure 1). In describing the Olema Creek Formation, Grove, et al. (1995) wrote “the eastern edge of the (Quaternary Olema Creek) formation has been modified by post-depositional faulting” on the Eastern Boundary fault.

The Eastern Boundary fault was mapped (State of California EFZ map, 1974) from surface geomorphic expression through three levels of fluvial terraces (Grove, et. al, 1995), which presumably correlate to the last three sea-level highstands (Grove, personal communication). This suggests that the fault ruptured in the Quaternary, and if the most recent terrace is Holocene, the fault ruptured in the Holocene.

Knudsen, et al. (2002)

Knudsen, et al. (2002) evaluated the slip history of the northern San Andreas between Bodega Head and Bolinas Lagoon. They wrote that the Eastern Boundary fault “is believed to have been active during the Holocene,” and possibly during the 1906 earthquake. The “…inferred east Boundary fault has been proposed to control dip-slip displacement on the eastern side” of Bolinas Lagoon, approximately 5½ miles south of the bridge. There was significant subsidence at Bolinas Lagoon in the 1906 earthquake.

Knudsen was contacted during preparation of this memo, and indicated the major movement on the Eastern Boundary fault is likely strike-slip. The calculated vertical offset of 1-3 mm/year could be taken as a minimum slip rate.

Bryant et al. (2002) USGS Fault Summary

The 1906 trace of the San Andreas is one of the most active faults in the world, with a slip rate of approximately 24 mm/year at this site (Bryant, et al., 2002). The Eastern and Western Boundary faults are considered late-Quaternary active by the California Geological Survey and the US Geological Survey (CGS, 2010).

Petersen, et al. (2011)

Petersen, et al. (2011) developed probability distribution functions for of off-fault displacements around strike-slip faults. They found high probability for off-fault displacements within a few hundred meters of the main fault trace. The frequency drops off very quickly with larger distances, and the off-fault displacements are generally only a few percent of the principal-fault displacements. Poor mapping accuracy and complex fault traces can give a greater apparent probability to displacements further away from the fault.

Topographic Maps, Stereo Air Photos and LiDAR Images

I evaluated the 7.5' topographic maps and air photos and of the Eastern Boundary fault in the area between Olema and Five Brooks (Figure 1) to assess the relative creek offset along the 1906 trace and the trace of the Eastern Boundary fault. While there is obvious right-lateral stream offset along the 1906 trace, short tributaries to Olema Creek are not obviously offset along the Eastern Boundary fault. This indicates that if the Eastern Boundary fault is primarily a strike-slip fault, it is much less active than the 1906 trace. Small stream offsets would not be obvious at the resolution of 7.5' topographic maps and air photos. It is possible to detect stream offset with high-resolution surveys across fault zones, but this is outside the scope of this project.

Mapping of the fault in the area of Point Reyes is considered poor, with potential errors in fault locations of 500 feet or more (Knudsen, personal communication). Hall et al. (1986) produced a detailed map of the 1906 trace of the fault at Five Brooks, and their traces closely match those of the Alquist-Priolo EFZ map and the USGS (2010). Hall et al. did not map the Eastern Boundary fault. Stereo air photos at the bridge site do not show obvious Eastern Boundary fault lineaments that pass through the bridge. LiDAR images (Figure 3) of the bridge site show a similarly poorly-expressed Eastern Boundary fault, with no obvious fault traces passing near or within the bridge footprint.

Site Visit

Martha Merriam and I visited the site in March 2013. The Eastern Boundary fault has, in places, well-developed geomorphic expression consistent with a strike-slip fault, suggesting relatively recent activity. In particular, the fault is very well expressed around Milepost 24.6 of Highway 1, with a sag pond and a saddle. We were not able to locate exposures of young sediments disturbed by faulting. Grove (personal communication) indicated that she knew of no exposures of faulted Holocene sediments along the Eastern Boundary fault. However, with cattle grazing and logging prevalent in the area since at least the 1850's, it is possible that young historical sediment covers any offset Holocene sediments.

We were unable to find any fault expression within or near bridge 27-0020. The streambed is thickly vegetated.

Literature Review and Site Visit - Conclusions

The 1906 trace of the San Andreas fault is highly active, with a slip rate of 24$\pm$3 mm/year, and its trace is clearly mapped from surface rupture. The 1906 trace is complex near the bridge, with several traces mapped at the surface. The Eastern Boundary fault is poorly understood, significantly less active than the 1906 trace, and approximately located. Nonetheless, it should be considered active and capable of producing offset at the bridge site, most likely coseismic offset.

CALCULATIONS OF EXPECTED OFFSET

To quantify potential fault offset, I used a spreadsheet developed by the Division of Research and Innovation in collaboration with Geotechnical Services based upon methods presented in Petersen, et al. (2011), and Abrahamson (2008). Both a deterministic fault displacement analysis and a probabilistic fault displacement analysis were performed. The input parameters included maximum magnitude, slip rate, mapping and base map errors, and empirical slip measurements from literature. The input parameters and discussion below are all based on the 1906 trace of the San Andreas, as initial calculations showed that the 1906 trace controlled the offset hazard, even though the low-slip Eastern Boundary fault lies closer to the bridge.

Mmax

The $\mathbf{M}_{max}$ of 8.0 is taken from the USGS fault parameter database (USGS, 2008). This value also agrees with the magnitude of the 1906 earthquake, taken to be from **M**7.7 to **M**8.3. Since the 1906 earthquake ruptured the entire length of the fault used to estimate the $\mathbf{M}_{max}$ value, offset associated with that event may be used in probabilistic calculations of displacement.

Slip Rate

Niemi and Hall (1992) conducted paleoseismic studies at the nearby Vedanta Wind Gap site. Their preferred slip rate is 24±3 mm/year. Prentice in a separate paper (2001) reported "…the best current geodetic estimate of San Andreas fault motion and locking depth near Point Reyes Station is 22.2±4.0 mm/year." I used the larger slip rate from Niemi and Hall (1992) because the geodetic slip rate applies to depths below approximately 12 km and this analysis is concerned with slip at the surface. Bryant (2002) used 24 mm/year and Dawson and Weldon (2012) use 24 mm/year as the UCERF3 best estimate rate.

Empirical Slip Measurements

Niemi and Hall (1992) reported two slip measurements from the 1906 earthquake, 4.9 and 5.5 meters. These two measurements, obtained at the Vedanta Wind Gap site 2.4 miles north of the bridge, were averaged and incorporated in the probabilistic offset calculations per Hecker, et al. (2013).

Site-to-Source Distance

The Double Point Alquist-Priolo EFZ Map (1974) and the USGS (2010) show the bridge lies 745 feet (227 meters) from the mapped main 1906 trace of the fault. Hall et al. (1986) mapped this area in detail and we believe that the mapped locations of the 1906 trace are accurate. The Eastern Boundary fault lies just 27 feet (8.2 meters) from the bridge. The Western Boundary fault lies 445 meters away from the bridge.

Type of Slip

The 1906 trace is a right-lateral strike-slip fault. The Eastern Boundary fault is a predominantly right-lateral strike-slip fault with a normal component. The normal component has been quantified through mapped elevation changes in Bolinas Lagoon (Berquist, 1978) but the magnitude of horizontal slip has not been studied.

Relative Slip of Multi-strand Faults

Very little is known about the Eastern Boundary fault. Because the Eastern Boundary fault lies very close to the bridge, we considered several ways of partitioning slip within the larger San Andreas fault zone.

Considering the Eastern Boundary fault as a separate seismic source is the most conservative approach. This would result in very large calculated potential offsets in the bridge (on the order of 1-2 meters). However, there currently is no evidence that the Eastern Boundary fault ruptures

separately from the main 1906 trace and most investigators posit that it ruptures with the 1906 fault.

We placed 95% weight on the 1906 trace and 5% on the Eastern Boundary fault. The Western Boundary fault was excluded from this analysis for two reasons: because it lies over 450 meters away from the bridge and does not contribute to the combined offset hazard at the bridge site; and because the spreadsheet used to calculate hazard does not have the option to have site-to-source distances for more than two faults. Inputting three faults into the spreadsheet requires that one fault be located directly under the bridge (d=0), which changes the combined hazard.

Calculated Potential Offset at the Bridge

Fault Offset on the 1906 Trace

The deterministic offset for the 1906 trace of the fault is 7.5 meters (Wells and Coppersmith, 1994). The probabilistic offset (5% in 50 years, or 1000 year return period) on the 1906 trace is 5.9 meters. This calculated offset incorporates nearby empirical measurements (Niemi and Hall, 1992).

Fault Offset within the Bridge Footprint

To assess the probability of fault rupture within the bridge footprint, I assigned 95% of the slip to the 1906 trace, and 5% to the Eastern Boundary fault. The low percentage indicates the uncertainty associated with this scenario. The calculated combined potential offset within the bridge footprint is 0.4 m (1.3 feet) deterministically or 0.3 m (1 foot) probabilistically.

Vertical Displacement

Vertical displacements of approximately 10% of the horizontal offset should be assumed to occur temporally with horizontal displacements in the bridge footprint. This corresponds to approximately 0.04 m (1.6 inches) for the larger deterministic case and 0.025 m (1 inch) for the probabilistic offset.

Table 1 - Results of Offset Calculations

Scenario	**M_{max}**[1]	**Slip Rate**[2]	**Site-to-source distance**	**Deterministic offset in bridge footprint**	**Probabilistic offset, 975 yr return in bridge footprint**
1906 trace 95% EBF 5%	8.0	24 mm/yr	227 m (1906) 8 m (EBF)	0.4 meters	0.3 meters

RECOMMENDATIONS

If the bridge can withstand a lateral fault offset of up to 0.4 meters (1.3 feet) approximately perpendicular to and anywhere within the bridge footprint, then no further work is recommended at this time. If this potential offset is too large, I request we consider the probabilistic offset value of 0.3 meters (1 foot). If both values are too large, we can discuss further investigations, such as additional mapping, geophysics or trenching, which could be used to better define the location of the Eastern Boundary fault, and/or identify faults near or within the bridge footprint and constrain the likelihood of surface rupture within the bridge footprint.

If you have any questions, please contact Anna Sojourner at (510) 622-8839.

c: TPokrywka, CRisden, Daily File
ASojourner/mm
Attachments: Figures 1 – 5

[1] CT fault database: http://dap3.dot.ca.gov/shake_stable/v2/technical.php
[2] Niemi and Hall (1992)

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State of California, 1974, State of California Special Studies Zones, Inverness Quadrangle, Official Map, 1:24,000

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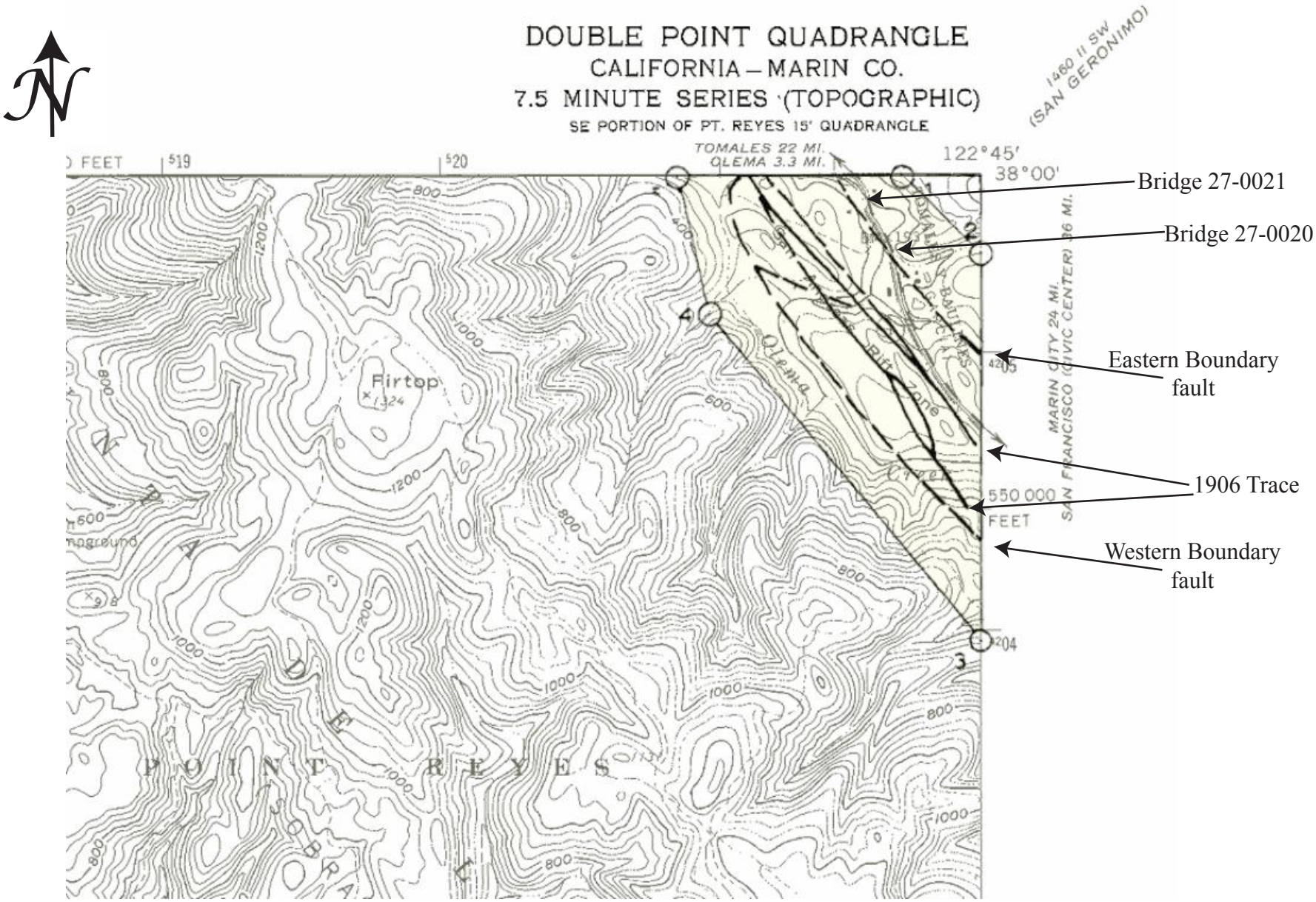
0 SCALE ~5.2 miles

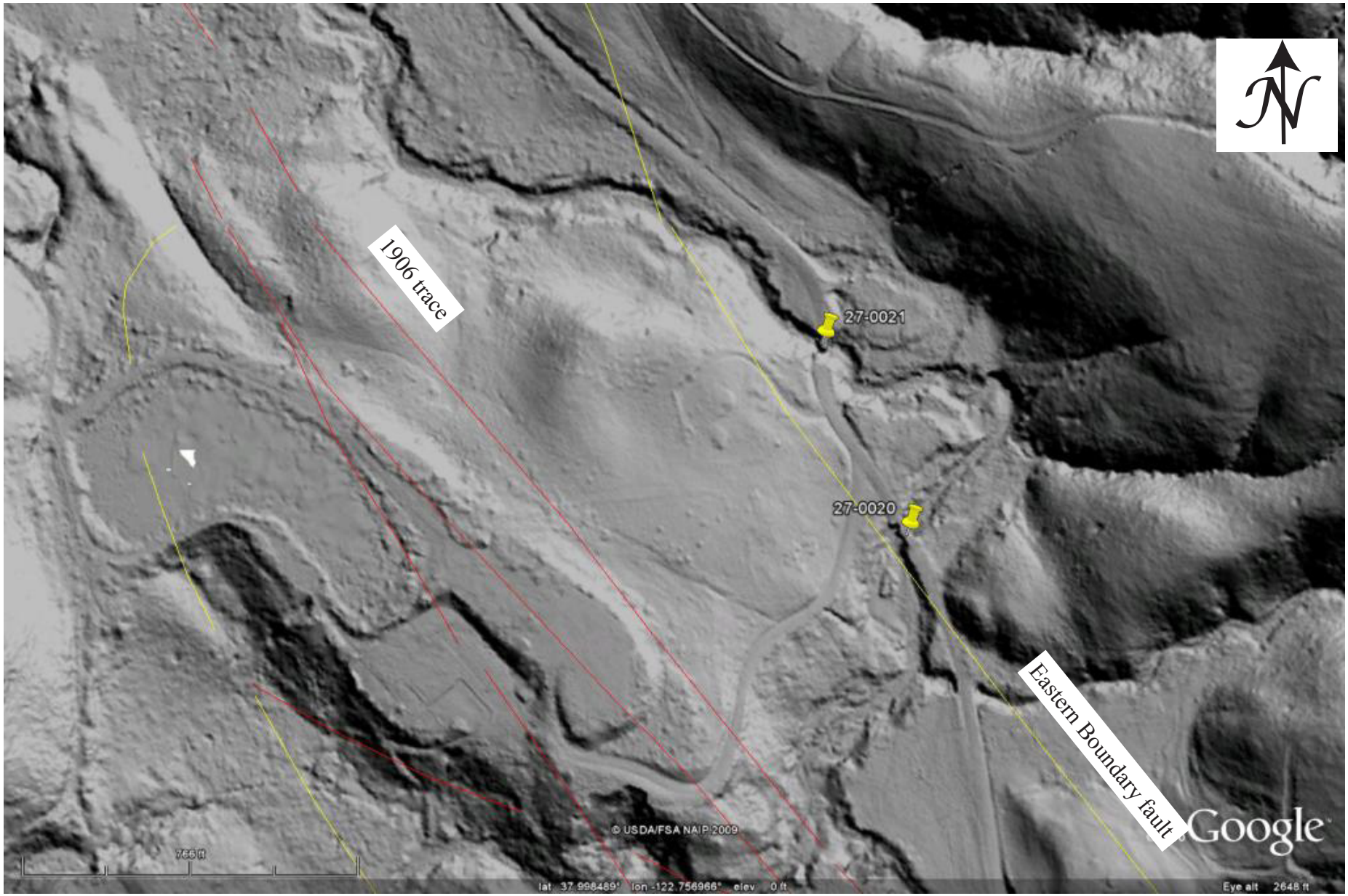
Figure 1	Location Map
04-MRN-1	PM 22.81-22.96
EFIS 04-000001016	August 2013



SCALE 1:24,000

Source: State of California, 1974, State of California Special Studies Zones, Double Point Quadrangle, Official Map, 1:24,000

Figure 2	**Alquist-Priolo Fault Map**
04-MRN-1	PM 22.81-22.96
EFIS 0000001016-N	August 2013

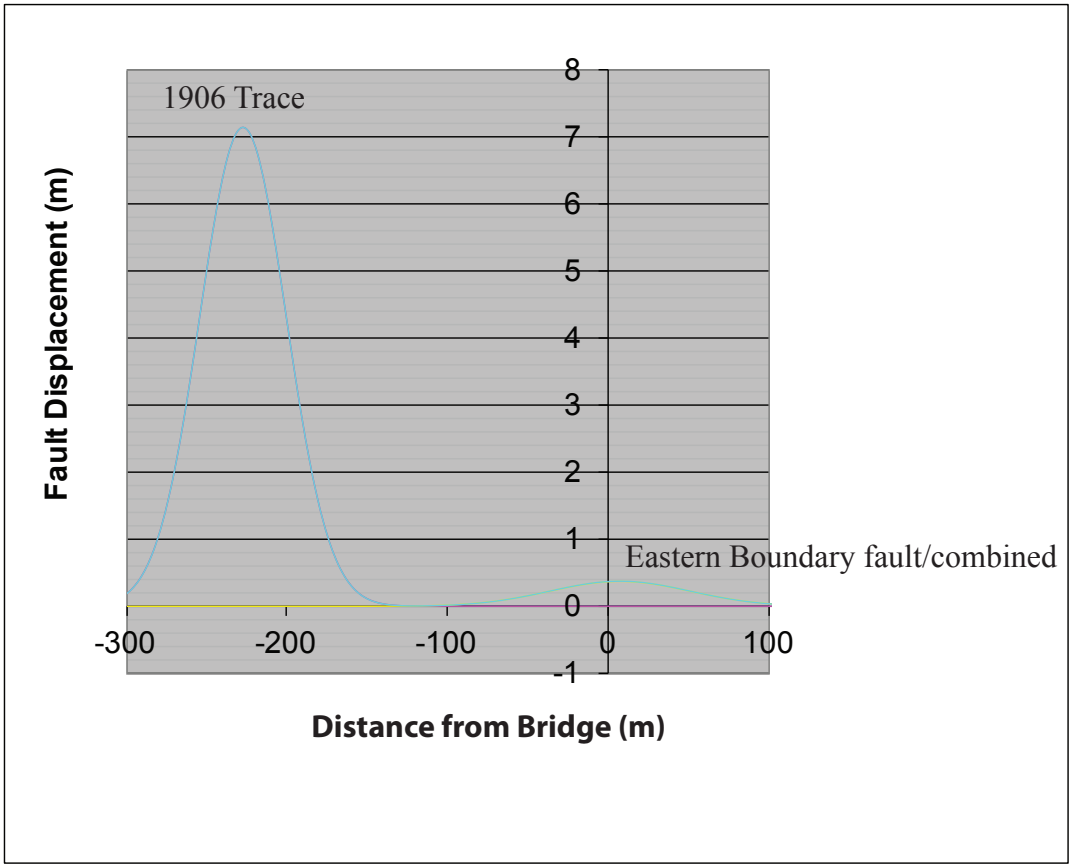


0 SCALE ~750 feet

LEGEND
Red - Historic fault
Yellow - Holocene/latest Pleistocene fault

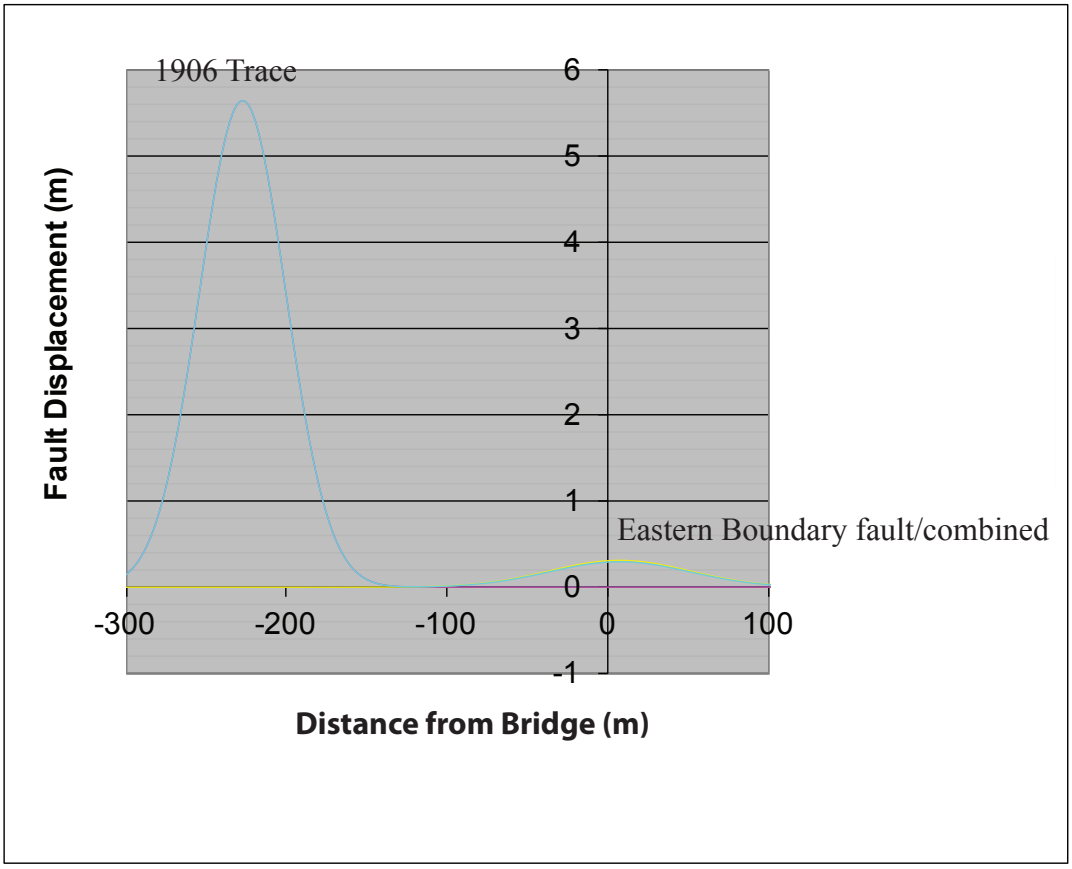
Source: USGS, 2010

Figure 3	**LiDAR Image - Olema Creek**
04-MRN-1	PM 22.81
EFIS 04-000001016	August 2013



Graph showing deterministic offset within the bridge footprint.
Offset at the bridge (distance = 0) could be up to 0.4 meters.

	Figure 4	**Deterministic Offset**
	04-MRN-1	PM 22.81
	EFIS 04-0000001016-N	August 2013



Graph showing probabilistic offset within the bridge footprint.
Offset at the bridge (distance = 0) could be up to 0.25 meters.

	Figure 5	**Probabilistic Offset**
	04-MRN-1	PM 22.81
	EFIS 04-0000001016-N	July 2013