Appendix E
Fault Rupture Evaluation Technical Memorandum

SR 710 North Study

TECHNICAL MEMORANDUM

Fault Rupture Evaluation for the SR 710 North Study, Los Angeles County, California

PREPARED FOR:	Michelle Smith/Metro
COPY TO:	Caltrans
PREPARED BY:	Eldon Gath, P.G., C.E.G./Earth Consultants International Dario Rosidi, Ph.D., P.E., G.E./CH2M HILL Ravee Raveendra, P.E., G.E./CH2M HILL
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REGISTERED PROFESSIONAL ENGINEER
MAHESWARAN RAVEENDRA
No. GE2743
Exp: 6/30/2015
GEOTECHNICAL
STATE OF CALIFORNIA

REGISTERED GEOLOGIST
ELDON M. GATH
No. EG 1292
CERTIFIED ENGINEERING GEOLOGIST
STATE OF CALIFORNIA
Expires: 3/31/2014

Introduction

This technical memorandum presents the results of preliminary fault rupture evaluations completed as part of environmental documentation for the State Route (SR) 710 North Study. Five Alternatives are being evaluated during the ongoing environmental documentation process. The five Alternatives are No Build, Transportation System Management/ Transportation Demand Management (TSM/TDM), Bus Rapid Transit (BRT), Light Rail Transit (LRT), and Freeway Tunnel. Figure 1 shows the general vicinity of the SR 710 North Study area.

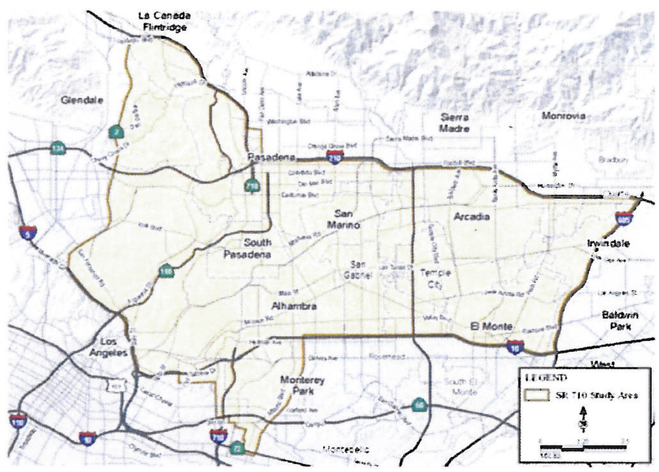

Figure 1. SR 710 North Study Area.

Fault ruptures are a particularly important consideration during the environmental assessment of two of the SR 710 North Study Alternatives: the Freeway Tunnel and LRT Alternatives. Both Alternatives will be located in tunnels over much of their lengths:

- Freeway Tunnel (Dual Bore Option): The proposed Freeway Tunnel Alternative includes approximately 60-foot-diameter, 4.2-mile-long, twin bored tunnels and cut-and-cover tunnels at both ends of the bored tunnels. The freeway tunnels will extend from the existing southern stub of SR 710 in Alhambra, north of I-10, and connect to the existing northern stub of SR 710, south of the I-210/SR 134 interchange in Pasadena. The invert of each tunnel will be roughly parallel to the ground surface at an average depth of about 200 feet below ground surface (bgs), except at the portals where the tunnels daylight.
- LRT: The LRT Alternative will consist of twin bored tunnels approximately 4.5 miles long, and would be located between Valley Boulevard on the south and the existing Fillmore Station on the Metro Gold Line on the north.

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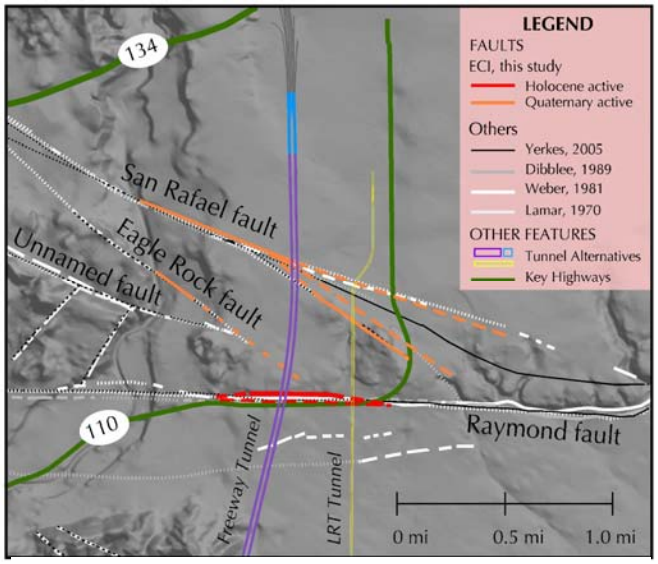

Figure 2. *Map of the potentially active faults that may impact the proposed tunnel routes (there are different mapping interpretations and locations for San Rafael, Eagle Rock, and other northwest-trending faults, but in this discussion, they are collectively referred to as the Eagle Rock-San Rafael fault zone).*

The LRT Alternative would also consist of approximately 3.0 miles of overhead structure from the Metro Civic Center Station on the south to Valley Boulevard on the north. The LRT tunnel invert depth is approximately 80 feet bgs; the diameter is approximately 20 feet.

The two proposed tunnel alignments will both cross active fault zones (Figure 2), necessitating a discussion in the environmental documentation of the potential hazards caused by the fault zone crossings and whether these hazards can be reasonably mitigated in future design. In order for the environmental documentation to discuss the hazards and methods for mitigating the impact of fault crossings, the potential displacements across the tunnel alignments, if one of the faults were to rupture during a seismic event, needs to be estimated.

A preliminary assessment of fault displacements for the two Alternatives was performed using deterministic and probabilistic fault displacement hazard analyses (DFDHA and PFDHA, respectively). For the DFDHA, several approaches for estimating fault displacement (Wells and Coppersmith, 1994; Hanks and Bakun, 2008; Wesnousky, 2008) based on fault length alone were compared, but Wells and Coppersmith was used to estimate fault displacement because it is the most commonly used in practice. For the PFDHA, probabilistic methods (Youngs et al., 2003; Petersen et al., 2011; Chen and Petersen, 2011) were used to quantify the magnitude of displacement for a given earthquake return period, consistent with Metropolitan Transportation Authority (Metro) and California Department of Transportation (Caltrans) seismic design criteria. These displacement evaluations considered the San Rafael, Eagle Rock, and Raymond faults, which are the three principal fault systems crossing the LRT and Freeway Tunnel alignments.

This technical memorandum begins the discussion on how to develop tunnel displacement estimates using the DFDHA and PFDHA methods. The memorandum presents a brief summary of the geologic data that are available and how those data may fit together with the regional fault systems, including potential ruptures from one fault onto another. It also presents the preliminary results of DFDHA and PFDHA that were performed to estimate the fault rupture displacements at the fault-tunnel crossing locations during future earthquakes on the Raymond, Eagle Rock, and San Rafael faults. These displacement estimates are based on return periods and seismic performance guidance required by Caltrans and Metro for earthquake ground motions.

The results presented herein were developed based on limited geologic data on the faults, and therefore should be considered preliminary and subject to change in the subsequent design phases. The design displacement estimations were limited by an absence of paleoseismic studies for some of the faults, by a lack of replicated quantitative data in the studies, and by inconsistencies in the data across paleoseismic studies, as explained later in this memorandum. Additional field investigation and studies should be conducted after the preferred Alternative is selected to update and verify these fault displacement estimates.

Fault Background Data

Figures 3 and 4 show generalized locations of the faults discussed in this technical memorandum. Table 1 summarizes the consensus information of the faults that could contribute to the rupture hazard at the tunnels. There are very limited data concerning the slip rates or recurrence intervals of surface-rupturing earthquakes for any of these faults; there are two published paleoseismic studies for the Raymond fault, one study for the Hollywood and Santa Monica faults, and none for the other faults. As such, there is difficulty in providing reasonable values for fault displacements. All of these faults are relatively short, and individually would generate displacements of less than 1 meter. However, there are some discussions within the scientific community that these faults could rupture together (Marin et al., 2000; Weaver and Dolan, 2000), with slip transferring from one to the other, in a cascading event that would result in a larger magnitude event and much larger displacements on each of the faults. The following subsections provide a discussion of each of the primary faults in the area and then identify potential fault models that could result in fault displacements across the tunnels.

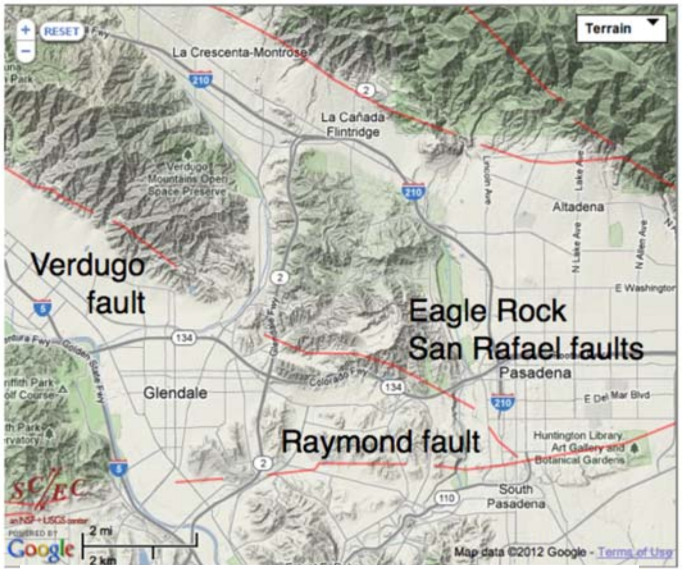

__Figure 3.__ Map of the potentially active faults that may impact the proposed tunnel routes involving a complex rupture of the Eagle Rock and/or San Rafael faults with the Verdugo fault.

__Figure 4.__ Map of the potentially active faults that may impact the proposed tunnel routes through a complex rupture involving the Raymond and multiple fault segments to the west. Sierra Madre fault (S-M) and Clamshell Sawpit fault (C-S) also are shown.

TABLE 1
Summary of Fault Data*
SR 710 North Study, Los Angeles County, California

Fault	Length (km)	Magnitude	Slip Rate (mm/yr)	Recurrence Intervals (years)	Comment
Raymond	21	6.7	0.5 - 2.0	3,000	Slip rate and recurrence poorly constrained: 4 to 5 mm/yr has also been reported.
Eagle Rock	11	6.2	0.3 - 0.6	10,000+	Slip rate and recurrence unconstrained.
Verdugo	21	6.7	0.6	10,000	Slip rate and recurrence unconstrained.
Hollywood	15	6.6	0.9	10,000	Slip rate and recurrence poorly constrained.
Santa Monica	24	7.0	1.0	10,000	Slip rate and recurrence poorly constrained.
Malibu	34	6.6	0.3	10,000	Slip rate and recurrence poorly constrained.

* Data sourced from referenced papers, the Southern California Earthquake Center (SCEC) online fault database [http://www.data.scec.org/significant/fault-index.html] and Caltrans fault database (Caltrans, 2012).
km – kilometer(s)
mm/yr – millimeters per year

Raymond Fault

The primary active fault through the tunnels is the Raymond fault (Bryant, 1978). This north-dipping, east-west-trending fault has a dominant left-lateral sense of offset (Jones et al., 1990), though some north side up reverse slip is also likely. The percentage of lateral to vertical (L:V) slip varies along the trace of the fault; it has been estimated at a ratio of about 5:1 (L:V). Within the tunnel crossings, a case could be made that the vertical displacement is 75 feet across a horizontal displacement of 2,300 feet, resulting in a 30:1 (L:V) ratio based on the cumulative offset of the Pasadena fan.

Figure 5 depicts logs of two paleoseismic trenches on the Raymond fault. There is similarity in the expression of the fault in both trenches even though the trenches were excavated miles apart. Although not noted in either study, similar near-surface partitioning frequently isolates the strike-slip movement component onto the steeper fault, while the shallower fault accommodates most of the compressional movements.

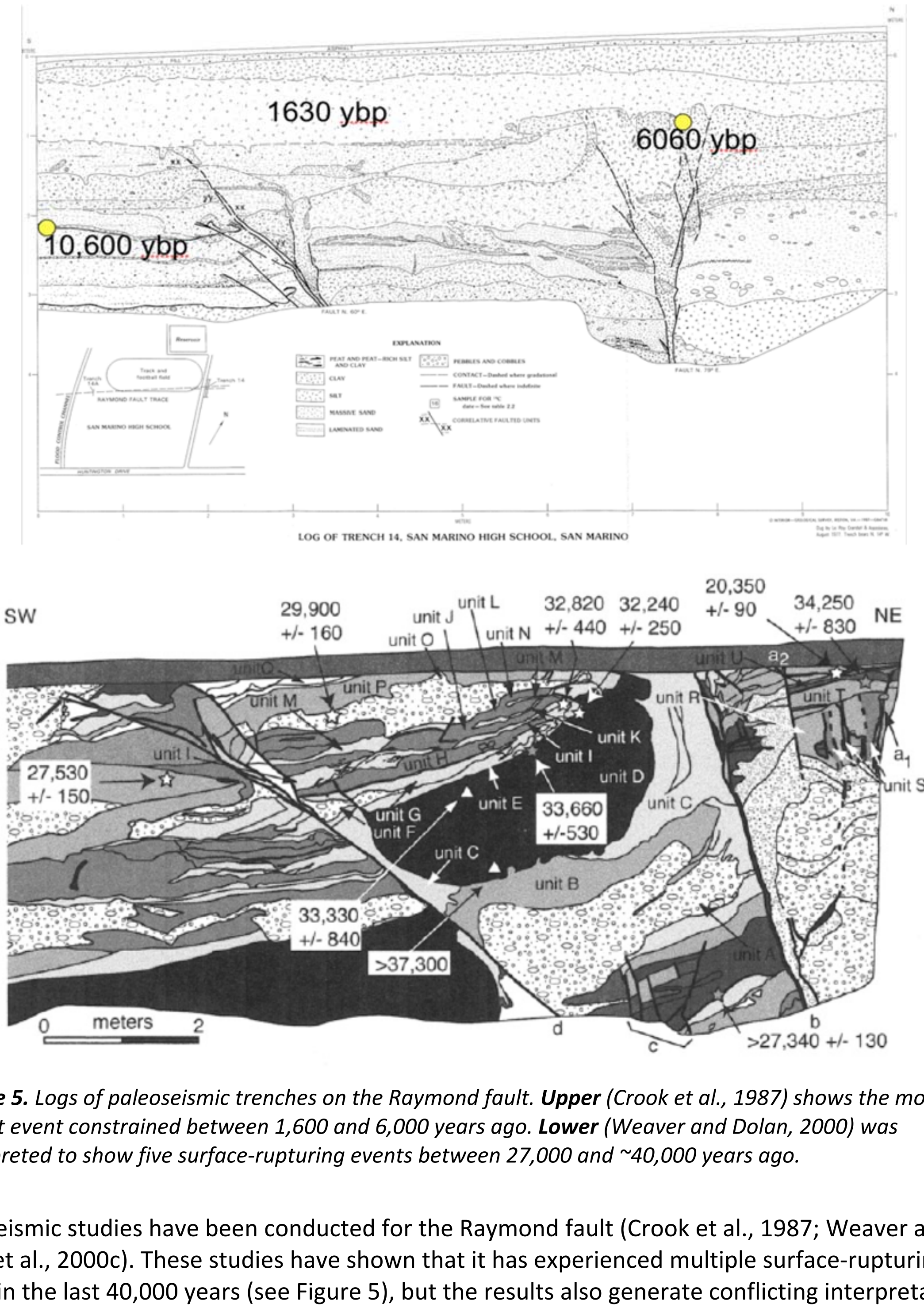

Figure 5. *Logs of paleoseismic trenches on the Raymond fault.* ***Upper*** *(Crook et al., 1987) shows the most recent event constrained between 1,600 and 6,000 years ago.* ***Lower*** *(Weaver and Dolan, 2000) was interpreted to show five surface-rupturing events between 27,000 and ~40,000 years ago.*

Three paleoseismic studies have been conducted for the Raymond fault (Crook et al., 1987; Weaver and Dolan, 2000; Dolan et al., 2000c). These studies have shown that it has experienced multiple surface-rupturing earthquakes in the last 40,000 years (see Figure 5), but the results also generate conflicting interpretations for the average recurrence interval between events, as well as the date of the last event. While these data may be interpreted as an example of temporal clustering of events, it also could be interpreted as missed events in the paleoseismic records due to inconsistent stratigraphic preservation.

Based on a series of events between 27,000 and 40,000 years ago, Weaver and Dolan (2000) calculated a recurrence interval of about 3,300 years for the Raymond fault. However, based on offsets of younger deposits, the recurrence interval could be as long as 5,000 to 10,000 years between events. The last event is inferred to have occurred between 1,000 and 2,000 years ago (Weaver and Dolan, 2000), though this estimate is somewhat poorly constrained.

A subsequent study showed a post-25,000-year channel offset of 42 meters resulting in a slip rate of 1.5 mm/yr along a 10-meter-wide zone of almost pure left-lateral strike-slip faulting (Dolan et al., 2000c; Marin et al., 2000). The California Geological Survey (CGS) lists the Raymond slip rate as low as 0.5 mm/yr (CGS, 2013), while the (still draft) Unified California Earthquake Rupture Forecast (UCERF3) fault compilation by Dawson and Weldon (2012) reports a 2.0 mm/yr slip rate using the same data as Marin et al. (2000). Yeats (2012, p. 108), however, reports a slip rate of 4 +1/-0.5 mm/yr for the Raymond fault, a value that seems too high based on the geomorphic expression of the fault.

Table 1 provides a summary of fault data used in the scenario analysis discussed below.

Hollywood, Santa Monica, and Malibu Faults

The Hollywood, Santa Monica, and Malibu faults also have been shown to have ruptured to the surface in the past 10,000 years, and all have a similar left-lateral reverse sense of slip. Paleoseismic studies of the Hollywood and Santa Monica faults (Dolan et al., 1997, 2000a, and 2000b) suggest that these two faults have recurrence intervals of about 10,000 years, and that the Santa Monica fault last broke 1,000 to 3,000 years ago, while the Hollywood fault last ruptured 6,000 to 9,000 years ago.

The slip kinematics of the Hollywood, Santa Monica, and Malibu faults are similar to the Raymond fault; that is, dominantly left-lateral with a reverse component, which is why they are frequently considered as individual parts of a larger fault system. Currently, the collected paleoseismic data for these faults do not support temporally coincident ruptures, although the data set is small. For analysis purposes, however, these faults could still be considered as rupturing together with the Raymond fault in various rupture scenarios.

Verdugo, Eagle Rock, and San Rafael Faults

The Eagle Rock/San Rafael fault zone has no quantitative investigations. The Eagle Rock fault is considered by some to be the southern continuation of the Verdugo fault (Yeats, 2004), and is also listed in the Caltrans Fault Database (Caltrans, 2012); however, there is no discussion of how the strain from the Verdugo would be apportioned across the Eagle Rock and San Rafael splays. No paleoseismic studies have been published for the Verdugo fault.

As discussed previously, the scenario of combining the Raymond fault with a rupture on the Eagle Rock fault has no field evidence to confirm its plausibility. But the Eagle Rock (and San Rafael) faults do seem to merge just west of Raymond Hill, and it is possible to infer that Raymond Hill is being elevated as a result of this strain transfer. A joint rupture cannot be a common event, however, because the tectonic geomorphology of the Eagle Rock fault is much less developed than that of the Raymond fault, suggesting it has a lower slip rate or longer recurrence interval to refresh it on the landscape.

Despite this observation, the tectonic geomorphology of the Raymond fault is much better developed east of Arroyo Seco, near its intersection with the Eagle Rock/San Rafael faults. No data have been published to confirm or refute the presence of Holocene-age offsets on the Eagle Rock/San Rafael faults, nor on the Verdugo fault farther northwest.

Proposed Fault Rupture Models

At the tunnel-fault crossing locations, or just slightly east of them, the Eagle Rock and unnamed faults join with the Raymond fault, and its geomorphic expression becomes much stronger on the landscape. This could indicate that the Raymond fault is structurally linked in some manner to the Verdugo-Eagle Rock/San Rafael fault system, and that the rate of slip on the Raymond fault changes west-to-east at this location of the fault (see Figure 6). All of the paleoseismic investigations on the Raymond fault lie to the east of this interaction, and therefore may not be truly representative of the paleoseismic behavior of the fault at the proposed tunnel locations, if this scenario is viable.

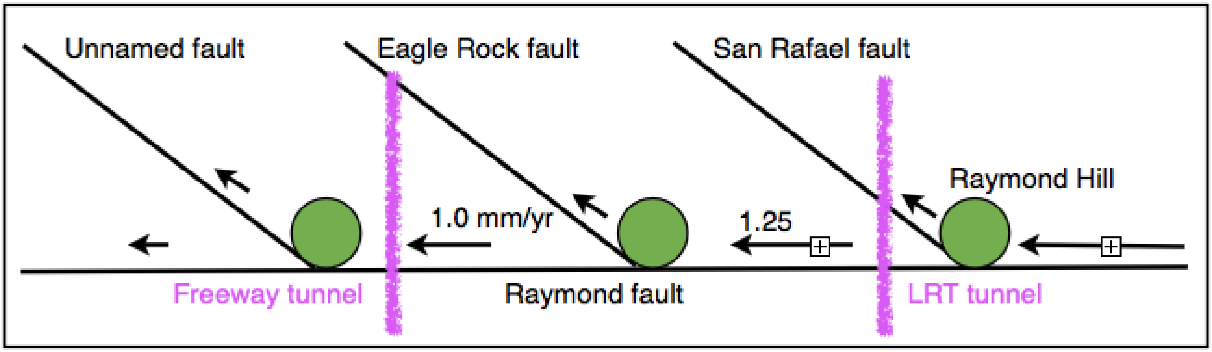

Figure 6. *Schematic illustration of a possible structural interaction that would bleed slip off the Raymond fault and onto the Eagle Rock/San Rafael fault system.*

The model shown in Figure 6 does not satisfy the current mapping of the faults across the northeast margin of the hills. However, it satisfies a mechanism to explain the topographic uplifts and left-lateral displacements on the secondary faults. As with the other fault parameters, there are inconsistencies between existing mapping interpretations and the assumed fault parameters based on published sources.

Another possible scenario is that the Raymond fault ruptures easterly onto the Clamshell Sawpit segment (see Figure 4), thereby involving the Sierra Madre fault. This is another untested hypothesis, because no paleoseismic studies have been completed on the Clamshell Sawpit fault or on this portion of the Sierra Madre fault. Because of all these uncertainties, it seems premature to include additional structural models into the current analysis. For that reason, this analysis concentrates on the Raymond fault as a single source, with some consideration on the cascading rupture scenarios with the Hollywood, Santa Monica, and Malibu faults.

Implications of Cascading Rupture Scenarios

A number of uncertainties exist for the fault systems that are located in or near the LRT and Freeway Tunnel alignments. One of the key uncertainties is whether separate seismic events could cascade as a single large rupture scenario, as has been suggested. The idea of cascading events is important as the resulting displacements could increase appreciably from those associated with single events. Two possible cascading scenarios involving the Raymond fault are discussed in the following sections.

Raymond–Hollywood Fault System

One scenario involves a combination of the Raymond and Hollywood faults into a single cascading event. A number of factors suggest this is a very unlikely event:

- Existing geologic data are inadequate to resolve the inconsistencies between slip rate, earthquake recurrence, and earthquake magnitude/displacement.
- The slip rate on the Raymond fault has been geologically constrained at about 1.5 to 2 mm/yr. This fits the various models and the geomorphic expressions of the fault better than the higher reported value of 4 to 5 mm/yr.
- At 1.5 mm/yr, the displacement events should occur on average every 350 to 700 years. This is highly divergent from the 3,000–5,000–10,000-year recurrence intervals derived from the paleoseismic studies.
- Temporal clustering of events or missing paleoseismic events are both Alternative interpretations to explain the average recurrence interval inconsistency. Temporal clustering means that the average 3,000-year recurrence interval is defined by two to four temporally close earthquake events followed by a long quiescence period.
- At a 3,000–5,000–10,000-year recurrence and at 1.5 mm/yr, the strain accumulation would be 4.5, 7.5, and 15 meters, which could be the clue that temporal clustering of events is the norm because these large displacement events are not credible for the Raymond fault alone or even with adjacent faults.

- In order to generate such large displacements in single events, the length of the fault must be increased by linking it to other faults in a “cascade” rupture.

Based on fault geometry, the Hollywood fault is the most likely fault to either transfer slip onto the Raymond or to accommodate slip from the Raymond fault, but there are difficulties with this linkage.

- Taking the date of the last rupture on the Hollywood fault as approximately 6,000 to 9,000 years ago (Weaver and Dolan, 2000), and the last event on the Raymond fault as less than 2,000 years ago, it appears that these two faults do not always rupture together. But it is still possible that they do occasionally rupture together, perhaps whenever the Hollywood fault ruptures, or that rupture-linking events have been missed in the paleoseismic data.
- The Hollywood fault has a recurrence interval of 10,000 years. Combining the lengths of the Raymond and Hollywood faults would result in a fault length of 35 km, capable of M6.9 and only 0.8 to 1.3 meter of surface displacement; this is well below the amount needed to account for the 42 meters of displacement in <25,000-year-old deposits, as measured by Dolan et al. (2000c).
- Linking the Santa Monica and Malibu faults to the Hollywood-Raymond scenario does result in larger event displacements; however, such linkages are also not supported by the current geological studies, and it is considered to be implausible.
- The problem cannot be solved deterministically from the existing paleoseismic data, because there are too many conflicting results and interpretations within those data.

At this time, it does not seem realistic to design for a scenario event involving the Raymond and Hollywood fault systems. This scenario cannot be demonstrated geologically and has probabilities as low as 1 in 10,000+ years, which would include any of the fault linkage scenarios.

Raymond–Eagle Rock/San Rafael Fault System

The second cascading scenario involves the Raymond, Eagle Rock, and San Rafael fault systems. A number of factors suggest this is also a very unlikely event:

- The Eagle Rock fault zone is more complex than the Raymond because there are three subparallel faults (San Rafael, Eagle Rock, and an unnamed fault) to consider, there are very little hard data to evaluate, and the faults are more difficult to locate precisely using only borings.
- Any of the three faults could be more of the primary hazard than the other two, but equally plausible arguments can be made that they are all three similar in hazard potential, or are all effectively inactive faults now and pose no hazard.
- If they were to rupture separately as individual fault strands, their displacements would be 0.2 to 0.3 meter. Even if they were to rupture as a part of the Verdugo fault system, their displacements would be only about 1 meter.
- Of the three, only the San Rafael fault may traverse the Freeway Tunnel Alternative because the Eagle Rock and unnamed faults may terminate against the Raymond just west of the alignment.
- The width of the Eagle Rock/San Rafael faults through the Freeway Tunnel is probably small (less than 10 meters), but the three faults are separated through a distance of almost 1,000 meters.
- The drilling did reduce the uncertainty in locations of both the Raymond and San Rafael fault traces to less than 25 meters, but left open the possibility of minor secondary faults below the resolution of the drilling correlations.
- The subsurface investigation completed few borings on both sides of the Raymond and San Rafael faults in an attempt to better refine their location, width, and (in the case of the San Rafael) hazard potential.

At this time, it does not seem realistic to design for this scenario event, as it also cannot be demonstrated geologically and has probabilities as low as 1 in 10,000+ years, which would include any of the fault linkage scenarios.

Deterministic Fault Displacement Hazard Analysis (DFDHA)

An initial estimate of fault displacements was made by conducting a DFDHA. The earthquake magnitudes and the average and maximum surface rupture displacements for the faults crossing the project were estimated in the DFDHA using the length of the faults. The regression plots of Wells and Coppersmith (1994) were utilized for these estimations, as shown in Figures 7 and 8, for the various joint or cascading rupture scenarios. Figure 7 shows the various scenarios for the Raymond-Eagle Rock fault system; Figure 8 illustrates the Raymond-Hollywood rupture scenarios.

On the left-side of Figures 7 and 8, the 21-km length of the Raymond fault results in an earthquake magnitude of M6.6 to 6.9 and displacements per event of 0.5 to 0.9 meter. On the right-side plots, the Raymond fault (red) rupture is progressively combined in length with other scenario fault segments, resulting in progressively longer faults capable of larger earthquake magnitudes and rupture displacements. Table 2 summarizes these potential cascading events and their displacement magnitudes estimated using the Wells and Coppersmith (1994) plots. The assigned probabilities for the joint rupture events are best estimates based on available data.

TABLE 2
Fault Rupture Scenarios involving the Raymond Fault
SR 710 North Study, Los Angeles County, California

Fault	Length (km)	Magnitude	Rupture* (meters)	Probability (years)	Comment
Raymond	21	6.7	0.5 - 0.9	1/3000	Single fault scenario.
Eagle Rock/San Rafael	11	6.2	0.2 - 0.3	1/10,000	Single fault scenario on one or the other.
Verdugo + Eagle Rock/San Rafael	32	6.8	0.7-1.1	1/10,000	Combined based on Caltrans Fault Database.
Raymond + Eagle Rock	32	6.8	0.7 - 1.1	1/10,000	Unlikely scenario.
Raymond + Eagle Rock + Verdugo	53	7.0	1.7 - 2.0	1/15,000	Very unlikely scenario.
Raymond + Hollywood	36	6.9	0.8 - 1.3	1/10,000	Plausible scenario.
Raymond + Hollywood + Santa Monica	60	7.3	1.8 - 4.0	1/15,000	Improbable scenario.
Raymond + Hollywood + Santa Monica + Malibu	94	7.5	3.0 - 7.0	1/20,000	Very improbable scenario.

* Average and maximum rupture displacements.

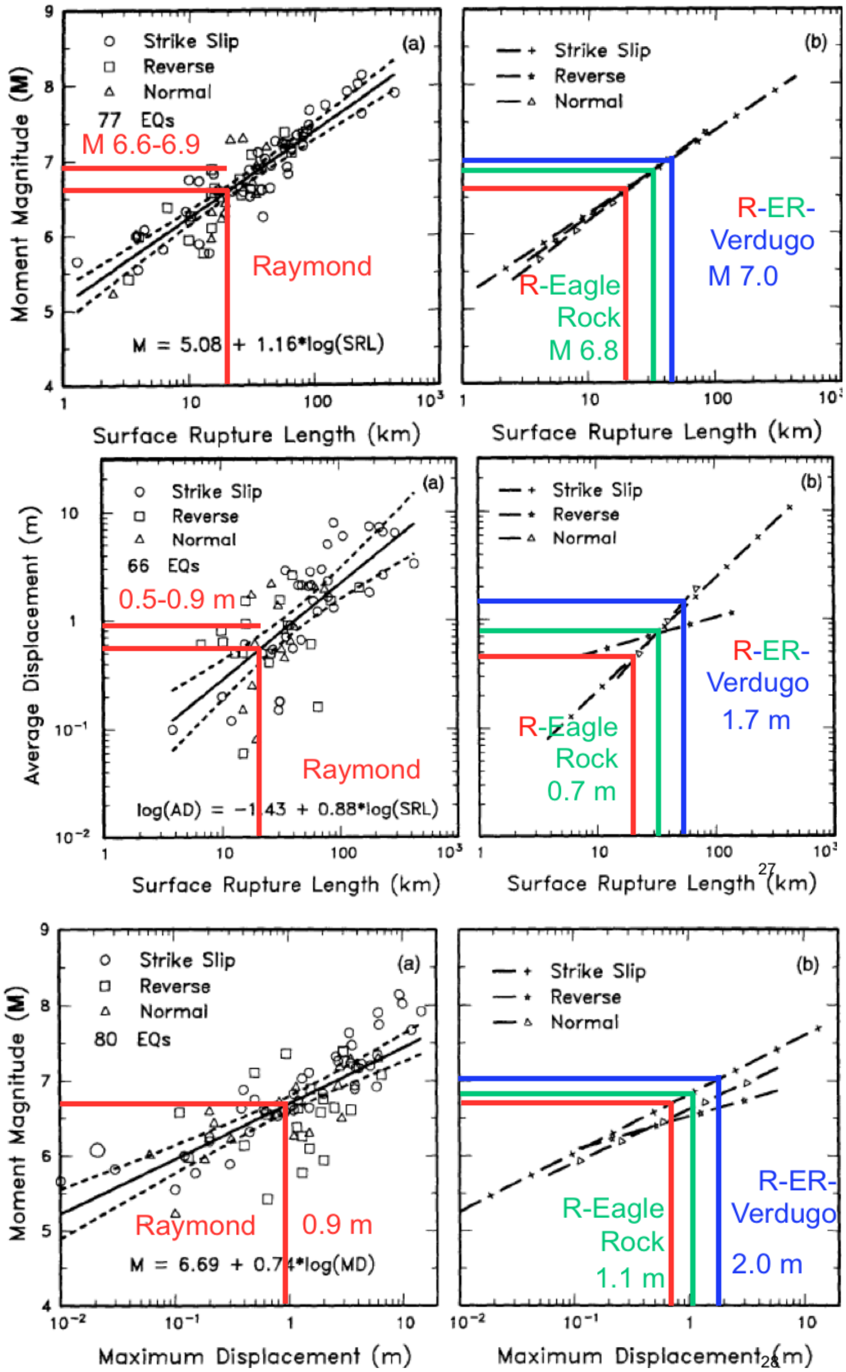

Figure 7. *Series of plots showing the increase in earthquake magnitudes and surface rupture offsets, as the length of the fault increases in a cascading rupture using the regression equation plots of Wells and Coppersmith (1994): Raymond-Eagle Rock Fault System.*

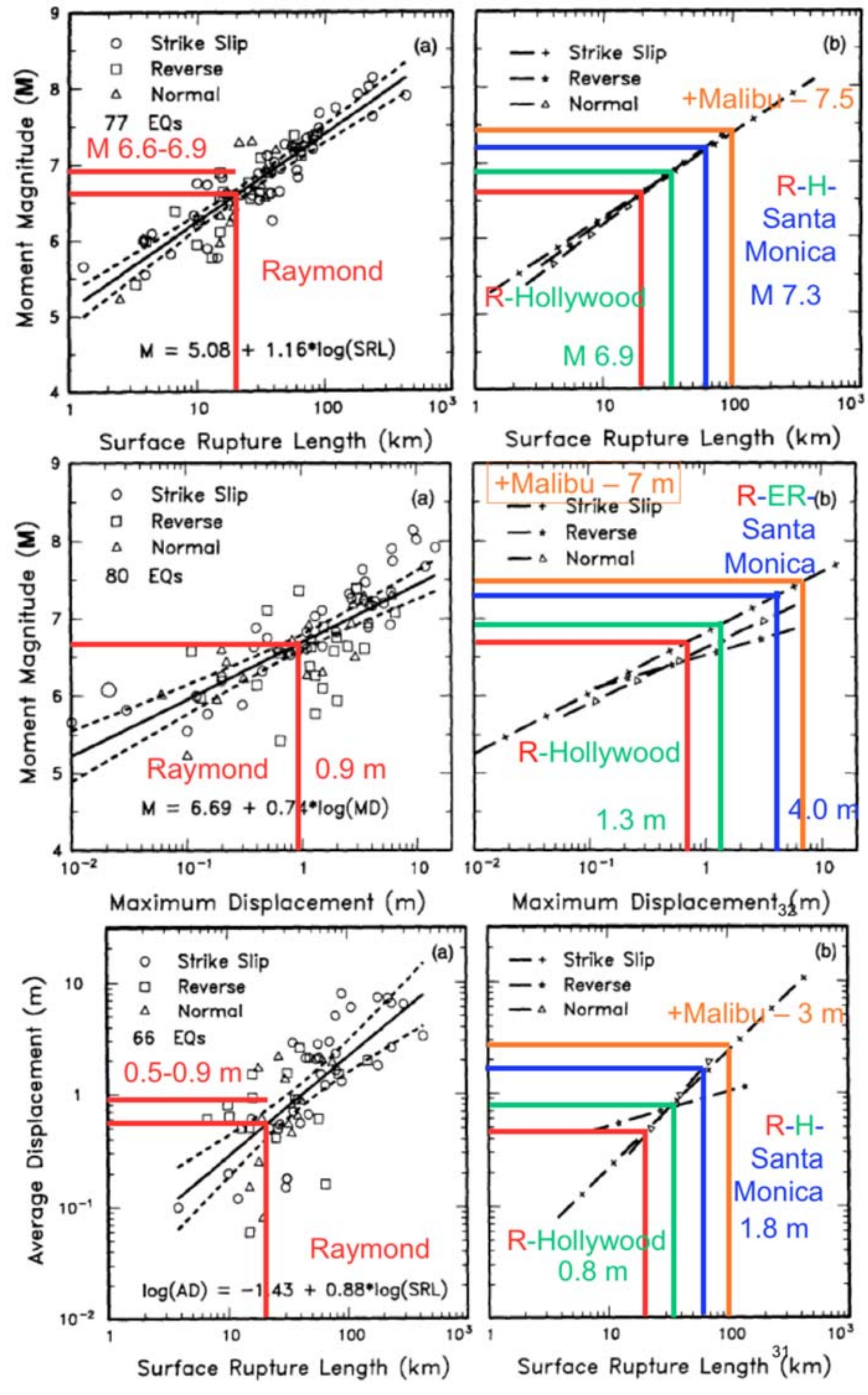

Figure 8. *A similar series of plots as those shown in Figure 7 for a more plausible earthquake scenario showing the increase in earthquake magnitude and surface rupture offsets as the fault length increases in a cascading rupture using the regression plots of Wells and Coppersmith (1994): Raymond-Hollywood-Santa Monica and Malibu Fault System.*

Note that Hanks and Bakun (2002 and 2008) and Wesnousky (2008) have reanalyzed and updated the Wells and Coppersmith plots. However, at these lower-magnitude ranges, the differences are not significant in the Hanks and Bakun model. Wesnousky (2008) replotted the Wells and Coppersmith data set by adding in more data from recent earthquakes. He generated three different fault length relationships for strike-slip faults (Relationships A, B, and C), as shown in Figure 9. Using these displacement relationships would result in larger average and maximum displacements than those estimated using the Wells and Coppersmith (1994) models, especially if the Power Law and Log-Linear relationships (B and C relationships) are used. Currently, there is no agreement on the validity of one relationship over the others, as all are considered statistically valid. The results from these Wesnousky (2008) relationships for a Raymond fault rupture of 21 km are as follows:

- Relationship A – Linear: 0.2-meter average and 0.6-meter maximum
- Relationship B – Power Law: 0.9-meter average and 2.2-meter maximum
- Relationship C – Log-Linear: 0.7-meter average and 1.6-meter maximum

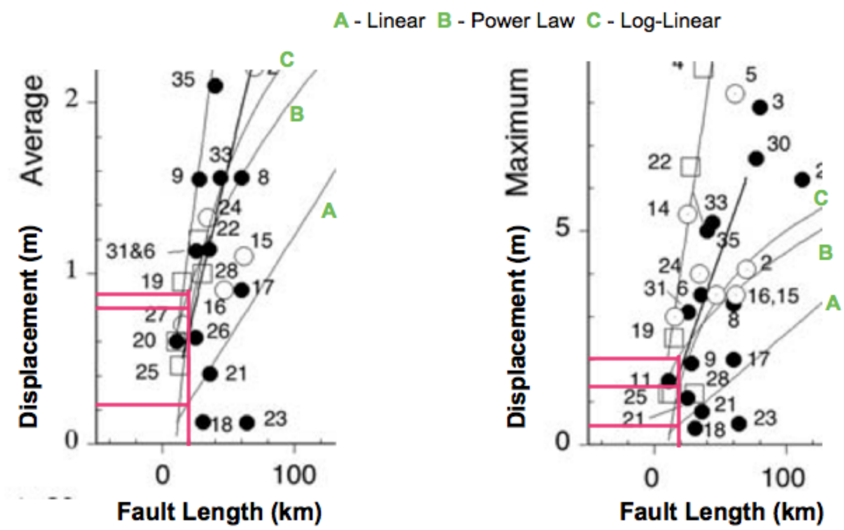

Figure 9. *Fault length – displacement plots for the Raymond fault using the Wesnousky (2008) plots. Lines A, B, and C are for strike-slip faults.*

Probabilistic Fault Displacement Hazard Analysis (PFDHA)

A PFDHA was performed for the Raymond and Eagle Rock/San Rafael faults to estimate the displacements as a function of annual rate of surface-fault displacement. The fault rupture displacements from cascading ruptures involving the Raymond fault with the Hollywood, Santa Monica, and Malibu were not considered in the PFDHA, since these cascading events cannot be demonstrated geologically and have probabilities as low as 1 in 10,000+ years. For the Eagle Rock/San Rafael fault, a combined rupture with the Verdugo fault was used in the analysis, based on the scenario shown in the Caltrans fault database (2012). For the current study, fault rupture due to principal faulting on a strike-slip fault, which is the primary faulting style of the Raymond and Verdugo-Eagle Rock/San Rafael faults, was considered.

Methodology

The methodology used in this study follows the model (Earthquake Approach) initially proposed by Youngs et al. (2003), as modified by Petersen et al. (2011) and Chen and Petersen (2011). In this model, the annual rate (v) of fault surface displacement that exceeds a specified value, d, at a site location, k, is expressed as:

$$v_k(D > d) = \propto (m^0) \int_{m^0}^{m^u} f(m) \left[\mathrm{P_k}(sr \neq 0 \backslash m) * \mathrm{P}(D > d) \backslash m) \right] dm$$

Where: $\propto (m^0)$ = annual rate of all earthquakes with magnitudes ≥ m^o

m^0 = minimum magnitude considered (M_w 5.0 was used for this study)

f (m) = probability density function of magnitude

$\mathrm{P_k}(sr \neq 0 \backslash m)$ = conditional probability that fault rupture extends to the surface (or to tunnel depth) at location k, given an earthquake with magnitude m occurs

$\mathrm{P}(D > d \backslash m)$ = conditional probability that fault displacement exceeds d, given an earthquake with magnitude m occurs

In the above equation, only the principal faulting from earthquake occurrences is considered; no secondary (distributed) fault displacement and uncertainty in the location of fault trace are modeled. The fault crossing model definition is shown in Figure 10.

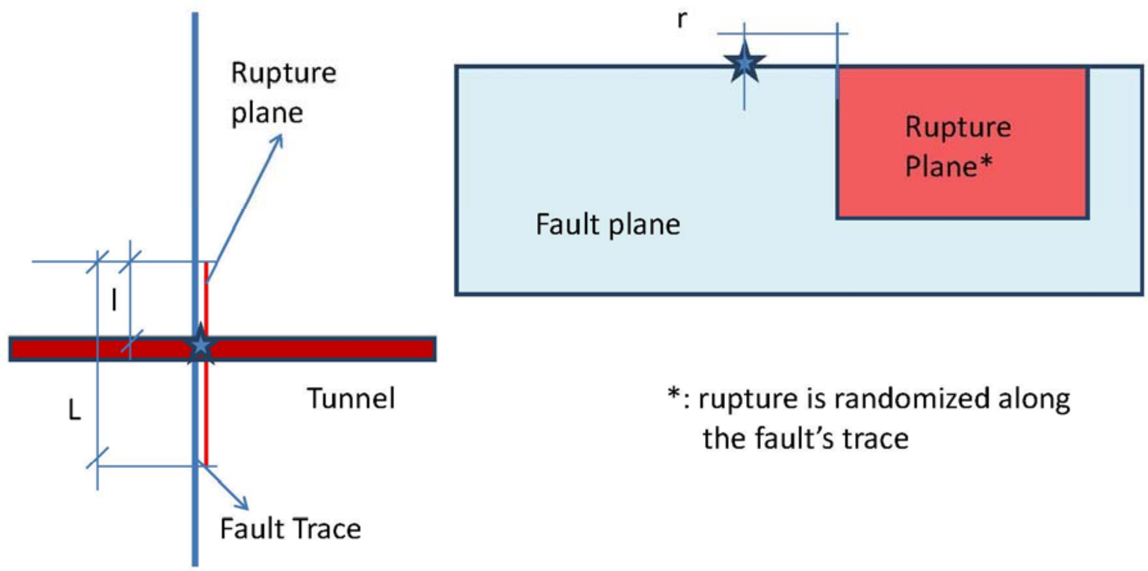

Figure 10. *Definition of Fault Crossing Model.*

The probability that nonzero displacement occurs at the tunnel depth at location k, $P_k(sr \neq 0 \backslash m)$, is calculated by randomizing the earthquake hypocenter along the fault trace and taking the ratio of fault ruptures that extend to the tunnel depth (or within a specified distance, Δ, from the tunnel depth) to the total number of ruptures for a given magnitude m. Specifically, this conditional probability of having surface rupture is estimated using the model proposed by Wells and Coppersmith (1994) for all faulting mechanisms, as follows:

$$P_k(sr \neq 0 \backslash m) = \frac{e^{a+b*m}}{1+e^{a+b*m}} \quad for\ r \leq \Delta$$

$$= 0 \qquad for\ r > \Delta$$

Since the term for the probability of having a displacement at the ground surface is included in the analyses, the hypocenter depth is not randomized. For the conditional probability that fault displacement exceeds a specified value, d, the bilinear model of Petersen et al. (2011) for strike-slip faulting was utilized:

$$\ln(D) = 1.7969 * m + 8.5206 * \left(\frac{l}{L}\right) - 10.2855 \quad for\ \frac{l}{L} < \left(\frac{l}{L}\right)'$$

$$= 1.7658 * m - 7.8962 \qquad for\ \frac{l}{L} \geq \left(\frac{l}{L}\right)'$$

$$\left(\frac{l}{L}\right)' = -0.0036 * m + 0.2804$$

The standard deviations for the first and second equations in natural log units are 1.2906 and 0.9624, respectively.

Seismic Source Characteristics for PFDHA

The seismic source parameters used in the PFDHA for the Raymond and Verdugo-Eagle Rock/San Rafael faults are listed in Table 3, along with the weights assigned to the various parameter values. .

TABLE 3
Seismic Sources Parameters for PFDHA
SR 710 North Study, Los Angeles County, California

Fault	Length (km)	Seismogenic Depth (km)	Magnitude Recurrence Model	Slip-rate (mm/yr)	Maximum Magnitude
Raymond	21	13 (0.2) 15 (0.6) 17 (0.2)	Characteristic (1.0)	1.0 (0.3) 1.5 (0.3) 2.0 (0.3) 5.0 (0.1)	6.5 (0.2) 6.7 (0.6) 6.9 (0.2)
Verdugo + Eagle Rock/San Rafael	32	13 (0.2) 15 (0.6) 17 (0.2)	Characteristic (1.0)	0.6 (1.0)	6.6 (0.2) 6.8 (0.6) 7.0 (0.2)

* Values in parentheses are weights.

Four slip-rates were assigned to the Raymond fault, with the majority of weight (90 percent) given to the most probable values of 1.0 to 2.0 mm/yr (see Table 1) and a small weight (10 percent) assigned to the high value reported by Yeats (2012). The characteristic earthquake magnitude recurrence model and a b-value of 1.0 were used for the analyses.

Results of PFDHA

The calculated fault rupture hazard curves for the Raymond and Verdugo-Eagle Rock/San Rafael faults are shown in Figure 11. The calculations were performed for a Δ value of 200 meters to account for the depths of the freeway and LRT tunnels and at the LRT fault crossing locations. Since the fault crossing locations at the LRT and freeway tunnels are close to each other (relative to the length of the fault), the results calculated herein for the LRT tunnel can also be used for the freeway tunnel.

As can be seen from Figure 11, the median fault displacements at the tunnel-Raymond fault crossing location for return periods of 1,000 and 2,500 years are ±5 centimeters (0.05 meter) and ±55 centimeters (0.55 meter), respectively. The calculated displacements at the tunnel-Verdugo-Eagle Rock fault crossing location for the same return periods are insignificant (less than 1 centimeter [0.01 meter]).

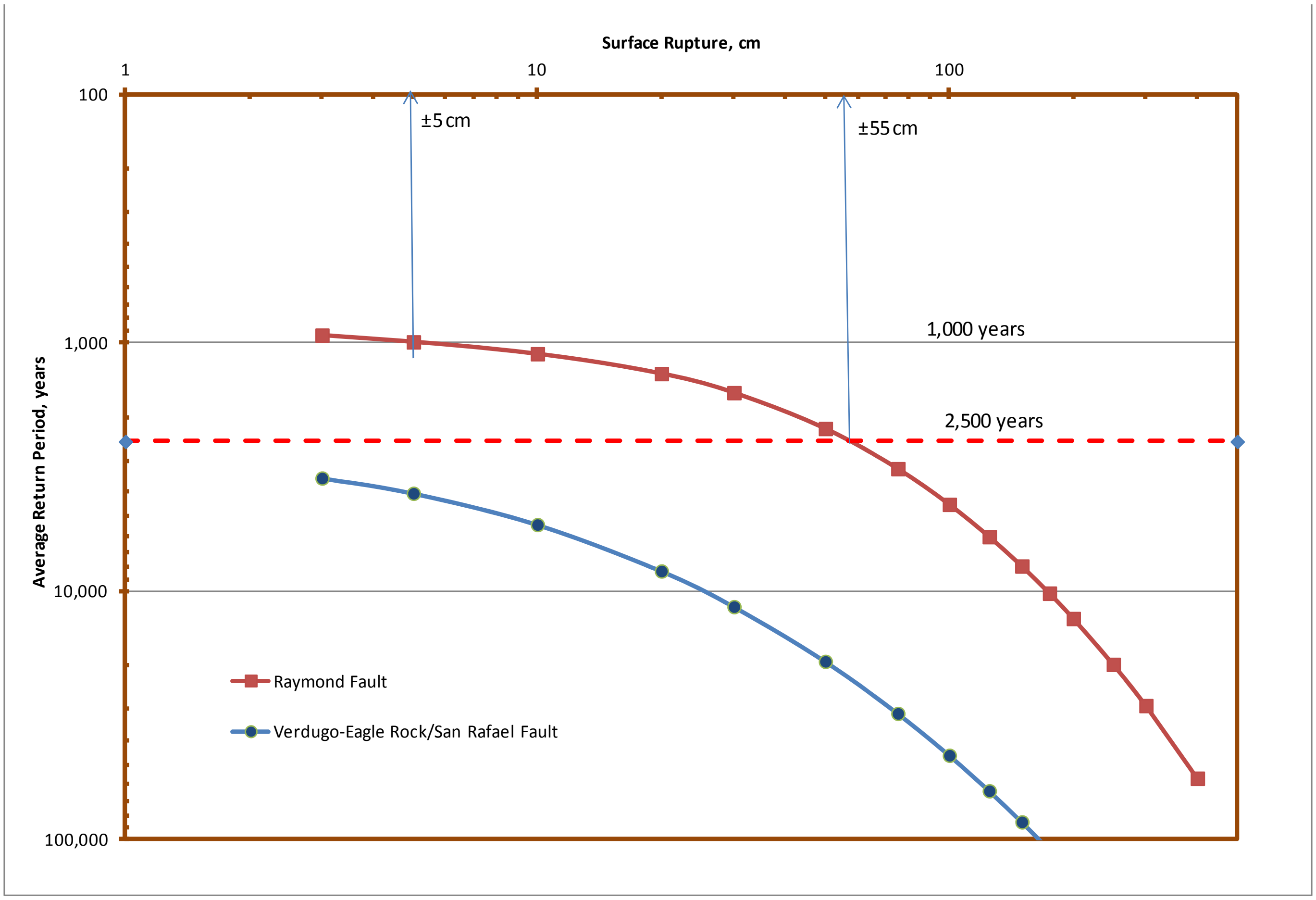

Figure 11. *Calculated Fault Displacement Hazard Curves for Raymond and Verdugo-Eagle Rock/San Rafael Faults.*

Seismic Design Criteria

The appropriate seismic design criteria for the tunnels, relative to fault displacement, will depend on whether the LRT or the Freeway Tunnel option is selected for implementation. The following two sections summarize the criteria for each of these options.

LRT Tunnel

Metro Supplemental Seismic Design Criteria (Revision 5, 2013) will be used for the LRT. It uses "Important Transit Facility" for LRT classification. Two levels of seismic event, consisting of Maximum Design Earthquake (MDE) and Operating Design Earthquake (ODE), must be considered for LRT tunnel design in accordance with the Metro Supplemental Seismic Design Criteria.

- The MDE is defined as ground motion with a 2,500-year return period; the performance under the MDE event is as follows:
  - No collapse.
  - Structures are allowed to behave in an inelastic manner.
- The ODE is defined as ground motion with a 150-year return period; the performance under the ODE event is as follows:
  - Tunnel remains serviceable; no interruption in rail service during or after ODE.
  - Structures behave essentially elastic.

Relative to Metro's seismic design criteria, the MDE and ODE requirements would have to be satisfied for fault displacements that have an average return period of 2,500 years and 150 years, respectively.

Freeway Tunnel

No Caltrans seismic design criteria for tunnels are currently available. For this preliminary design phase to support the environmental documentation, it was agreed that the Caltrans seismic design criteria for an Ordinary Nonstandard facility will be used as the basis for seismic design of the Freeway Tunnel Alternative. This facility classification is equivalent to Recovery Route classification. Two levels of seismic event, consisting of Safety Evaluation Earthquake (SEE) and Functional Evaluation Earthquake (FEE), should be considered for the Freeway Tunnel design. Project site-specific seismic design criteria will be developed in future design phases and used for final design of the Freeway Tunnel.

- The SEE is defined as ground motion with a 1,000-year return period; the performance under the SEE event is as follows:
  - Minimal to moderate damage may occur, as long as moderate damage is confined to local areas.
  - The ductility of the tunnel should be between 2.5 and 3.0, similar to the ductility used in bridge capacity design.
- The FEE is defined as ground motion with a 100-year return period; the performance under FEE is to ensure that the tunnel is fully functional with minimal damage.

Relative to Caltrans seismic design criteria, the SEE and FEE requirements would have to be satisfied for fault displacements that have an average return period of 1,000 years and 100 years, respectively.

Design Summary

The fault rupture displacements at the fault crossing locations, relative to different design criteria for the LRT and Freeway Tunnel Alternatives, are summarized below.

LRT Tunnel

The seismic design criteria for the LRT are based on a fault rupture displacement with a return period of 2,500 years for the MDE and 150 years for the ODE, as discussed above. The following displacements are recommended for preliminary design.

- **Raymond Fault:** The deterministic estimates for the average and maximum offsets using the Wells and Coppersmith (1994) model are 0.5 meter and 0.9 meter, respectively. The probabilistic estimate for the MDE is 0.55 meter, while that for the ODE is less than 0.05 meter. As discussed above, these estimates are for ruptures on the Raymond fault only; no cascading ruptures were considered because of their low probability of occurrence.

Because of the large range of inconsistencies in the geological understanding of the Raymond fault, as discussed above, a left-lateral fault offset of 1.0 meter and a vertical reverse offset of 0.2 meter is considered appropriate for the Raymond fault, across a fault zone of 25 meters in width. This is based on the maximum rupture displacement for a 21-km-long fault, with a 20 percent vertical uplift component distributed onto one major and several minor fault strands. At the proposed tunnel depth, it is estimated that 75 to 100 percent of this displacement would occur on a single (main) fault strand, while any additional deformation would most likely be distributed on the hanging wall (north side).

Note that somewhat larger displacements than Wells and Coppersmith (1994) are obtained with the Power Law and Log-Linear formula of Wesnousky (2008), while a smaller value is obtained from his linear formula. However, the Wells and Coppersmith (1994) model is the most widely used model in practice and is considered appropriate for these preliminary estimates.

- **Verdugo-Eagle Rock and San Rafael Faults:** The deterministic estimate for maximum offset using the Wells and Coppersmith (1994) model for the 11-km Eagle Rock or San Rafael fault is 0.3 meter left-lateral and 0.2 meter reverse-vertical. Combining the Verdugo fault would increase the fault length to 32 km and the maximum offset would increase to 1.1 meters. The probabilistic displacements for MDE and ODE were estimated to be insignificant.

  As discussed previously, no data have been published to confirm or refute the presence of Holocene-age offsets on the Eagle Rock/San Rafael faults, nor on the Verdugo fault farther northwest. These faults are not in Alquist-Priolo Act fault zones, and per the Caltrans Memo to Designers (2013), they are not candidates for fault displacement mitigation. In addition, there is a large range of inconsistencies in the geological understanding of these faults and the uncertainty as to how they would rupture together and how they would interact with the Raymond fault in a joint rupture. For the purpose of this technical memorandum, prepared for the environmental documentation process, the Verdugo-Eagle Rock and San Rafael faults are considered active, though they could have a 10,000+ year recurrence rate.

  Because only the San Rafael strand of the Verdugo-Eagle Rock/San Rafael fault zone trends across the LRT tunnel alignment, it seems reasonable to reduce the 1.1 maximum displacement of the entire fault zone by about 50 percent. For the conceptual/preliminary design, therefore, preliminary design values of 0.5 meter left-lateral and 0.25 meter reverse-vertical could be considered for the LRT tunnel crossing. While this is likely a 10,000+ year event scenario, there are insufficient fault data presently to preclude it in the preliminary/conceptual design phase. These preliminary fault offset values should be updated by performing additional geological/fault investigations in future design phases.

Freeway Tunnel

The seismic design criteria for the Freeway Tunnel are based on fault rupture displacement with a return period of 1,000 years for the SEE and 100 years for the FEE, as discussed above. The following displacements are recommended for preliminary design.

- **Raymond Fault:** The deterministic estimates for the average and maximum offsets using the Wells and Coppersmith (1994) model are 0.5 meter and 0.90 meter, respectively. The probabilistic estimate for the SEE is 0.05 meter, while that for the FEE would be less than 0.05 meter. Similar to the LRT tunnels, these estimates are for ruptures on the Raymond fault only, without any contributions from the cascading events.

  Per the Caltrans Memo to Designers (2013), the design fault offset is taken as the larger of:

  – Deterministically derived *average* displacement

  – Probabilistically derived displacement consistent with a 5 percent in 50 years probability of exceedance or a 975-year return period

  Displacement estimates from the DFDHA exceed displacements from the PFDHA, and therefore, the deterministically derived average displacement should be used as a basis of design according to the Caltrans Memo to Designers (2013). Based on this Caltrans procedure, a left-lateral fault offset of 0.5 meter and a vertical reverse offset of 0.1 meter can be considered for the Raymond fault, across a fault zone of 25 meters in width. This is based on the average rupture displacement for a 21-km-long fault, with a 20 percent vertical uplift component distributed onto one major and several minor fault strands.

At the proposed tunnel depth, it is estimated that 75 to 100 percent of this displacement would occur on a single (main) fault strand, while any additional deformation would most likely be distributed on the hanging wall (north side).

- **Verdugo-Eagle Rock and San Rafael Faults:** Based on the Wells and Coppersmith (1994) model, the average deterministic displacement for an 11-km fault is 0.2 meter left-lateral and 0.1 meter reverse-vertical (can be assigned across a fault zone 50 meters in width). Combining the Verdugo fault would increase the fault length to 32 km and the average offset would increase to 0.7 meter. The SEE and FEE probabilistic displacements were estimated to be insignificant and are less than 0.01 meter.

  As discussed above in the LRT design summary, there are no published or unpublished data that indicate the San Rafael or Verdugo-Eagle Rock faults have had Holocene-age offsets. These faults are also not in Alquist-Priolo Act fault zones, and per the Caltrans Memo to Designers (2013), they are not candidates for fault displacement mitigation.

  Because the San Rafael and Eagle Rock strands of the Verdugo-Eagle Rock/San Rafael fault zone trend across the Freeway Tunnel alignment at separate locations, it seems reasonable to reduce the 1.1 maximum displacement of the entire fault zone by about 50 percent at each fault. For preliminary design, the above-mentioned deterministic fault offsets for the LRT tunnels (0.5 meter left-lateral and 0.25 meter reverse-vertical) could be considered for the Freeway Tunnel. While this is likely a 10,000+ year event scenario, there are insufficient data to preclude it in the preliminary/conceptual design phase. These preliminary fault offset values should be updated by performing additional geological/fault investigations in future design phases after the preferred Alternative is selected.

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