

A Simplified Probabilistic Fault Displacement Hazard Analysis Procedure: Application to the Seattle Fault Zone, Washington, USA

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ABSTRACT

This paper extends a simplified probabilistic fault displacement hazard analysis (PFDHA) procedure to estimate the probability of surface fault displacement for the relatively low average slip rate Seattle fault zone in Washington, USA. The proposed procedure incorporates recent research to estimate earthquake magnitude and fault displacement—two key inputs to any PFDHA. A parametric study evaluates the sensitivity of the results to changes in the key PFDHA input parameters. Probabilistically-determined fault displacement hazard along the Seattle fault is most sensitive to fault type; and the choices of empirical models for maximum earthquake magnitude and average surface fault rupture scaling.

Introduction

Ever since the extensive damage that accompanied the 1971 Sylmar earthquake in California, policy makers, engineers and scientists have grappled with ways to mitigate surface rupture hazards to buildings and urban lifeline infrastructure. While the California Alquist-Priolo Earthquake Fault Zone Act mandates avoidance for structures for human occupancy, building across active faults can often be unavoidable. The need to provide transportation, water, gas and electrical infrastructure to existing facilities often precludes avoidance as a viable active fault mitigation strategy. In the many situations structural design needs to accommodate surface fault displacement at a level of risk acceptable to infrastructure owners and the communities they serve. For engineers, therefore, a major design consideration is their ability to use accepted, robust analytical procedures to accommodate coseismic ground deformation and/or differential displacements that can range from centimeters to up to 10 meters (m) in a single earthquake (ASCE 1984). The quantification of active fault or fault zone coseismic displacement becomes a vital input for seismic design of critical facilities that cross active faults.

Existing guidelines for surface fault rupture assessment and mitigation typically suggest that displacement design be based on a deterministic evaluation. Deterministic evaluations use empirical earthquake magnitude-fault displacement scaling relations to predict the amount of fault rupture for a given earthquake magnitude and/or average fault slip rate. Deterministic analyses are often calibrated with detailed site investigations including shallow trenching where the facilities cross the active faults. Field-determined values can then be adjusted to the known level of uncertainty and potential consequence of failure. The process, however, is generally not used for small- to medium-sized projects because of the substantial cost of site-specific investigations. Deterministic evaluations provide single-value estimates, but are limited because they do not account for any uncertainties associated with input parameters.

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An alternative approach is probabilistic fault displacement hazard analysis (PFDHA). Youngs et al. (2003) describe two general methods for PFDHA—probabilistic-earthquake-based and displacement-based approaches. These approaches were developed for normal faults encountered at the proposed nuclear waste disposal facility at Yucca Mountain, Nevada, USA (Stepp et al. 2001). A similar probabilistic-earthquake-based approach was developed for the Wasatch fault in central Utah, USA by Braun (2000). Petersen et al. (2011) and Moss and Ross (2011) extended the probabilistic earthquake approach and applied it to strike-slip and reverse faults in California, USA. More recently, Shantz (2013) presented simplified procedures developed by the California Department of Transportation (Caltrans)—the Caltrans procedures—to evaluate fault displacement on strike-slip faults in California. The Shantz (2013) procedures are based on the method developed by Abrahamson (2008). The underlying methodology for these methods/procedures is probabilistic-earthquake-based. The procedures are similar in approach to methods applied in probabilistic seismic hazard analysis (PSHA). The probabilistic-earthquake-based approach in PFDHA relates surface fault displacement to the occurrence of an earthquake; but unlike PSHA, the earthquake approach in PFDHA replaces the ground motion prediction equation with a fault displacement prediction equation.

This paper presents a simplified PFDHA procedure that is an application and extension of the Caltrans procedures—originally developed for strike-slip faults in California—to estimate the probability of surface fault displacement for a low slip rate reverse fault. The extended procedure reported in this paper incorporates up-to-date research on earthquake magnitude and fault displacement estimation. We applied the extended procedure to a known, active reverse fault—the Seattle Fault Zone (SFZ)—in Washington.

Simplified Fault Displacement Hazard Analysis Procedure

Caltrans Procedures

The Caltrans fault displacement hazard analysis procedures (Caltrans procedures) assume that the site of interest is located on a fault that ruptures to the surface during large earthquakes within a narrow range of magnitudes (characteristic earthquake). The Caltrans procedures have the following key steps:

- Estimate the characteristic earthquake magnitude (moment magnitude or M_w) for the fault of interest using known or estimated fault parameters, e.g., fault length and/or area. Earthquake magnitudes are estimated using empirical earthquake magnitude scaling relations.
- Estimate the recurrence interval of the characteristic earthquake using the following equation:

$$Tr = \frac{M_0}{0.8\dot{M}_0}$$

Where \dot{M}_0 is the moment rate and M_0 is the seismic moment. The moment rate is estimated using the equation $\dot{M}_0 = \mu AS$, where μ is the crustal rigidity; A is the effective fault area after taking into account any aseismic factor; S is the fault slip rate. The seismic moment is estimated using the relation developed by Hanks and Kanamori (1979).

- Estimate the lognormal distribution of the average surface rupture displacement value for the characteristic earthquake using an empirical average fault displacement prediction equation.

- Estimate the fault rupture hazard curve using the following equation:

$$v(d) = \alpha P(D > d | M_w)$$

Where α is the mean annual rate of earthquakes with a minimum magnitude or greater from a specific source and d is a specific fault displacement level.

The Caltrans procedures, however, were developed to estimate the surface rupture probability for relatively high slip-rate faults located in the North America-Pacific plate boundary zone in California. The Seattle fault is a reverse fault located away from the major plate boundary. To reflect its specific faulting style and regional tectonic setting, we extended the Caltrans procedures by selecting appropriate empirical magnitude scaling relation and empirical displacement prediction equations. Selection of these empirical relations is discussed below.

Maximum Moment Magnitude Scaling Relation

Similar to PSHA, a fundamentally important component in PFDHA is the need to estimate the earthquake magnitude from fault parameters such as fault rupture length/width and/or fault area. A wide range of empirical earthquake scaling relations have been developed based on different worldwide historical datasets and using varying regression forms. Different scaling relations can result in significant different earthquake magnitude estimates.

We adopted the scheme of Stirling et al. (2013) to select empirical earthquake magnitude scaling relations according to their relevance to predefined tectonic regimes, such as plate boundary crustal regime and fault slip types. Caltrans procedures use the equations developed by Hanks and Bakun (2008) that, according to Stirling et al. (2013), are most suitable for strike-slip faults located on fast-moving plate boundaries. The Seattle fault studied in this paper, however, is a reverse fault located away from the major plate boundary. We selected three regression equations for use in reverse fault setting, including Stirling et al. (2008), Wesnousky (2008) and Yen and Ma (2011), referred to as S08, W08 and YM11 hereafter. These magnitude scaling equations were selected because they were developed recently using relatively robust and applicable datasets, and they were recommended by Stirling et al. (2013) for reverse fault tectonic regimes. Among the three equations, the Yen and Ma (2011) magnitude scaling relation had the highest quality score from Stirling et al. (2013) and/or was the most suitable regression for the contractional tectonic regime in this part of western North America.

Average Fault Displacement Prediction Equation

Fault displacement prediction equations in PFDHA characterize the ground displacement along a fault ruptured under earthquakes with varying magnitude. Historical fault rupture data have been collected and global scaling relations developed to relate fault displacement amount and earthquake magnitude. Out of the available equations, three alternatives are considered and compared in this paper, including the equations presented in: 1) Wells and Coppersmith (1994) for all fault types, 2) Hecker et al. (2013) for all fault types, and 3) Moss and Ross (2011) for reverse faults. These equations are referred to as WC94, H13 and MR11, respectively.

The variability of displacement at the site is defined in terms of the coefficient of variation (CV) about 0.5 as estimated in Hecker et al. (2013), instead of using the variability in the global scaling relations between average displacement and earthquake magnitude. The

variability for the global relations, according to Hecker et al. (2013), is a likely overestimation of the fault-specific variability in average displacement because it contains possible fault-to-fault and regional variations as well as observational uncertainties.

Case Study

Seattle Fault Zone

We illustrate the simplified PFDHA procedure with the SFZ as a case study. The east-west striking SFZ presents a fault rupture hazard to the Puget Sound region with a metropolitan population of approximately 3.6 million people. The integrity of regional lifelines—transportation, energy, water, and other critical infrastructure—is an important factor in earthquake resilience for the wider Puget Sound community. Many major lifelines are oriented north-south along the eastern side of Puget Sound and are located perpendicular to the SFZ (Figure 1). These lifelines include three interstate freeways, at least one 500 kW electric transmission line, at least three natural gas or liquid fuel pipelines, and at least three major sewer lines (Haugerud et al. 2002; Ballantyne et al. 2005). Any future surface rupture of the SFZ can be expected to generate surface displacement across these lifelines.

The SFZ is mapped as an approximately 5-kilometer (km)-wide, 70-km-long series of east-west striking, south- and north-dipping reverse-slip faults that separate the Seattle basin to the north (footwall) from the Seattle uplift in the south (hanging wall) (Johnson et al. 1999; Liberty and Pratt 2008). The SFZ juxtaposes Neogene-age (23 to 2.6 million years ago) rocks to the south with younger Quaternary-age (last 2.6 million years) basin fill to the north. The hanging wall of the SFZ includes a number of north-dipping backthrusts, such as the Toe Jam Hill (on Bainbridge Island) and Waterman Point faults (on Pt. Glover Peninsula). These faults dip northward into the main south-dipping faults and locally create “pop-up” structures (Blakely et al. 2002; Nelson et al. 2003). The backthrusts are not considered to be independent seismogenic sources that produce large earthquakes and associated surface fault rupture. Instead, the backthrusts accommodate slip on the main, south-dipping SFZ faults, and therefore, only experience displacement when the main SFZ ruptures.

This PFDHA requires geological input parameters for fault length, fault dip, fault locking depth, average fault slip rate, rigidity and the aseismic factor. Creep has not been observed for the SFZ and the aseismic factor is assumed to be zero. The crustal rigidity is assumed to be 3.0×10^{11} dynes/cm². The other fault rupture parameters were taken or derived from the open literature. The following sections discuss each parameter briefly. Table 1 summarized the values selected for use in the PFDHA.

Fault Length

Published estimates of the total length of the SFZ range from 68 km (Johnson et al. 1999; Blakely et al. 2002) to 75 km (Brocher et al. 2000). We use a total fault length of 69 km, as preferred by the authors of the Seattle Fault section of the US Geological Survey (USGS) Quaternary Fault and Fold Database (Johnson et al. 2004).

Fault Dip

Estimates of the fault dip range from 25° to 80° (Johnson et al. 2004). We use an intermediate dip value of 55° south because it is the mean of Johnson et al.’s (1999) estimate range from 45° to 65°.

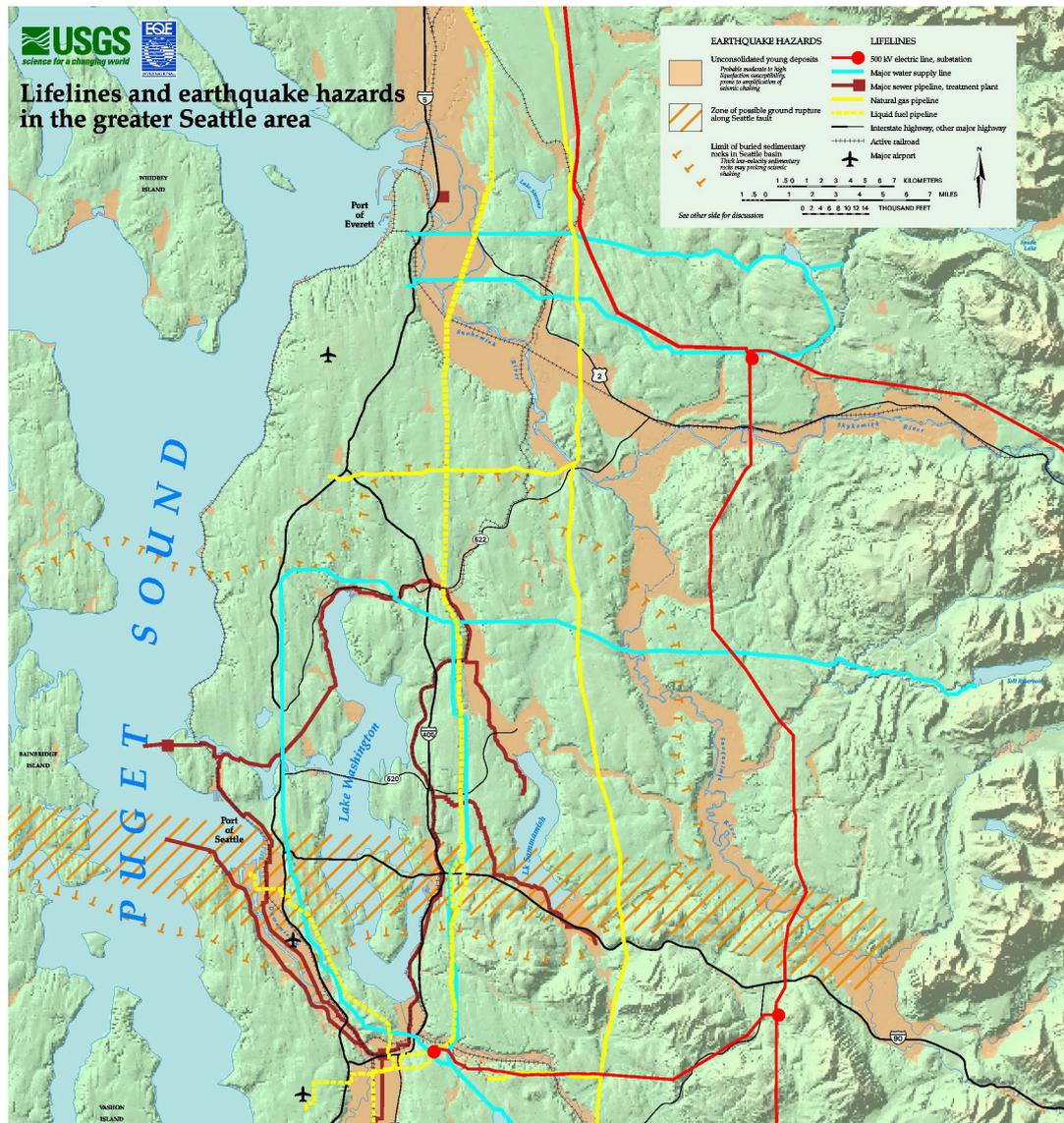


Figure 1. Location of Seattle fault zone (SFZ) and major lifelines. The SFZ (hatched area) intersects a 500kV electric line (red); major sewer lines (dark red); natural gas or liquid fuel pipelines (yellow); interstate and other major highways (black) (figure after Haugerud et al. 2002).

Fault Locking Depth

We estimate the hypocentral depth for the earthquake that generates slip on the SFZ to be about 18 km. This depth is the median depth of instrumental seismicity ($M > 2$) in the Puget Sound region ($n = 340$). Nearly 99% of the located earthquake hypocenters have specified hypocentral depths above ~34 km. This depth, however, is probably deeper than most surface-rupturing events, and we favor the shallower depth of 18 km. This depth is in accordance with the result of Blakely et al. (2002) who reported that 60% of earthquake hypocenters in the region surrounding the SFZ occur at depth between 15 km and 25 km, with a mean depth of 17.6 km.

Average Fault Slip Rate

Estimates of the average fault slip rate for the SFZ range from 0.2 millimeters per year (mm/year) to 1.0 mm/year (Johnson et al. 2004; Johnson et al. 1999; Calvert et al. 2001; ten Brink et al. 2002; Nelson et al. 2003). Nelson et al. (2003) estimated average slip rates as high as 2 mm/year based on paleoseismic trench data. They concluded, however, that this higher fault slip rate probably results from temporal clustering of earthquakes and is not representative of the long-term average slip rate. We use the preferred slip rate assigned by the USGS Quaternary Fault and Fold Database, 0.9 mm/year (Johnson et al. 2004).

Table 1. Fault parameters for the SFZ.

Parameter	Preferred Value	Lower Limit	Upper Limit
Fault Length (km)	69	68	75
Dip Angle (°)	55	25	80
Fault Locking Depth (km)	18	15	25
Slip Rate (mm/year)	0.9	0.2	1.0

Results

The main output of a PFDHA is a hazard curve showing the annual exceedance probability (AEP) of a fault displacement exceeding fault displacement levels. The hazard curve for SFZ displacement near Seattle, Washington is shown in Figure 2. Since the estimated characteristic M_w 7.3 earthquake has a recurrence interval of about 3,300 years, the fault displacement for return periods less than 3,300 years, such as 150 years and 2,500 years, is negligible. The estimated fault displacement for 10,000-year return period is close to 1.6 m.

Parametric Study of Fault Parameters

We completed a limited parametric study to assess the sensitivity of the analysis results to reasonable and possible variations in the “best estimate” fault parameters. The best-estimate analysis case that uses the preferred parameters is listed in Table 1 and empirical equations—YM11 and MR11 for reverse faults—is the “baseline” case. The parametric study results indicate that within the range of generally accepted SFZ fault activity parameters, the surface fault rupture hazard is most sensitive to the average fault slip rate and dip angle. It is much less sensitive to locking depth and fault length. For example, an increase in dip angle from 25° to 55° results in a 4% and 19% increase in fault displacement at 5,000-year and 10,000-year return periods, respectively. In comparison, the estimated fault displacement only increases by 1% and 2% at 5,000-year and 10,000-year return periods, respectively, when the fault length increases from 69 to 75 km.

Parametric Study of Scaling Relations

The results of a parametric study on maximum earthquake magnitude scaling relation and average fault displacement prediction equation are shown in Figure 3. Application of the empirical equations—YM11 and MR11 for reverse faults—is the baseline case. Compared to the baseline case, the cases using alternative moment magnitude scaling relations provided an appreciably lower fault displacement hazard at a 5,000-year return period. The cases using the average displacement prediction equations—WC94 and H13 for all faults—result in a much higher fault displacement at 5,000- and 10,000-year return periods.

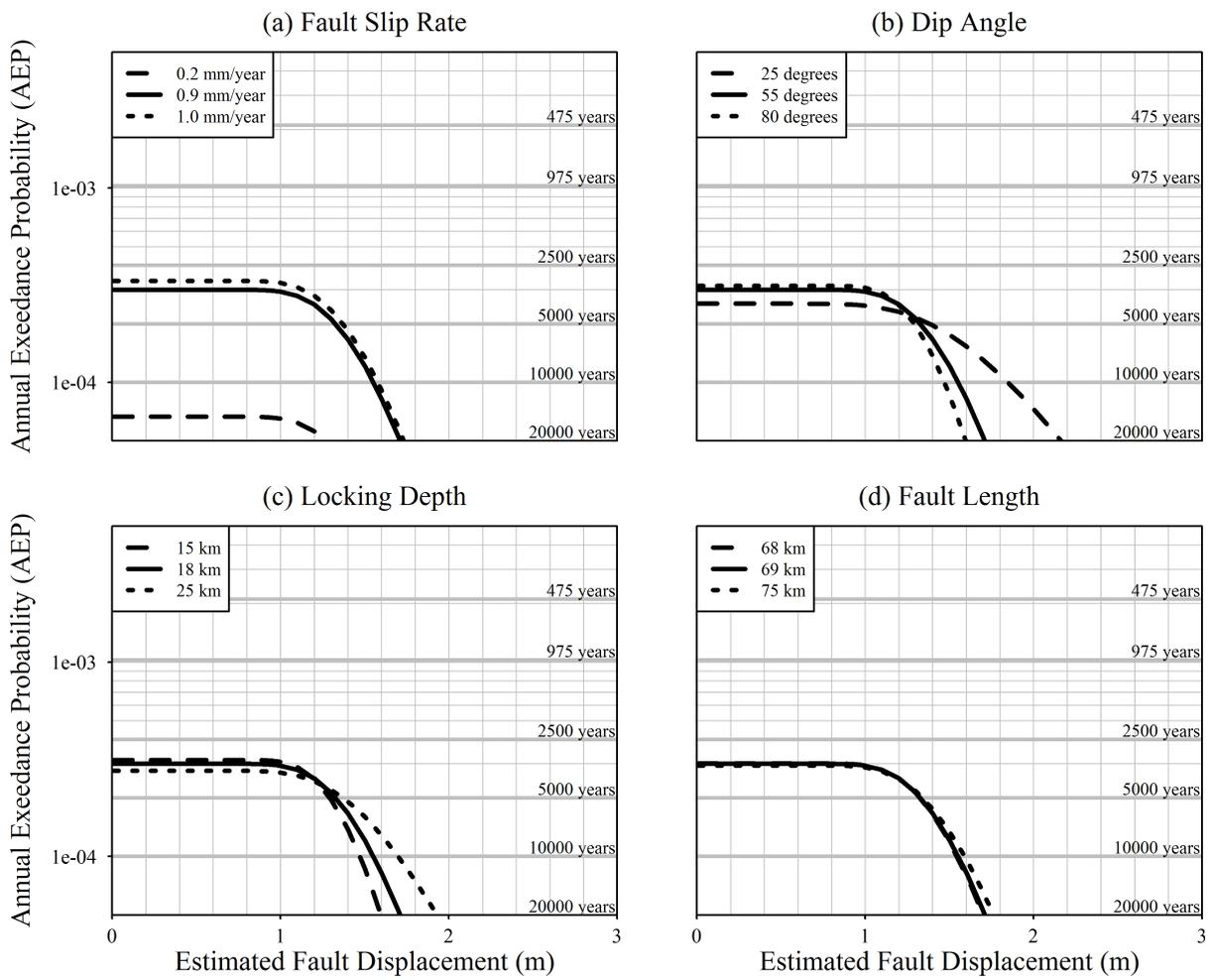


Figure 2. Fault displacement hazard curve and its sensitivity to (a) fault slip rate; (b) dip angle; (c) locking depth; (d) fault length.

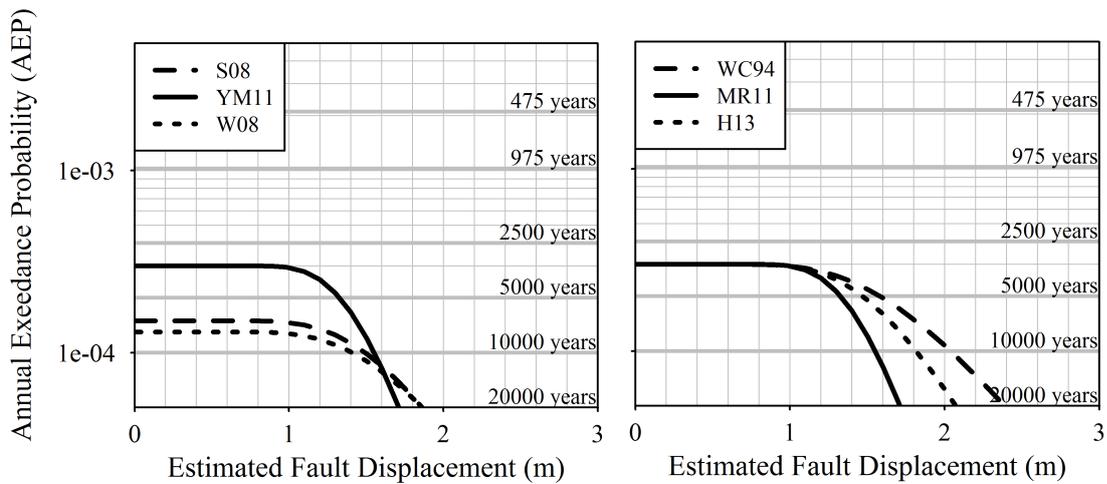


Figure 3. Sensitivity of fault displacement hazard curve to (left) earthquake magnitude scaling relations; (right) average displacement prediction equation.

Discussion

The Caltrans procedures of Shantz (2013) have been applied and extended in this study to estimate fault rupture hazard for the relatively low average slip rate SFZ in Washington, USA. The extended procedure incorporates recent research results on earthquake magnitude and fault displacement estimation. The SFZ fault rupture hazard curves can be used to support informed, risk-based decision making for lifeline owners and operators in the Puget Sound area.

We note that both the original and extended Caltrans procedures have several assumptions that may limit their wider applicability. For example, both procedures assume that the surface fault rupture at any point is the average displacement occurring on the fault even though historic surface fault ruptures show asymmetric slip distributions (Wesnousky 2008; Petersen et al. 2011). Another assumption is that the SFZ is the only contributor to the fault displacement hazard at the site. That is, all fault slip occurs on the SFZ and the slip is from earthquakes occurring on the specific fault rather than triggered by large slip on other crustal faults. The off-fault displacement from other crustal faults is assumed to be negligible compared to the primary fault displacement. We recognize that in some design applications it will be necessary to estimate the amount and distribution of off-fault deformation as well as slip on the primary rupture surface.

Unlike PSHA, PFDHA is a relatively new procedure and less mature in its practical applications. Nevertheless, this site-specific PFDHA procedure incorporates the best estimates of fault parameters, current understanding of the PFDHA methodology; and a range of established empirical magnitude and fault displacement scaling relations. Our results indicate that the fault displacement hazard is sensitive to the fault parameters and empirical relations used to estimate the maximum earthquake magnitude and average fault rupture along the fault. PFDHA is subject to significant uncertainties, and careful consideration is needed when characterizing the contributing faults and selecting empirical relations.

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