FAULT DISPLACEMENT HAZARD FOR STRIKE-SLIP FAULTS

M.D. Petersen¹, R. Chen²

ABSTRACT

In this paper we summarize data, methods, and models developed for a probabilistic assessment of fault displacement hazards across the U.S. We compare earthquake displacement data and empirical fault displacement models that have been developed for normal faults, strike-slip faults, and reverse faults. In general, the data and models are similar near the center of the fault for the three faulting types, but differ near the ends with the strike-slip data being lower than the reverse and normal faulting data. We also compare these U.S. models with data and equations developed using Japanese fault displacement data. The Japan model is also similar to the U.S. models near the center of the fault but decays less rapidly near the ends of the fault. In addition, we discuss impacts of models developed to analyze off-fault strain on secondary faults, multi-strand displacement hazard, and various mapping quality factors. For our study, we show example fault displacements for a M 7 fault with recurrence of 800 and 1600 years. We conclude that a deterministic assessment of fault displacements is often higher than the probabilistic displacements for less active faults with earthquake rupture recurrence that is longer than the hazard return period of interest. Fault displacement hazard is applied in engineering applications for buildings, bridges, pipelines, and nuclear facilities. We present three applications for fault displacement hazard at nuclear facilities and important structures.

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Introduction

Fault displacement hazard can be a significant cause of damage in the near field of a fault rupture. In California legislation, builders are required to simply avoid a Holocene fault (e.g., 1972 California Alquist-Priolo Fault Zoning Act that accounts for faults with movement during the past 11,000 years). However, in some cases it is difficult or impossible to relocate the structure or lifeline and so engineering design is required to accommodate potential future fault displacements. For example, many pipelines in areas of active tectonics require a fault crossing (e.g., the Alaska pipeline crossing of the Denali, Alaska fault that ruptured in a November 3, 2002, M 7.9 event). For lifeline engineers, the consequences of a rupture displacement on a pipe or other system may impact the land and those who rely on the water, oil, or other resources being transported. Transportation engineers typically assess displacement hazard for bridges and roads that cross major faults to avoid collapse. Engineers are capable of avoiding or limiting the potential damage by adding some level of flexibility to the structural system.

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This paper describes methods of assessing the hazard of fault displacement. Fault displacement data have been collected and digitized over the past decades for many large global earthquakes. Global empirical data have been analysed and used in developing models for probabilistic fault displacement hazard analysis (PFDHA). Typically, models account for displacements that are highest in the middle and decay near the ends of the fault. Displacements are typically quantified in terms of earthquake magnitude and location along the fault strike or are normalized by the average displacement. In the U.S. three PFDHA methods have been developed for various styles of faulting. Youngs and others [1] developed probabilistic and deterministic models for normal faults associated with the proposed Yucca Mountain Nuclear Waste Repository. This analysis was based on 184 earthquakes. Petersen and others [2] developed models for strike-slip displacements for the Pacific Earthquake Engineering Research Center based on 22 global earthquakes. Moss and Ross [3] developed fault displacement models for reverse faults using displacement data from 53 events with sizes between M 6.1 and 7.9. Each of these models has been applied in developing engineering designs for buildings, bridges, pipelines, and nuclear facilities. Takao [4] has also developed data and equations for Japan earthquake displacements of all types.

Several factors are important in assessing fault displacement: earthquake magnitude, location and size distribution of displacements as a function of magnitude and position on the fault, earthquake rate (recurrence), probability of surface rupture, probability of off-fault rupture on secondary faults, and quality of fault mapping. Most of these parameters have been analysed and models have been published (e.g., references above and Wells and Coppersmith [5]; Coppersmith and Youngs [6]). Probabilistic fault displacement hazard methodologies were developed to assess displacements both on and off main-strand ruptures [1, 2]. In addition, recent research also considers the quality of mapped fault traces (Petersen and others [2]) in assessing the location of future ruptures. Additional research by Chen and others [7-9] developed improved estimates of epistemic uncertainty (mapping inaccuracy) and aleatory variability (natural fluctuations) for the strike-slip displacement models. They suggest that the quantification of aleatory variability in rupture location is challenging because of limited data and many factors affecting the interpretability of available data. They compiled a dataset from displacement data obtained in trenches, which identifies paleoseismic events and by reanalysing trench logs from decades of fault investigations for research and development projects in California. They conclude that although the data are not sufficient for establishing a meaningful statistical distribution, it is possible to infer an upper bound and a lower bound to aleatory variability in the location of where future ruptures will occur. Chen and Petersen [8] provided guidance on how to partition slip on multiple parallel fault strands in developing a scenario rupture analysis for the San Andreas Fault.

In this paper we compare fault displacement models and show examples of how these are being used by engineers for designing projects across the United States. We use “recurrence” to describe the average number of years between earthquakes and “rate” to describe the average number of earthquakes per year, the rate is the inverse of the recurrence. In this paper we use “return period” or a probability statement “2% probability of exceedance in 50 years” to describe the hazard level of ground shaking. The annual rate of exceedance is the inverse of the return period (e.g., 475 years is equivalent to 0.0021).
First, we compare the published displacement data for normal faults (Youngs and others [1] and reverse faults (Moss and Ross [3]) with the data we compiled for strike-slip faults (Petersen and others [2]). In addition, we compare the models with Japanese data compiled by Takao [4]. Additional data and models that characterize fault displacements can be found in Lettis and others [10], Wesnousky [11], and Pezzopane and Dawson [12].

Figure 1 shows the normalized fault displacement ($D/D_{ave}$) data for normal faults and the on-fault distance ratio ($l/L$) which is 0.5 at the middle and 0.0 at the ends of the faults. The average displacements can be computed using magnitude scaling equations or by compiling statistics on displacements at a site. The normal displacement data are shown in this figure, as published by Youngs and others [1] (green circles), and regression lines for different percentiles (green lines). These data are compared with the strike-slip data (blue circles) and the regression data (red lines). The normal and strike-slip data are quite similar near the middle of the fault ($l/L=0.5$). However, the strike-slip fault displacements tend to be smaller than normal faults near the end of the fault ($l/L<0.2$). The strike-slip equations (red lines) fall off faster near the end of the fault compared to the normal equations (blue lines).

![Comparison with Normal Faulting Data](image_url)

**FIGURE 1.** Comparison of normal (green circles) and strike-slip (blue circles) $D/D_{ave}$ data for global normal faulting earthquakes. Normal fault displacement regressions are shown with blue lines [1] and strike-slip with red lines ($5^{th}$, $15^{th}$, $50^{th}$, $85^{th}$, and $95^{th}$ percentiles from bottom to top).
top) is from Petersen and others [2]. Normal faulting data is from Youngs and others [1].

FIGURE 2. Comparison of reverse (green circles) and strike-slip (blue circles) $D/D_{ave}$ data for global earthquakes. Strike-slip fault regressions are shown with red lines [2]. Reverse faulting data are from Moss and Ross [3].

Figure 2 shows displacement data similar to Figure 3 but for reverse faults compared to the strike-slip faults. The published data shown for reverse faulting do not show the regression lines because the author did not publish those regressions in this particular plot [3]. The data for reverse faults appear to be similar to the data for strike-slip faults near the center of the fault.
However, strike-slip displacements are lower than reverse displacements near the end of a fault.

Figure 3 shows displacement data similar to Figure 3 and 4 but for Japanese data of all faulting types [4]. Again, the Japanese data near the middle of the fault are similar to the regressions for strike-slip faults. The strike-slip data seem to have more variability near the end of the fault compared to the Japanese data. The regression equations for the strike-slip and Japanese displacements are quite different near the end of the fault because of the difference in these datasets.

COMPARISONS OF U.S. FAULT DISPLACEMENT HAZARD CURVES

Empirical fault displacement models have been developed for normal faults by Youngs and others [1], strike-slip faults by Petersen and others [2] and reverse faults by Moss and Ross [3]. The California Department of Transportation (CALTRANS) designs bridges and roads and they often need to perform a PFDHA for structures that cross active faults. They developed a simplified PFDHA methodology for all three fault types by applying Wells and Coppersmith [5] displacement values as well as the uncertainties provided in the published models. They do not allow for smaller displacements at the ends of the fault rupture or other complications in the model.

For illustration purposes, we developed a hazard assessment for M 7 earthquakes with two different recurrence intervals of 160 years and 800 years to show how the recurrence impacts the hazard. Figure 4 shows hazard curves calculated for a site at the middle of a generic fault with recurrence of 160 years using the simplified (CALTRANS) displacement calculations for
normal, strike-slip, and reverse faulting mechanisms as well as hazard curves using the published normal and strike-slip fault displacement calculations. The equations agree for annual rates of exceedance of 0.0008 (recurrence 1,429 years) or greater. However, for smaller annual rates of exceedance (longer recurrence) the curves can differ significantly. CALTRANS generally considers a 0.001 rate (recurrence about 1000 years) in their design procedures so this simplification appears to be reasonable for assessing this hazard level from a M 7 earthquake. The hazard curves show displacements of a little more than 2 m for an annual rate of exceedance of 0.001 (1,000 year recurrence) which is consistent with about a 5% probability of exceedance in 50 years. For smaller rates of exceedance or longer recurrence intervals the hazard values are more dispersed ranging from about 4 m to 8 m at a 0.0001 annual rate of exceedance (10,000 year recurrence). The deterministic displacement for a M 7 using Wells and Coppersmith [5] is about 1.0 m.

Hazard curves for strike-slip and normal are quite similar whereas the hazard falls off more quickly for reverse faults. Part of this difference in displacement hazard can be taken into account by the difference in probability of surface rupture. Magnitude 7 ruptures typically occur up to the surface 87% of the time for strike-slip and normal faulting mechanisms but only about 47% of the time for reverse faulting mechanisms.

![Hazard Curves](image)

**FIGURE 4.** Hazard curves for M 7 displacements for M 7 earthquake on very active fault with recurrence of about 160 years.

We also developed a hazard assessment for M 7 earthquakes on a less active faults with recurrence of about 800 years. Figure 5 shows the hazard curves for various fault types computed
using the CALTRANS simplified method and for the strike-slip and normal published equations. The displacement hazard reaches more than 3 m for a return period around 10,000 years but for return periods of about 1,000 years the equations suggest displacements less than 1 m. These hazard curves indicate less than 1 m of displacement for annual rates of exceedances that are between 0.001 and 0.0005 events per year (900 year to 2000 year recurrence levels). The deterministic (scenario-based) displacement hazard for a M 7 earthquake is between 0.90 m and 1.12 m for the three faulting types (see box in Figure 5). For an earthquake with M 7 and return period of about 800 years, the deterministic displacement typically occurs about once every 1600 years while for the 160-year scenario the displacement occurs once every 320 years or so. Often engineers consider 475-year or 975-year return period in their design procedures. Thus, for M 7 earthquakes on faults that rupture with return periods longer than about 2000 years the deterministic displacement is often similar to or larger than the probabilistic value.

FIGURE 5. Hazard curves for M 7 displacements on a fault with recurrence of about 800 years. Data within box provide information on rupture parameters (displ = deterministic displacement, surface rup = probability of surface rupture).

EXAMPLES OF PFDHA ON ENGINEERED STRUCTURES
In this section we discuss several applications of how the PFDHA is being used at sites across the U.S. We discuss assessments at Diablo Canyon Nuclear Facility, the Memorial Stadium at University of California at Berkeley, and the American Nuclear Society recommendations for nuclear facilities.
1.1 EXAMPLE 1: OFF-FAULT DISPLACEMENTS AT DIABLO CANYON NUCLEAR FACILITY

The Diablo Canyon Nuclear Power Plant (DCPP) license was recently up for renewal and the operator and regulator assessed the hazard from the Shoreline fault [13]. The investigators felt that off-fault ruptures of the Shoreline fault (600 m from the power block and as close as 300 m from the Dresser couplings) might impact the site so they applied probabilistic methods to assess the likelihood of off-fault rupture displacement values of 1 or 2 cm occurring at the DCPP facility, which are amplitudes of displacement that piping can tolerate. In addition, they felt that the new methodology required a range of assumptions (e.g., magnitude of future ruptures, distance from rupture source) to assess the core damage frequency. Results indicate that the annual rate of exceedance of these 1-2 cm displacements were less than $2 \times 10^{-7}$ (5,000,000 year return period) and results varied by an order of magnitude depending on input assumptions. It was suggested that the rate was so low that the hazard from secondary rupture at the location of couplings would have negligible impact on the seismic core damage frequency [13].

1.2 EXAMPLE 2: ON-FAULT DISPLACEMENTS AT THE MEMORIAL STADIUM U.C. BERKELEY

The Memorial Stadium at University of California at Berkeley was built on a complex right bend of the Hayward fault. The active fault ruptures approximately every 140 years and is characterized by several distributed fault traces and no single well-defined structure. The median deterministic displacement for a future rupture of a M 6.9 earthquake is 1.2 m and the 84th percentile is 2.6 m. AMEC GEOMATRIX [14] performed a PFDHA and deterministic analysis and determined that the horizontal displacement could occur on a single trace of width less than about 0.5 m, as discrete displacements on multiple fault traces, or as distributed slip across a zone of deformation with width of up to 4 m. They also considered that vertical displacement of as much as one-third of the horizontal displacement would be expected to occur during the earthquake rupture. As a result of their assessment they recommended a fault displacement of 0.9 m at 10% probability of exceedance in 50 years (475-year) and 1.9 m for a 10% probability of exceedance in 100 years (949-year) which are the hazard levels considered for the design earthquake and maximum considered earthquake (MCE). These displacements are similar to the total probabilistic values for M 6.7 and 6.9 earthquake scenarios. Uncertainty in the location of the fault is ± 5 m.
4.3 EXAMPLE 3: AMERICAN NUCLEAR SOCIETY – NATIONAL STANDARD CRITERIA

The American Nuclear Society published an American National Standard Criteria for assessing tectonic surface fault rupture and deformation at nuclear facilities [15]. They developed an outline of procedures and methods for performing PFDHA for surface rupture hazard and also for probabilistic tectonic deformation hazard analysis. A decision path was developed to show how fault displacement hazard analysis should take place to determine the potential for surface fault rupture. The authors recommend detailed site characterization to define the zone of permanent ground deformation (PGD) prior to using the decision path. From a fault displacement hazard, the site will probably not face a severe fault displacement hazard if it is located outside of the PGD zone or is inside the PGD zone but located greater than 200 m from the principal fault, and the distance of two times maximum the building dimension has no Quaternary faulting. If the building is located within the PGD zone, within 200 m of principal faulting and/or distributed faulting is close to or intersects the building, then a PFDHA should be considered to demonstrate that the site is acceptable. If the building is intersected by principal faulting that is late Quaternary or Holocene age, then the site is not supportable and should be moved.

5.0 DISCUSSION AND CONCLUSIONS

Uncertainties are large in estimating fault rupture hazard. The American National Standard Criteria [15] indicates that the results of PFDHA should reflect the aleatory and epistemic uncertainty in model inputs. They recommended that an uncertainty analysis be performed to determine fractile hazard curves which quantify the confidence in the determination of the hazard. In addition, they recommend that the aleatory component of location uncertainty should be assessed. When assessing the total uncertainty, it is important to consider both the within-event and between-event variability. These uncertainties are typically both very large and it is not clear if they are both considered in every assessment. The PFDHAs applied in the U.S. have typically considered global data, and it is reasonable to consider whether these global uncertainties are appropriate for the specific region where the hazard is being assessed. For example, sometimes the global data uncertainties may indicate displacements larger than observed within a small region (non-ergodic). It is important to point out that the global uncertainties applied in these equations can be reduced by site-specific geological and geophysical studies of the fault geometry, earthquake rates, and historic rupture displacements. If a geologic study is not available then one could default to the global distributions. Probabilistic approaches that have been used in engineering design and analyses vary significantly in complexity. The simplest approach is for a scenario earthquake with a given magnitude and frequency of occurrence. Such analysis is often based on Wells and Coppersmith [5] magnitude and average displacement regression and considers only the uncertainty from this regression. Adding uncertainties and probability distributions in other input parameters often leads to increasing complexity and higher or lower estimated rupture hazards depending on specific parameters and distributions. For example, adding additional uncertainties in fault displacement data such as those shown in Figures 1 to 3 increases rupture hazards. Adding uncertainty in the scenario magnitude likely will also increase estimated hazards. On the other hand, incorporating a magnitude distribution instead of using a characteristic magnitude for a given fault will likely cause a decrease in hazard. Adding uncertainty in rupture location reduces displacement estimates on the mapped fault, but increases rupture hazard in areas near the fault trace by allowing variability in the location of the future rupture. Because some components of PFDHA tend to reduce displacement estimates, Wells and Kulkarni [16] suggest careful
considerations in the implementation of the individual effects of individual components within PFDHA.

Another important consideration is the appropriate hazard return period that is applied in the PFDHA or the fractile applied for the scenario displacement. We showed in our examples that the probabilistic displacements for earthquakes with recurrence about 160 years were much higher than median deterministic displacements for return periods of less than 1,000 years \((10^3)\). However, the probabilistic displacements for a return period of 800 years are lower than the deterministic displacements for a hazard return period of less than 1,000 years \((10^3)\). Wells and Kulkarni [16] suggest that many engineering projects in the U.S. consider designs for a return period of 475 years with a life-safety performance objective. Several groups, including CALTRANS, consider important structures with return period of 975 years. However, Wells and Kulkarni [16] suggest that consideration of even longer return periods is appropriate since the damage consequences and risk due to fault displacement may be greater than the strong ground shaking for comparable hazard levels. Nuclear power plants typically consider return periods longer than those applied in typical engineering projects and those plants are often sited away from very active faults. The deterministic fault displacement hazard may be larger than the probabilistic values for less active faults with an earthquake rupture recurrence that is longer than the hazard (return period) of interest.

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7.0 REFERENCES


