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MAPPING FAULT RUPTURE HAZARD FOR STRIKE-SLIP EARTHQUAKES

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SUMMARY

We present fault displacement data, regressions, and a methodology to calculate in both a probabilistic and deterministic framework the fault rupture hazard for strike-slip faults. To assess this hazard we consider: (1) the size of the earthquake and probability that it will rupture to the surface, (2) the rate of all potential earthquakes on the fault (3) the distance of the site along and from the mapped fault, (4) the complexity of the fault and quality of the fault mapping, (5) the size of the structure that will be placed at the site, and (6) the potential and size of displacements along or near the fault. Probabilistic fault rupture hazard analysis should be an important consideration in design of structures or lifelines that are located within about 50m of well-mapped active faults.

INTRODUCTION

Earthquake displacements can cause significant damage to structures and lifelines located on or near the causative fault. Recent fault ruptures from earthquakes have caused failure or near-failure on bridges (Japan, 1995; Taiwan, 1999; Turkey, 1999), dams (Taiwan, 1999) and buildings (California, 1971). Earthquake ruptures in the 1971 San Fernando, California earthquake (M 6.7) caused extensive structural damage and resulted in legislation of the Alquist-Priolo Earthquake Fault Zoning Act. This Act prevents construction of habitable buildings on the surface trace of an active fault (defined as having ruptured within the past 10,000 years). However, it may not be possible to relocate many structures and lifelines away from an active fault and loss of these facilities can significantly impact society. Therefore, it is essential to consider the effects of fault rupture displacements when designing structures near fault sources. The 2002 Denali earthquake showed that major lifeline structures can be designed to accommodate fault displacement if the potential for location and size of displacement is known.

The methodology presented here is an extension of the probabilistic fault displacement hazard assessments of Stepp et al. [1] and Youngs et al. [2] for the proposed Yucca Mountain highlevel nuclear waste repository in Nevada and of Braun [3] for the Wasatch Fault in central Utah. Those studies analyzed normal-fault displacements while this study is focused on strike-slip fault displacements. In addition, we have found that the distribution of displacement about a previously mapped fault depends on accuracy of mapping and complexity of the map trace.

In this paper we present fault rupture data and a methodology to assess fault rupture hazard. In addition, we present an example of a fault rupture hazard assessment for a line of sites that intersect a fault. The overall goal of the project is the development of improved design-oriented conditional probability models needed for estimating fault rupture hazard within either a deterministic or probabilistic framework.

METHODOLOGY

Several parameters are important in determining the fault rupture hazard at a site: (1) the size of the earthquake and probability that it will rupture to the surface, (2) the rate of all potential earthquakes on the fault (3) the distance of the site along and from the mapped fault, (4) the complexity of the fault and quality of the fault mapping, (5) the size of the structure that will be placed at the site, and (6) the potential and size of displacements along or near the fault. To develop the methodology, we consider a fault and site *(x,y)* as shown in Figure 1. The structure has a footprint with dimension *z* that is located a distance r from the fault and a distance *l*, measured from the nearest point on the fault to the end of the rupture, point *P*. The rupture in this case does not extend along the entire fault length and ruptures a section located a distance *s* from the end of the fault. The displacement on the fault has as intensity *D* and the displacement at a site off the fault has intensity *d.*

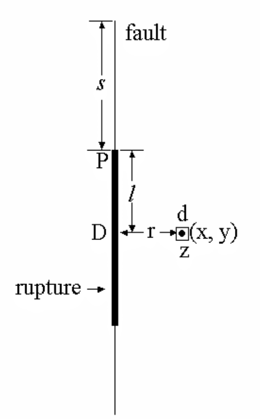

FIG. 1: Definition of variables used in the fault rupture hazard analysis

For assessing the fault rupture hazard we construct five probability density functions that describe parameters that influence the displacement on or near a fault rupture. The first two probability density functions characterize the magnitude and location of ruptures on a fault ($f_M(m)$, $f_s(s)$), the next density function characterizes the distance from the site to all potential ruptures ($f_R(r)$) and the last two probability density functions define the displacements at that site ($f_{Z,R,M}(P)$, $f_D(D(D_{max}, l))$).

The first probability density function, $f_M(m)$, describes the magnitude-frequency distribution along a fault. Typically, in hazard analysis it is assumed that a fault has a preferred size of rupture, that can be determined from consideration of the physical constraints on the length or area of the fault, complexity of the fault along strike, crustal rheological properties along the fault, or rupture history. Observations indicate that faults do not always rupture the entire length (e.g., 1933 Long Beach, 1989 Loma Prieta earthquakes) and may also rupture along with adjacent faults (e.g., 1992 Landers, California earthquake). The size of the earthquake given the fault dimensions is also uncertain (Wells and Coppersmith, [4],[5]). From all known potential rupture scenarios, we develop a probability density function for the various sizes of earthquakes along the fault.

Once we determine the potential sizes of the earthquakes, we need to assess how often these ruptures occur. We define a rate parameter, α, that constrains how often the earthquakes occur in the model. This rate parameter is based on the long-term fault slip-rate, paleoseismic rate of large earthquakes, or the rate of historical earthquakes. The density function for the magnitude frequency in conjunction with the annualized rate parameter defines the frequency of each earthquake rupture along the fault.

The second probability density function describes the probability of a rupture at a specific place along a fault, $f_s(s)$. We consider the potential for the partial rupture occurring over various portions of the fault. The range of s is from zero to the fault length minus the rupture length. If the rupture is distributed uniformly along the fault, then f_s(s) is a constant, which is equal to one over the fault length minus the rupture length.

If we simply consider magnitude and rupture variability, the probability that displacement d is greater than or equal to d_0 at a location *(x,y)* and with a foundation size z is given by:

$$\lambda(d \geq d_0)_{xyz} =$$

$$\alpha \int_m f_M(m) \int_s f_s(s) P[sr \neq 0 \mid m] P[d \neq 0 \mid l, r, m, z, sr \neq 0] P[d \geq d_0 \mid l, r, m, d \neq 0] ds dm, \quad (1)$$

where $P[sr{\neq}0|m]$ is the probability of having surface rupture given a magnitude m event. This term accounts for the possibility that an earthquake rupture on a fault will not reach the surface. For example, the 1989 Loma Prieta (M 6.9) and 1994 Northridge (M 6.7) earthquakes did not extend up to the surface and would not present a fault rupture hazard. We obtain this probability from regressions of global earthquake ruptures as published by Wells and Coppersmith [4].[5]. The term $P[d{\neq}0|l,r,m,z,sr{\neq}0]$ represents the probability of having non-zero displacement at a location (l,r) for a foundation size z given magnitude m event with surface rupture, and $P[d{\geq}d_0 \mid l,r,m,d{\neq}0]$ is the probability of the non-zero displacement d greater than or equal to a given value d_0 at a location (r,l). When the site is located on the main fault ($r=0$) we use D to denote the displacement at ($r=0,l$) and then (1) becomes:

$$\lambda(d \geq d_0)_{xyz} =$$

$$\alpha \int_m f_M(m) \int_s f_s(s) P[sr \neq 0 \mid m] P[D \neq 0 \mid l, r = 0, m, z, sr \neq 0] P[D \geq d_0 \mid l, r = 0, m, D \neq 0] ds dm$$

.

The data indicate a discontinuity between $P[d \neq 0 \mid l, r \to 0, m, z, sr \neq 0]$ and $P[D \neq 0 \mid l, r = 0, m, z, sr \neq 0]$ as well as a discontinuity between $P[D \geq d_0 \mid l, r = 0, m, D \neq 0]$ and $P[d \geq d_0 \mid l, r \to 0, m, d \neq 0]$.

The third probability density function defines the distance perpendicular to the fault. If the fault has multiple strands that could rupture in an earthquake, this aleatory variability should be considered in the fault rupture hazard model. This is not due to the fault mapping quality, which is epistemic and treated in a logic tree. We define a density function $f_R(r)$ to denote the variability, the expected rate (1) becomes:

$$\lambda(d \geq d_0)_{xyz} =$$

$$\alpha \int_m f_M(m) \int_S f_s(s) P[sr \neq 0 \mid m] \int_r P[d \neq 0 \mid l, r, m, z, sr \neq 0] P[d \geq d_0 \mid l, r, m, d \neq 0] f_R(r) drdsdn \quad (2)$$

We need to take into account the size of the structure that will be placed at the site. We define a probability density function for the surface displacement given the structural footprint size, the distance from the fault, and the magnitude of the earthquake that ruptures the surface. The Probability $P[d \neq 0|l,r,m,z,sr \neq 0]$ is not a constant for a given distance r and grid size z. It should also depend on l and m. Our data do not allow us to derive these relations for l, therefore, for this analysis we have ignored the dependences on l. From these data we can derive a density function $f_{Z,R,M}(p)$ for the above probability to have value p for a given grid size z, distance r, and magnitude.

$$\lambda(d \geq d_0)_{xyz} =$$
$$\alpha \int_m f_M(m) \int_s f_S(s) P[sr \neq 0 \mid m] \int_r f_R(r) \int_p f_{Z,R,M}(p) p P[d \geq d_0 \mid l, r, m, d \neq 0] dpdrdsdm, \quad (3)$$

Finally, we develop a probability density function for displacements along the main fault $f_D(D(D_{max},l))$. The magnitude m is related to the probability of $d \geq d_0$ through the displacement D on the main fault at a point nearest to the site (x,y) that is a function of the maximum displacement (usually at middle of the fault rupture) D_{max} and the location of this point on the rupture (l) or $D=D(D_{max},l)$. The displacement on the fault D has aleatory variability also. Therefore, we have:

$$P[d \geq d_0 \mid l, r, m, d \neq 0] = \int_D P[d \geq d_0 \mid D(D_{\max}, l), d \neq 0] f_D(D(D_{\max}, l)) dD \quad (4)$$

where $f_D(D(D_{max},l))$ is the density function for $D= D(D_{max},l)$ given magnitude m and location l. If formula (4) is inserted into (3), we get the final formula with aleatory variability of rupture distribution on the fault, multiple fault rupture traces, displacement variability on the main fault, and probability variability of having non-zero displacement. The final formula for the probabilistic fault rupture hazard is:

$$\lambda(d \geq d_0)_{xyz} = \alpha \int_m f_M(m) \int_s f_S(s) P[sr \neq 0 \mid m] \int_r f_R(r) \int_p f_{Z,R,M}(p) p \times$$
$$\int_D f_D(D(D_{\max}, l)) P[d \geq d_0 \mid D(D_{\max}, l), d \neq 0] dDdpdrdsdm \quad (5)$$

This formula is used to assess the probabilistic fault rupture hazard at a site. If one desires to calculate the deterministic fault rupture hazard the formula would be modified by eliminating the rate parameter, α, from the equation. Alternatively, one could calculate the median

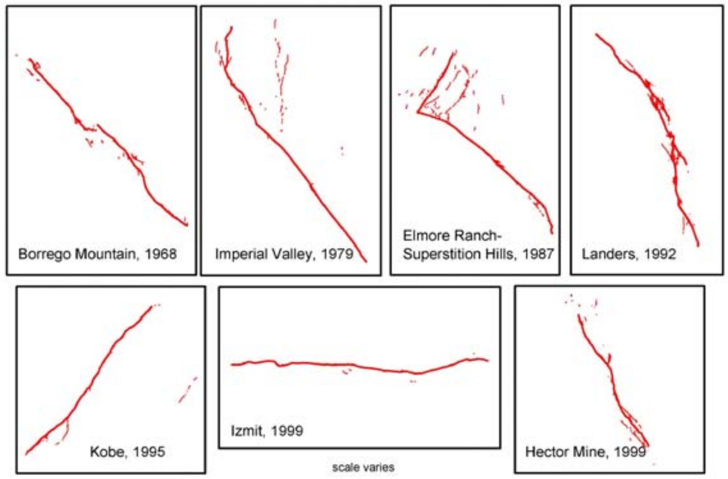

FIG. 2: Traces of faults used in analysis

displacement for a particular earthquake using the empirical data and relations that are described below.

DATA AND REGRESSIONS

Following earthquakes that rupture the ground surface, geologists have prepared detailed maps and measured displacement along the surface trace. We collected displacement data from published measurements obtained from studies of several large strike-slip earthquakes: 1968 Borrego Mountain (M 6.6), 1979 Imperial Valley (M 6.5), 1987 Elmore Ranch (M 6.2), 1987 Superstition Hills (M 6.6), 1995 Kobe (M6.9), 1992 Landers (M7.3), 1999 Izmit, Turkey (M7.4), and the 1999 Hector Mine (M7.1) (Figure 2). This data was processed using the ArcGIS Geographic Information System.

This fault displacement data is used with earthquake recurrence information provided by the National Seismic Hazard maps (Petersen et al. [6]; Frankel et al. [7]). To evaluate the fault hazard at a site we need to answer three questions:

(1) Where will future fault displacements occur?
(2) How often do surface displacements occur?
(3) How much displacement can occur at the site?

In this section we will discuss the data and model regressions that are used to evaluate each of these questions in a probabilistic sense.

Where will future fault displacements occur?
The primary method of assessing where future ruptures will occur is to identify sites of past earthquakes. We can identify these potential rupture sources by studying historic earthquake ruptures, defining seismicity patterns, and identifying active faults.

Historical ruptures are an important dataset to interpret future fault ruptures. Figure 2 shows examples of historic strike-slip earthquake rupture traces that have been used in this hazard assessment. These traces show a wide variety of rupture patterns. The largest fault displacements are along the principal fault, but significant displacements may also occur on distributed ruptures located several meters to kilometers away from the main fault. The displacement values are not shown, but have been compiled in ARC GIS files. The rupture patterns for a single earthquake may be fairly simple in some regions but quite complex in others, characterized by discontinuous faulting that occurs over a broad zone. This fault rupture complexity is often associated with en-echelon offsets, places where the fault strike changes, or intersections with other faults.

Holocene active faults are places where the likelihood is greatest that we will have future earthquakes. In California, legislation requires that the State Geologist identify those faults that are "sufficiently active and well-defined" to represent a surface rupture hazard. In order to do this, the California Geological Survey has examined the majority of the potentially active faults in the state and prepared detailed maps of those that can be shown to have ruptured to the ground surface in Holocene time. These faults are included in "Alquist-Priolo Earthquake Fault Zones" (A-P zones), which regulate development near active fault traces. In our analysis we have compared the maps of faults within A-P zones prepared before surface-rupturing earthquakes with maps of the actual surface rupture mapped following the event. This type of analysis provides a measure of the uncertainty in accurately locating future ruptures.

The 1999 Hector Mine earthquake is an example of an event that ruptured along a fault that had been mapped prior to the earthquake rupture. The California Geological Survey had evaluated the Bullion fault, found it to be "sufficiently active and well-defined" and established A-P zones in 1988 (Hart [8]). As shown in Figure 3, the 1999 event ruptured part of the Bullion fault. Much of the rupture occurred close to the previously mapped fault, including a section where the A-P map showed two principal traces of the fault. Much of the rupture near the top of Figure 3 and extending to the north, occurred on a fault east of the Bullion fault that had been previously mapped, but not evaluated for A-P zones because it lies in such a remote area. The event also ruptured secondary faults over a wide area at the south end of the rupture as shown in Figure 3. Displacements on these strands were on the order of a few centimeters. In evaluating the potential for surface fault displacements, we need to account for the potential that significant displacement can occur on previously unmapped faults and that secondary displacement can occur over a broad area. This example shows that the uncertainties in predicting the fault rupture may be up to a kilometer in some places along the fault.

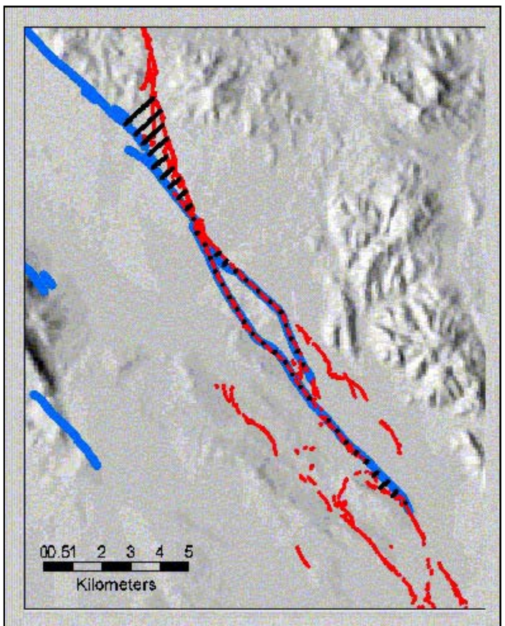

FIG 3: Comparison of previously mapped A-P fault (blue) and 1999 Hector Mine earthquake surface rupture (red)

The accuracy of mapping and complexity of the fault trace parameters are handled in a logic tree to account for our uncertainty in estimating the location of the fault traces. Faults mapped for A-P zones show the surface traces of the faults in four categories based on how clearly and precisely they can be located. Those four categories: "Accurately Located", "Approximately Located", "Inferred" and "Concealed", are shown on the A-P maps with different line symbols. We compared the fault traces mapped in each of these categories with later surface rupture. In general, the regressions show what a geologist would expect; that the "Accurately Located" and "Approximately Located" traces more accurately predict the surface rupture location. "Inferred" and Concealed" traces have greater variability in distance from the surface ruptures, although these distinctions are not as clear as one might expect. We examined the A-P fault traces and characterized them as "simple" or "complex". We expect that surface rupture will be more distributed and not as accurately predicted at

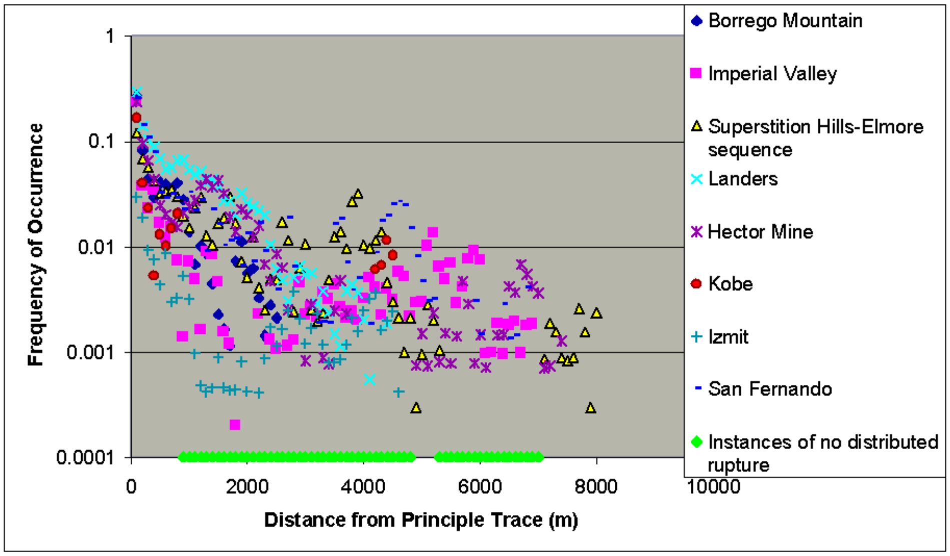

FIG 4: Frequency of earthquake displacements within 50 m cells as a function distance from principal trace

length and the rupture length for each magnitude.

Assessing the rates of occurrence of earthquakes is pertinent to probabilistic fault displacement hazard analysis and not necessary for the deterministic analysis. A probabilistic analysis accounts for how often the events occur whereas deterministic analysis simply gives a median (or some other fractile) displacement assuming that the event occurs.

How much displacement can occur at the site?

To assess probabilistic displacement hazard at a site, it is necessary to understand the potential for rupture at that site and the distribution of displacem dependent upon whether or not the site is located on the faul

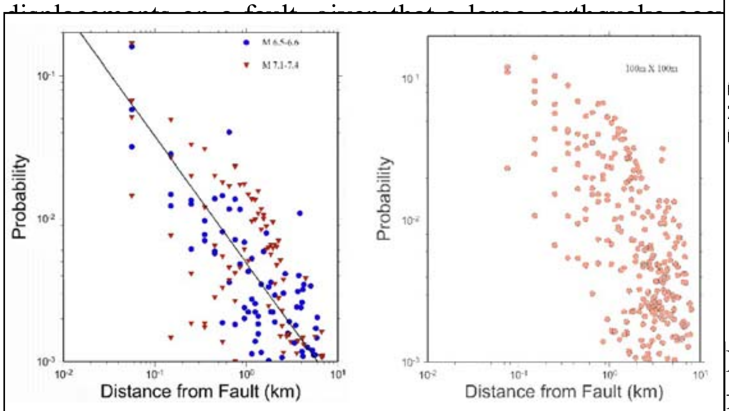

FIG 5: Probability of displacement as a function of distance from the main trace for (A) 25 m grid cell and (B) 100 m grid cell. Regressions for 25mX25m, log(p)= -2.3096-0.8872*log(r) for 100mX100m, log(p)= -1.9590-1.0910*log(r)

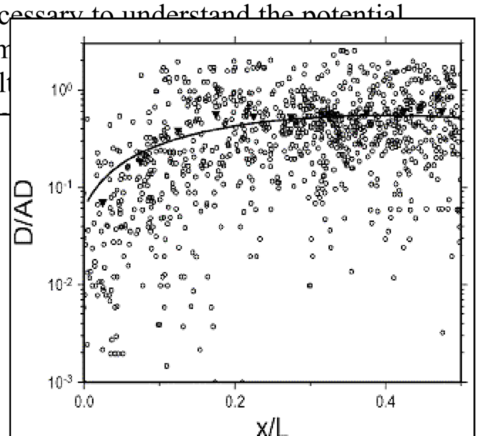

FIG 6: Displacement data on the fault. The y-axis indicates the measured displacement divided by the average displacement and the x-axis indicates the distance from the end of the fault x divided by the total length of the rupture.

with lengths of 25 m, 50 m, 75 m, 100 m, and 200 m. Figure 5 shows the rate of occurrence of displacement in 25m and 100m footprint areas. The frequency is very high for distances very close to the fault. However, this frequency drops off quickly and there is only about a 1 in 100

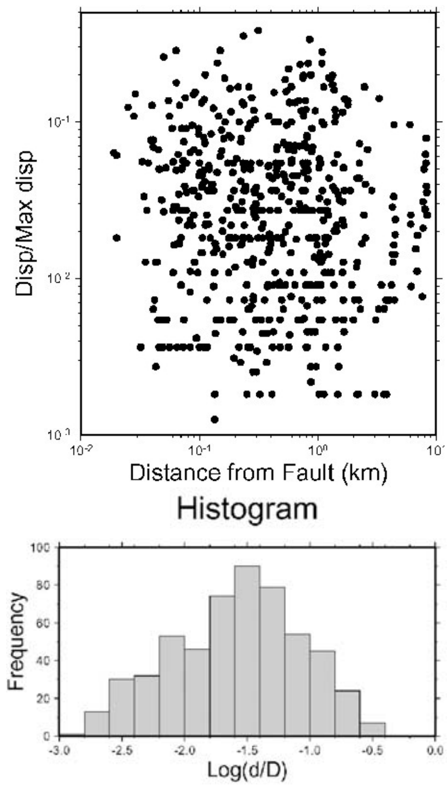

FIG 7: Displacement data for sites located off the fault. (A) A plot of normalized displacements (displacement divided by the maximum displacement on the fault) as a function of distance (with Superstition Hills data removed) and (B) a histogram showing the frequency of $\log_{10}$ normalized displacements for all the data shown in A.

chance of having rupture within a 50 m footprint if the distance is more than about 2 kilometers. The displacement data indicate that most of the displacements occur on or within a few hundred meters of the principal fault. Contrary to the results of Youngs et al. [2], we found no magnitude dependence on the potential for displacement in a cell.

Once we have calculated the likelihood for having displacements pass through a given area, we need to define a distribution of the size of the displacements. We separate the data into on-fault and off-fault displacements.

Figure 6 shows the displacements along the strike of the fault. We performed a polynomial regression on the on-fault data to obtain the typical distribution of displacements along a fault. In general the displacements are largest near the middle of the fault and falls off rapidly within about 10% of the end of the rupture.

The displacement data indicate that most of the displacements occur on or within a few hundred meters of the principal fault.

Figure 7 shows of the normalized off-fault displacements as a function of distance. The data indicates almost no correlation of displacements with distance. These displacements are typically quite small. The histogram indicates that the mode of the data is centered at about $10^{(-1.5)} = 0.03$, or about 3% of the displacements observed on the principal fault. Displacements range from less than 1% to about 32% of the values observed on the fault.

EXAMPLE

To illustrate the methodology and datasets, we assume a fault that has which has a characteristic magnitude 7.26 and with a recurrence of 250 years. This recurrence leads to an annual rate of 0.006 earthquakes per year. Figure 8 shows the examples of calculated displacement hazards on a cross line perpendicular to the fault. The vertical axis is the surface displacement to be exceeded with probabilities of 2%, 5%, and 10% in 50 years respectively. For this illustration, the fault trace location is assumed to be well located, with a standard deviation of 10 meters. The width of the zone with significant displacement hazards around the fault is mostly controlled by this standard deviation. The amplitude of the displacement hazards is controlled by the characteristic magnitude, recurrence rate, and the duration of the exposure for the hazards.

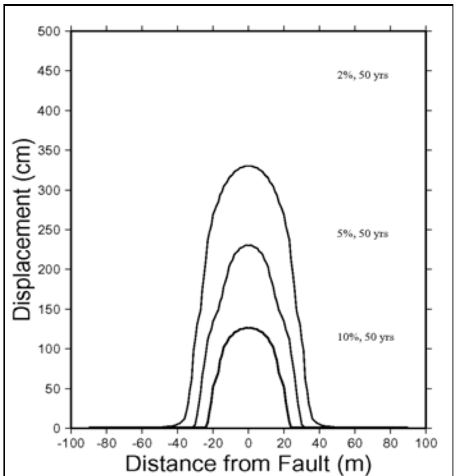

FIG 8: Example of fault displacement hazard on a transect that crosses the fault.

DISCUSSION AND CONCLUSIONS

We have assembled data on world-wide strike-slip earthquake surface rupture and compared it with pre-rupture fault mapping. In California, the fault maps prepared for zoning under the Alquist-Priolo Earthquake Fault Zones Act provide a uniform, detailed set of pre-rupture fault maps that are the basis for comparison for most of our data. We have analyzed the distribution of fault displacement about previously mapped fault traces and used that analysis to construct a system for evaluating the hazard of fault displacement in either a deterministic or probabilistic framework.

In order to consider the probability for surface fault displacement at a site, one must consider the rates of earthquakes on significant active nearby faults. For California, most of the activity rates for faults have been compiled and used in the National Seismic Hazard Maps (Frankel et al. [7]). With the rates of earthquakes, we can assess the potential for an earthquake to rupture to the ground surface using the regressions from world-wide data by Wells and Coppersmith [5]. For earthquakes that do rupture to the ground surface, we can obtain probabilistic estimates of displacement from the regressions for this study.

We have developed regressions for fault displacement considering that most earthquakes do not rupture entire faults, that the fault displacement tends to die-out rapidly near the ends of a rupture and that fault rupture does not always follow previously mapped faults. The potential for fault displacement to deviate from previously mapped fault traces appears to depend on several factors, which we have considered. Maps of faults prepared before the rupture show the traces of the faults with varying levels of perceived accuracy. Our regressions show that the two more accurate categories do correlate somewhat better with subsequent fault rupture, but the differences are not great. Surface displacements also tend to show greater complexity in areas where the fault geometry is complicated. We are currently developing rules for what constitutes "complex" fault geometry on pre-rupture mapping. Later regressions will include the potential for more broadly distributed displacement at fault bends, stopovers, branches and ends.

Using the formulation and data developed in this study, one can estimate the potential for surface fault displacement within an area of a lifeline or other project. The input required for this analysis includes the rate of earthquakes of various magnitudes on a nearby fault or faults (typically obtained from the documentation for the National Seismic Hazard Maps); the distance from the active fault (measured from the Alquist-Priolo Earthquake Fault Zone or similarly detailed map); the accuracy of the nearest fault trace on the detailed map; and the size of the site to be considered. Output of the analysis is the amount of displacement with a specified probability or corresponding to a particular deterministic earthquake. The potential displacement considers the potential displacement along the fault, the potential that the location of the fault varies from where it was mapped and the potential for distributed displacement around the trace of the fault.

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