Applications of probabilistic ground deformation hazard

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ABSTRACT: Faulting induced ground deformation can pose a serious hazard to buildings and infrastructure, and cannot always be mitigated by avoiding construction on potentially active fault structures. We present an overview of situations where a probabilistic analysis was used to develop design parameters in very different environments. These include infrastructure development across active faults, which is a more common problem for which several methodologies have been developed, ground deformation hazard on top of a blind thrust structure and finally subsidence hazard in an active subduction environment.

The solutions to these problems range from purely empirical, similar to PSHA, to fully numerical approaches in the case of the subsidence hazard. We have included both epistemic uncertainties and aleatory variability in these analyses, and show how, by including a numerical element, we can tailor the probabilistic approach to very different kinds of design parameters and problems to be solved.

It is important to anchor the numerical approach in observations on ground deformation. Especially in the case of surface faulting, the fault behavior in the overburden depends strongly on its mechanical properties, and we are in the process of calibrating the numerical approach with deformation data from recent earthquakes as well as field studies of fault geometry.

1 INTRODUCTION

Probabilistic Fault Displacement Hazard Analysis is commonly used in circumstances where a project site crosses or straddles an active fault. This analysis is limited to offset along the fault, or its immediate surroundings, and to assess the deformation related hazard further away from the fault one needs to extrapolate the hazard from the fault using numerical or empirical means. Similarly, for tsunami hazard analysis it is desirable to use a probabilistic surface deformation model as input to tsunami hazard calculations. For complex fault ruptures or recurrence models, or buried faults, the probabilistic analysis needs to be carried out all the way to the ground deformation. In this paper we present some examples of a probabilistic fault deformation hazard analysis, starting with a simple fault displacement hazard analysis, followed by a hybrid analysis for ground deformation

2 PROBABILISTIC FAULT DISPLACEMENT HAZARD

2.1 Methodology

Hazard analysis for fault displacement is an important tool for the evaluation of earthquake safety in structures that are built close to or on active faults. Due to the relatively short reach of fault displacements and associated ground deformation compared to the pervasiveness of ground shaking, it is not as commonly required as an ordinary Seismic Hazard Analysis but the are many situations where a ground deformation analysis is necessary. A major example is the design of infrastructure projects, roads, rails, aqueducts etc., where it is simply impossible to avoid building across active faults, or where existing zonation and rights of way make it impractical to do so.

There are two basic approaches to PFDHA (Hoffmann, 1991; Youngs et al., 2003):

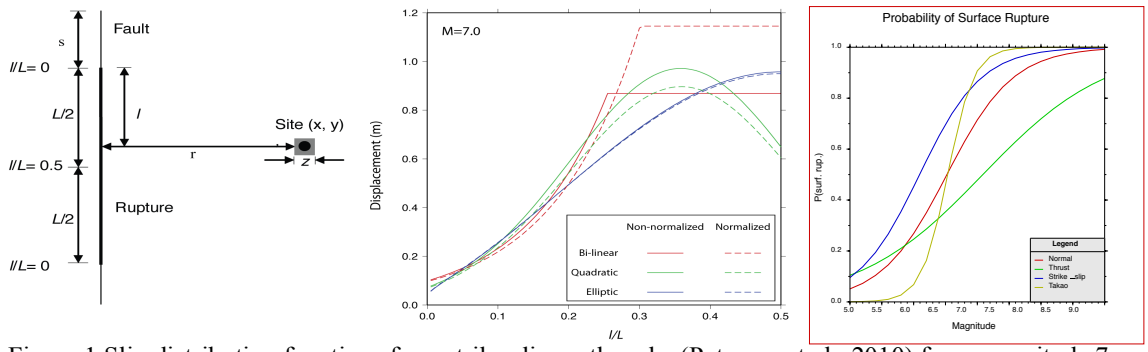

Figure 1 Slip distribution functions for a strike slip earthquake (Petersen et al., 2010) for a magnitude 7 earthquake. Shown on the left is the rupture and site geometry. In the middle are the slip distributions and on the right the probability distributions for the occurrence of surface rupture as a function of magnitude for three different mechanisms (Petersen et al., 2010) and for a combination fault mechanisms (Takao et al., 2014).

1. Direct (or Displacement) Method – the probability of slip is directly related to the rate of displacement on a fault and a slip distribution function.
2. Earthquake Method – in this method the displacements are related to the occurrence of earthquakes through scaling relations and/or slip distribution functions. The framework closely follows the approach of PSHA with the traditional attenuation relations replaced by magnitude and position dependent slip distribution functions and the hazard computed through an integration over magnitude and rupture locations

2.2 Direct method

The frequency of displacement exceedance $\nu(d)$can be written as:

$$\nu(d) = \lambda_{DE}.P(D > d)$$

where

d = displacement

λ_{DE} = rate of displacement events on the fault

P(D > d) = conditional probability that displacement *D* in an event exceed *d*.

This method forms a direct connection (hence its name) to the geological data from fault trench studies and other field observations. The rate of displacement events can simply be obtained by dating observed slip evens. Alternatively, it can be computed simply as the slip rate divided by the average slip per event. The conditional probability of exceedance slip (*P(D > d)*)can be obtained by measuring the amount of slip for many events at a site.

It is clear that this approach relies heavily on site-specific information and rupture, but Youngs et al. (2003) do give alternative methods to obtain the aforementioned functions, usually based on scaling relations and normalized data from other faults, although it seems that this would diminish the appeal of this method as one firmly based on local observations and makes it more similar to the Earthquake Method described later. Angell et al. (2003) present a comprehensive example of this approach in a PFDHA analysis for submarine pipelines in the Gulf of Mexico, which includes an extensive analysis of subsurface geophysical and geological data. Braun (2000) used this method to develop a PFDHA model for the Wasatch front using an extensive logic tree model and concluded that the results are strongly dependent on the choice of weights between the different branches, and thus that there is a strong sensitivity to epistemic uncertainties.

2.3 Earthquake Method

The Earthquake Method closely follows the procedures developed for PSHA. In general, the equation for the exceedance rate for displacement at a site (*k(d>D)*) on a fault has the following form (e.g. Youngs et al., 2003 for normal faulting; Petersen et al., 2010 for strike-slip faulting and Moss and

Ross, 2011 for thrust faulting):

$$k(D \geq d) = \sum_{m_j=m_0}^{m_u} \dot{N}(m_j).\left[\sum_{k=1}^{N} \Pr(D \geq d \mid r_k, m_j).\Pr(sr \neq 0 \mid m_j).\Pr(r_k \mid m_j)\right]$$

where :

1) $\dot{N}(m_j)$ is the mean number of earthquakes of magnitude m_j
2) $\Pr(D \geq d \mid r_k, m_j)$ is the probability that displacement D exceeds d given that an earthquake of magnitude m_j centered at a distance r_k occurs.
3) Pr $(sr \neq 0|m_j)$ the probability of surface rupture given magnitude m.
4) $\Pr(r_k \mid m_j)$ is the probability that an earthquake of magnitude m_j occurs with its center of rupture located at r_k.
5) m_0 is the minimum magnitude of earthquake engineering significance, and
6) m_g is the maximum magnitude for earthquake event considered.

The main differences between many of the papers are in the forms of terms 2 and 3. For the Petersen et al. (2011) model (see also Chen and Petersen, 2011) we show the functional form of these two terms in the following two sections, and we will discuss variations on these terms as used by other researchers after that.

2.3.1 *Slip distribution function*

The displacement for a rupture is not uniform over the entire rupture, but instead tapers towards both ends of the rupture, and is parameterized using the ratio *l/L* between the total rupture length (*L*) and the distance from the center of the rupture to the point on the rupture closest to the site (Figure 1). For this function, a log-normal distribution is assumed and Petersen et al. (2011) have determined several alternative functional forms, bilinear, quadratic or elliptic. Furthermore, they derived expressions both for displacement as a function of magnitude, and one for normalized displacement, for a total of six possible equations. For example, the quadratic relationship for normalized displacement (D/AD, D=displacement, DA=average displacement) has the form:

$$\ln(D) = \ln(AD) + 14.2824\, {}^{l}/_{L} - 19.8833\left({}^{l}/_{L}\right)^2 - 2.6279$$

with a sigma of 1.1419.

The six different relations have been plotted for a magnitude 7 earthquake in Figure 2. There is a considerable difference in slip distribution between the equations, especially close to the center of the rupture.

Youngs et al (2003), Moss and Ross (2011) and Takao et al (2013) have derived similar relations for normal and thrust mechanisms respectively, although only for the normalized relations (D/AD) as well as normalized with maximum slip (D/MD). Since the latter is bound between 0 and 1, both these authors use a Beta distribution for this case rather than a log-normal distribution. For the average displacement scaling, Youngs et al. (2003) used the Gamma distribution whereas Moss and Ross (2011) used a Weibull distribution.

The general form for the Youngs, Moss and Takao relations are:

$$F(y) = \frac{1}{\Gamma(a)} \int_0^{y/b} e^{-t}\, t^{a-1} dt \qquad \text{where: } a = e^{\left(0.7+0.34\frac{l}{L}\right)}, b = e^{\left(-1.4+1.82\frac{l}{L}\right)}, y = D/AD$$

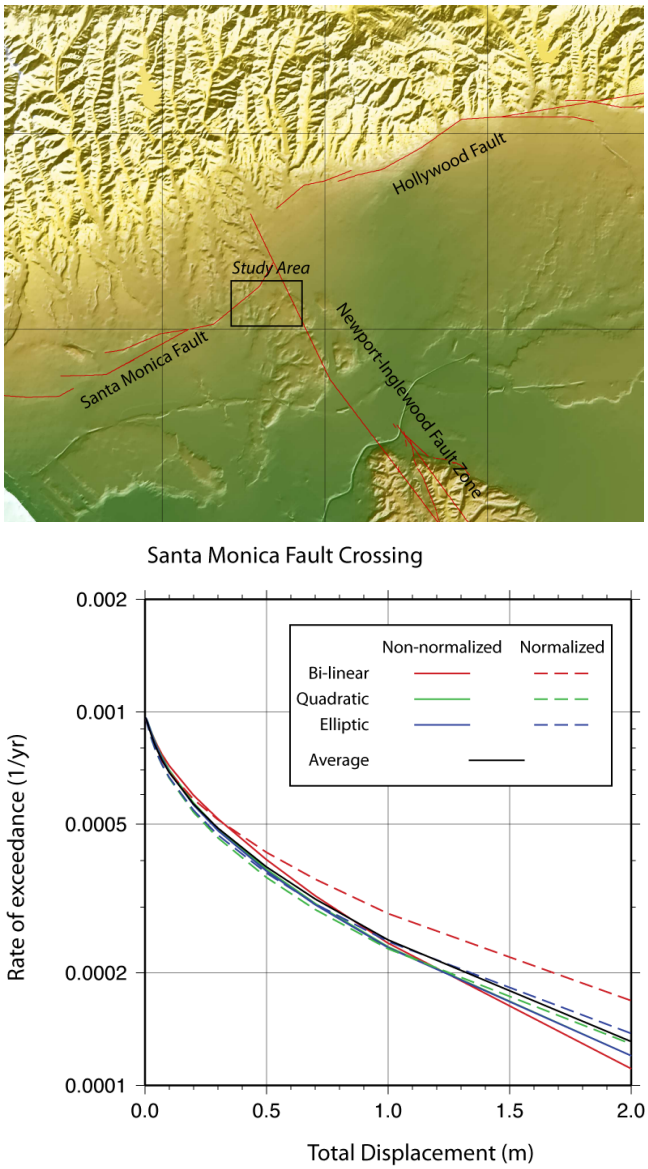

Figure 2. Example of a probabilistic fault crossing hazard analysis. a - (upper panel) Location of the site and faults. b (lower panel) - the hazard curves for the mean hazard and the disaggregated hazard for different equations shown on the bottom.

for scaling of slip (D) with respect to average displacement (AD), and:

$$F(y) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \int_0^y (1-t)^{b-1}\, t^{a-1} dt$$

where:

$$a = e^{\left(0.7-0.87\frac{l}{L}\right)}, b = e^{\left(-2.3-3.84\frac{l}{L}\right)}, y = D/MD$$

for scaling of slip with maximum displacement (MD).

The mean value for these relations is *a.b*, which implies a linear relationship between *ln(D/AD)* and *l/L*. In Figure 1 we show the differences between the Petersen and Takao models , and it clear, that there is a significant difference in shape of the curves between the various Petersen curves on the one hand and the Takao curves on the other.

Abrahamson (2008) adopted a uniform average displacement, from a global regression, rather than a distributed slip model and included the slip variability in an extra term to the sigma. Comparing this to site-specific slip variability he argued that the global model overestimates the variability by over a factor of two (.17 vs. .39 in log10 units) and used this as argument against ergodicity. This conclusion is based on Hecker et al. (2011), who demonstrate that the aleatory variability in slip from event to event at the same location is much smaller than the variability from global regressions, which emphasizes the importance of using local slip data over global models. However, unless local slip at a site is well-constrained, the global relations, and their variability should be used as they include both the inter-event slip variability, slip variability between points on the rupture and variability between different faults.

The main differences between the Petersen et al. (2011) papers and Takao et al. (2013) are in the forms of terms 2 and 3. The latter uses the beta an gamma distribution functions whereas Petersen et al. use (log) normal distributions. For the Petersen et al. (2011) we show the functional form of these two terms in the following section. These authors also present relations for faulting hazard away from the main fault. In our example however, we have instead on;y considered the main fault rupture, but apply it over the entire width of the potential fault zone since we radard a tunnel as a single structure that crosses the entire potential width of the fault.

2.4 Probability of surface rupture

$\Pr\,(sr \neq 0|m_j)$ is the probability that surface rupture (*sr*) occurs for a given magnitude, given) as:

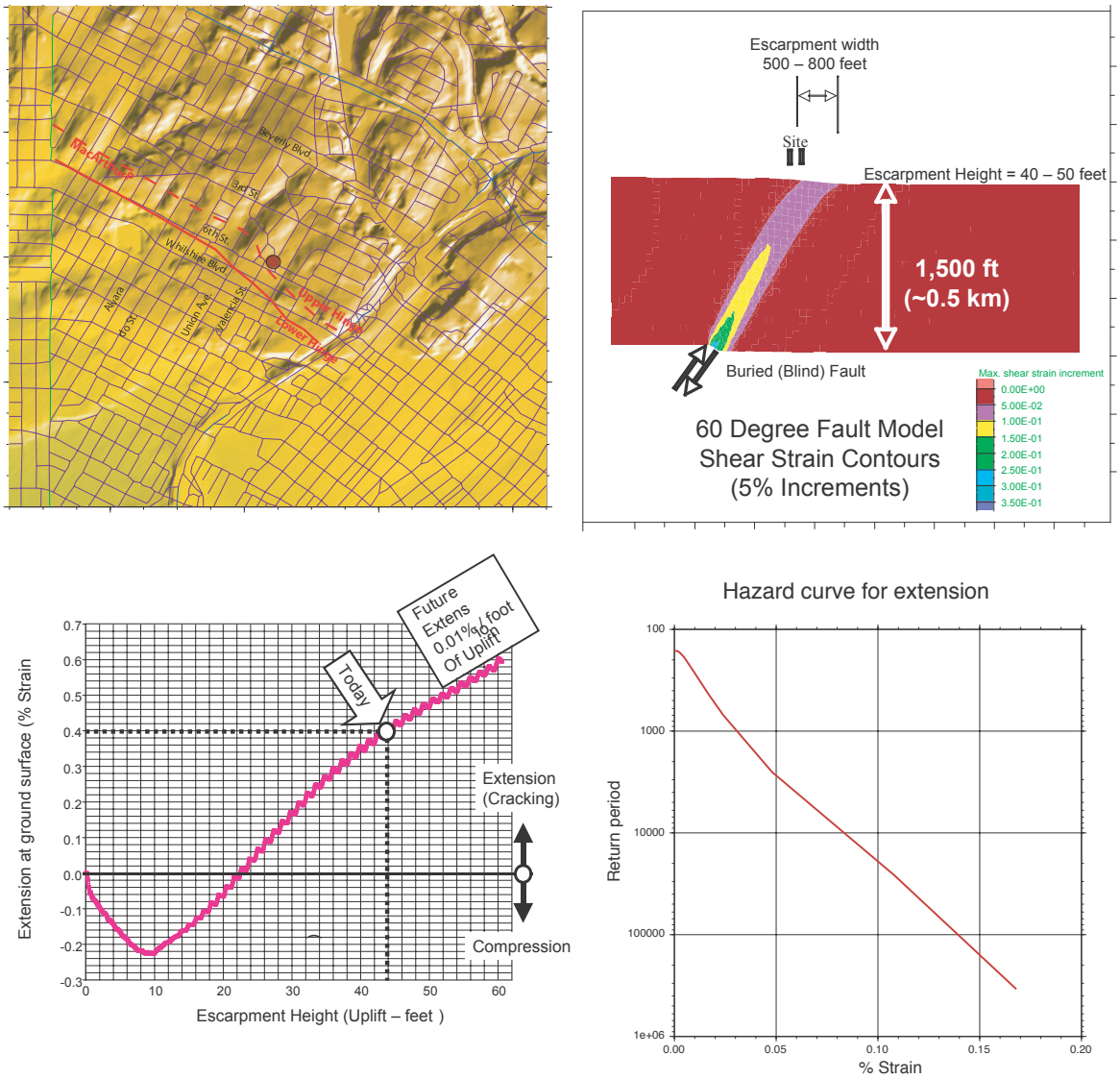

Figure 3. Surface deformation analysis for a blind thrust. a (upper left) - The location of the ramp and site. b (upper right) - a cross section showing the geometry and FLAC setup. c (lower left) - The horizontal strain history for the site. d (lower right) - the final strain hazard curve.

$$\Pr(sr \neq 0 | m_j) = \frac{e^{a+bm}}{1+e^{a+bm}}$$

with a = -12.51 and b = 2.053 for a strike-slip earthquake (Petersen et al., 2011), and a=-32.03 and b = 4.90 for the Japanese data (Takao et al., 2013). Thus, the probability of surface rupture for a thrust earthquake at magnitude 7.0 is only 0.48, compared to 0.86 for a strike slip event (Figure 2). Some authors have divided this function in two, one for the probability of surface rupture for the entire earthquake, and one for the probability of surface rupture reaching the site. The latter is sometimes inherently included in the previous term (slip distribution) and the integration process where we integrate over a range of rupture locations.

2.5 Example of a Probabilistic Fault Displacement Hazard study

Our example of a typical PFDHA study is taken from a hazard analysis carried out in the Los Angeles basin for a Metro tunneling project. The Los Angeles basin is bounded to the north by a major system of oblique faults, which include the Santa Monica and Hollywood faults. Our particular site is located on the Santa Monica fault just west of the transition to the Hollywood fault. Using fault characterization of the UCERF-2 model we performed an analysis of the probabilistic fault displacement.

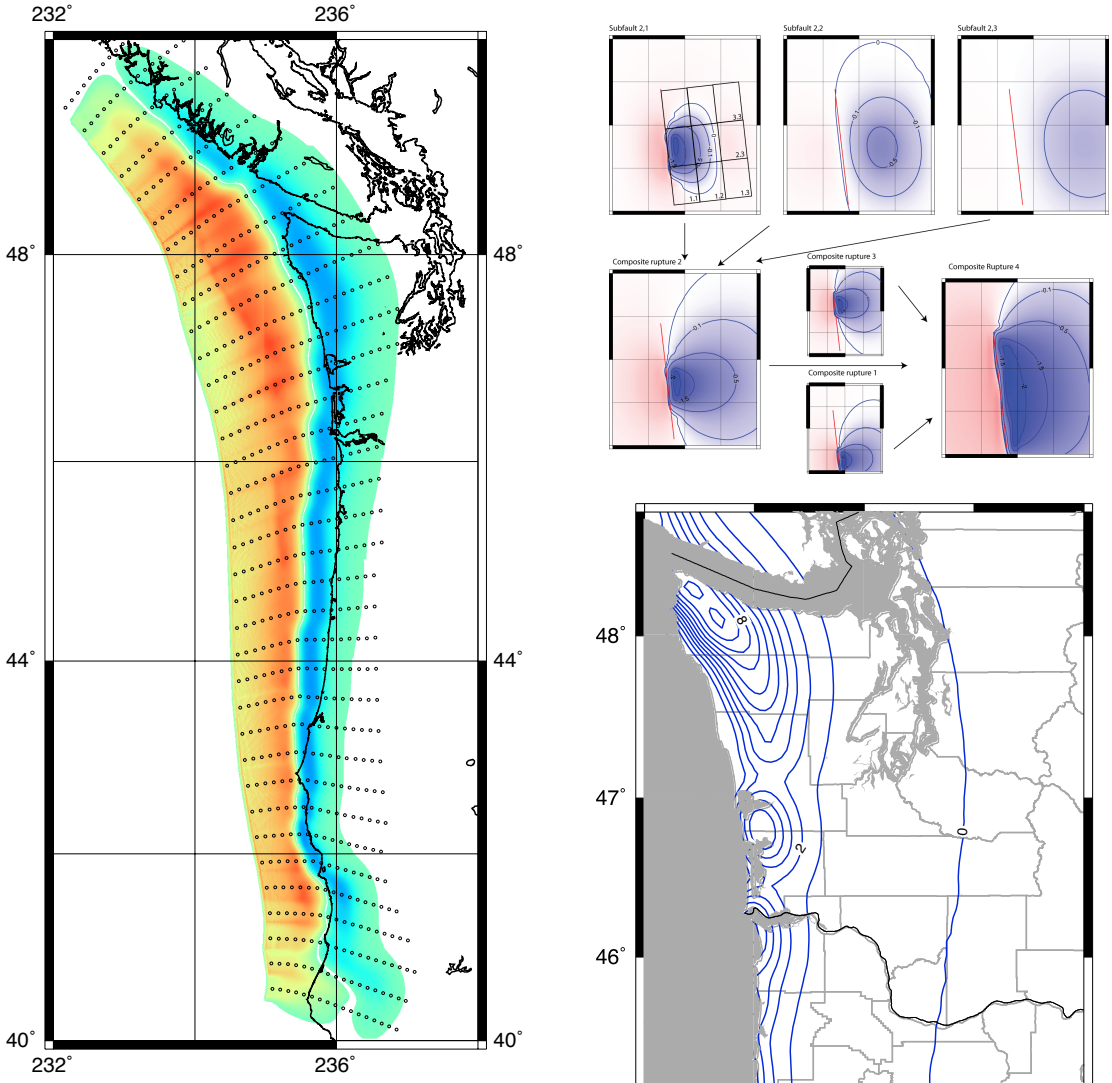

Figure 4. Development of a probabilistic subsidence map for ASCE 7-16. a (left panel) – the subduction interface is divided up in small subfault, for which displacement Green's functions are computed. b – (upper right) These are then summed to efficiently compute surface deformation for an arbitrary slip distribution (also shown in 4a) on the fault. c (lower right) - The final map of probabilistic subsidence.

The displacement hazard curve for the Santa Monica fault is shown in Figure 2. At very long return periods, it is clear that the normalized equations lead to larger displacements (Figure 2b) which is expected, as the total sigma for the normalized equations is larger than the non-normalized equations. The hazard at the longer return periods is in both cases dominated by events with a magnitude of about 7. Compared to the average deterministic value of slip for that magnitude (on the order of 1 m), the probabilistic values at typical probability levels (> 1/2500) are significantly lower. This is due to several factors: the return period of magnitude 7 events is quite long, on the order of 1000 yr or more, the probability of surface rupture is low, especially for the thrust scenarios (Figure 2) and the smaller events, and for the single-segment ruptures, the site is located at the end of the fault zone, which means that the ratio l/L is always small so that the expected slip is significantly lower than the average slip. Only the Santa Monica Fault models that include simultaneous rupture of the Santa Monica and Hollywood faults result in l/L values of more than 0.1.

3 FAULTING INDUCED SURFACE DEFORMATION

We have performed several studies of ground deformation hazard, in particular in the Los Angeles region using a numerical approach. An example is shown in Figure 3 where we present a ground deformation analysis of a site in the Rampart area, which appeared to be prone to extension at the top of the hanging wall. The site is on top of a blind thrust (Figure 3a), the Coyote Pass escarpment (Oskin et al., 2000) which runs through the downtown area of Los Angeles show uplift of more than 15 meters in some localities. It illustrates a common problem with blind thrust faults; they are often identified in populated areas long after they have been built up so that is impractical to avoid building on top of them.

In order to estimate the probabilistic extension hazard at the site, we needed to establish two key parameters: the uplift rate for the escarpment, and a relationship between uplift and extension (Figure 3c). The former was determined using an extension of standard probabilistic displacement hazard analysis. The latter was obtained from a finite element analysis using FLAC (Figure 3b), which was performed after the probabilistic uplift analysis was carried out. Ideally, these steps are all taken within the probabilistic framework, so that the end results are also fully probabilistic rather a combination of deterministic and probabilistic analysis.

The FLAC analysis of the development of the blind thrust yielded an extension history at the site as a function of the height of the escarpment (assuming a constant convergence rate throughout). Based on this analysis, we can estimate the present-day strain rate at the site and relate that directly to the probabilistic uplift rates, from an analysis similar to section 2. Combining these two gave us a probabilistic (extensional) strain rate (Figure 3d), which turned out to be small enough to negate the need for mitigation on measures.

4 PROBABILISTIC SUBSIDENCE ANALYSIS

As part of the new chapter on Tsunami design loads of ASCE 7-16, we have developed a model of probabilistic tsunami waveheights for offshore points along the coast of the western United States, Alaska and Hawai'i. These maps are created by integrating over a complete set of rupture models, with their recurrence rates, aleatory slip distribution as well as epistemic uncertainties expressed using a logic tree with branches for scaling models, rupture termination, shallow slip and long term slip distribution. In order to enable the integration over a large a comprehensive set of sources, we use the linearity of open ocean tsunami waves, which allows us to use pre-computed Green's functions to efficiently calculate the tsunami waveforms at offshore locations. This same principle also holds for the elastic surface displacement, which is also linearly dependent on the slip on a dislocation. We can therefore compute the probabilistic uplift and subsidence in the same manner as we computed the tsunami hazard analysis, rather than the more empirical approach of the preceding sections. In Figure 4 we show an example of this procedure for Cascadia.

The subduction zone interface is sub-divided in small subfaults (30 km x 10 km) (Figure 4a) for which we pre-compute displacement Green's functions for a grid spanning the entire Cascadia coastal region. Since the elastic deformation is linear, we can use this database of Green's functions to compute the deformation field of any arbitrary slip distribution on the interface very efficiently (Figure 4b). This allows us to perform an integration over a range of magnitudes, locations, and consider logic tree models, all similar to, and consistent with, PSHA practice. In Figure 4c we present the probabilistic subsidence map for the Cascadia region for a return period of 2500 years. This map is included in the current draft of the ASCE 7-16 chapter on tsunami loads and effects, and provides a regional correction to the site elevations due to tectonic subsidence. Although the procedure is trictly numerical, the input models, in terms of recurrence relations, magnitude distributions etc. are fully consistent with the source model used by the USGS for 2014 revision of the national seismic hazard maps.

5 CONCLUSION

Probabilistic analysis of fault displacement and ground deformation are becoming commonplace in the

evaluation of earthquake and tsunami hazards. Since there is little data available, especially for ground deformation hazard, it is advantageous to supplement the empirical methodology with results from a numerical analysis. The details of this process depend strongly on the problem at hand, and we have presented examples here for three different circumstances.

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