Characterizing the Hazard of Distributed Surface Fault Rupture

Chris Milliner[1]; Andrea Donnellan[1]; Rui Chen[2]; Jean-Philippe Avouac[3]; James Dolan[4]; Tim Dawson[2]; Yousef Bozorgnia[5]; Alex Sarmiento[5]; Chris Madugo[6]; Albert Kottke[6]; Christine Goulet[4]

[1]Jet Propulsion Laboratory, California Institute of Technology. [2]California Geological Survey. [3]California Institute of Technology, [4]University of Southern California, [5]University of California Los Angeles, [6]Pacific Gas and Electric

Fault surface rupture hazard

Seismic shaking is one of the primary hazards of earthquake occurrence that is considered in building design. Its probability is calculated using probabilistic seismic hazard analyses (PSHA) and delivered to the public as a series of products developed by the USGS National Seismic Hazard Mapping program. However, surface fault rupture also poses a significant hazard to nearby structures and distributed infrastructure (e.g., gas, water and telecommunication pipelines) that cannot avoid fault crossings. Probabilistic fault displacement hazard analysis (PFDHA) is an approach that defines the annual exceedance rate of surface faulting, that is used to inform building design criteria to mitigate for the effects of possible damage from distributed fault rupture. One of the key goals of PFDHA is to accurately constrain fault displacement prediction equations which characterize how the magnitude of displacement on secondary faults attenuates with distance from the primary fault strand. This is analogous to PSHA, which uses ground motion predictions equations to characterize how seismic shaking attenuates with distance from an earthquake source. However, compared to PSHA, the PFDHA approach is early in its development with the first studies that formulated the probabilistic theory published only 17 years ago (Youngs et al., 2003; Petersen et al., 2011). In practice PFDHA has seen limited adoption because of the significant uncertainty of the underlying fault displacement models which result in unrealistically large estimates of surface fault offset and potential overestimation of the hazard. Currently, quasi-probabilistic methods are used while the understanding for developing a more robust probabilistic framework is developed, specifically: location of fault rupture relative to pre-event fault mapping, models for secondary and distributed fault displacement occurring off the main fault, and how local site conditions and fault geometry influence displacements. Here, we outline the primary challenges facing the PFDHA approach, the various research and engineering groups required to solve them and how this can be achieved within the context of an earthquake center in California.

Developing next-generation Probabilistic Fault Displacement Hazard Maps

Improving PFDHA requires a coherent and effective multi-disciplinary research and engineering community to provide consensus around current issues of data standards, modeling assumptions and strategies. One of the main hurdles is that due to the practical challenges associated with measuring fault displacement in the field and the subjective nature of the measurement they are typically spatially sparse and have either large or unknown uncertainty. This is problematic when modeling how fault displacement changes with distance away from the primary surface rupture, as it is vital to understand how to interpret and include the uncertainties and its spatial variation. This therefore requires discussions with field geologists to help build an expert consensus of how to treat these uncertainties and data gaps. Such expertise is highly concentrated in California, including those from academic, state and federal agencies who have extensive experience mapping past ruptures such as the 1971 San Fernando event, 1992 Landers, 1999 Hector Mine, 2004 Napa, 2010 El Mayor, and 2019 Ridgecrest earthquakes.

Unlike the PSHA community, which has developed a shared database of ground motion recordings (e.g., the Next Generation Attenuation models [NGA]) which are used by hazard modelers to constrain ground motion models, the PFDHA community has not yet achieved this or come to an agreed-upon standard of formatting for the displacement measurements. This database problem is currently being addressed by an engineering group at UCLA (who compiled the current NGA seismic shaking database), and is an effort that requires continual input and discussions with field geologists who have experience collecting these types of data and hazard modelers and practitioners who intend to use these data to constrain the fault displacement models.

A recently proposed independent but complementary approach to measure how fault displacement varies across the fault rupture zone involves using geodetic imaging techniques such as pixel tracking algorithms applied to pre- and post-earthquake satellite images to detect shifts from tectonic displacement. These remote-sensing measurements hold promise as they are objective and have uncertainties that can be quantified. Development of a geodetic-based PFDHA approach is active and includes collaboration of geodesists, computer vision experts and seismic hazard practitioners at JPL, Caltech, California Geological Survey and USC who are working to improve the image correlation algorithms to retrieve the full 3D fault displacement, reduce sources of noise to lower the measurement uncertainty and modify the probability hazard theory that was originally adapted for field measurements.

Lastly, current PFDHA approaches are purely ergodic and empirical (relying on data from a limited number of well documented surface rupturing earthquakes to represent the general behavior of fault-zone deformation), with no formal input yet from the dynamic rupture modeling community who are starting to simulate distributed plastic and inelastic yielding of the surface with various rheologies (Ma & Andrews, 2010; Roten et al., 2017, *GRL*). Producing fault displacement prediction equations from outputs of these physics-based numerical simulations of distributed rupture is certainly the future for PFDHA and is the current state of the art for producing ground motion hazard maps (e.g., CyberShake which calculates full 3D wave propagation, Graves et al., 2017). However, to reach a non-ergodic PFDHA approach will require extensive calibration and validation of surface rupture simulations using observations of real earthquake surface ruptures. This will require partnership of the dynamic rupture modeling community (such as researchers at SDSU, UCSD and Stanford, see Roten et al., 2017, *Pure and Applied Geophysics;* Johri, Dunham et al., 2014) with observationalists including field geologists and geodesists.

Fostering multi-disciplinary research collaboration

An earthquake center in southern California, such as SCEC, is uniquely positioned to help address the wide-ranging challenges facing the nascent PFDHA method, as such a task requires a multi-disciplinary, community-based approach that includes experts from industry, academic institutions, and state and federal regulatory agencies who are actively researching these problems or are implementing the hazard models. SCEC's ability to foster multi-disciplinary collaboration is best exemplified by its attempts to support the burgeoning PFDHA community by hosting incubation-like workshops to discuss issues facing PFDHA (e.g., the 2019 Probabilistic Fault Displacement Hazard workshop in Pomona), the SCEC 2019 annual meeting, and by providing seed funding to conduct initial studies that can help lead to larger scale projects. We envision that a better understanding of the fault-zone mechanics, comprehensive compilation of geologic and geodetic observations of past surface ruptures into a shared database with reasoned quality control, and incorporation of physics-based surface rupture simulations will provide the PFDHA community a standard framework with which to build multiple and competing fault displacement prediction models. Having a range of these models and connecting them with earthquake simulators (e.g., UCERF) will produce ensemble forecasts that will ultimately help create effective and robust fault displacement hazard maps, equivalent to what PSHA is also working towards.