SUMMARY REPORT ON THE FAULT DISPLACEMNET WORKSHOP HELD ON OCTOBER 1, 2019

Prepared for SCEC by

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SCEC Award #19201

Workshop Title:

Probabilistic Fault Displacement: Critical Issues, Data Needs, and Interface Plans

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Introduction

We convened a one-day workshop on October 1, 2019 in Pomona, California to identify end-users' needs and interface issues related to the development of new state-of-the-art probabilistic fault displacement hazard analysis (PFDHA) models. The participants included experts from industry, government, and academia from the US and abroad specializing in seismic field geology, geodesy, model development, and simulations. Presentations and group discussions bearing on industry applications and needs, database development, currently available models, proposed new models, and fault rupture simulations were featured at the workshop.

The workshop was part of a larger program consisting of a multi-year, community-based Fault Displacement Hazard Initiative (FDHI) research project led by the University of California. The objectives of the FDHI project are to: (1) compile a modern "next-generation" database of coseismic fault displacements; (2) develop models to predict the amplitude and distribution of potential primary and distributed deformation due to surface fault rupture; (3) develop and validate dynamic rupture simulations to supplement or constrain models; and (4) produce engineering application guidelines for fault displacement hazard.

This document provides a brief summary of the workshop. Presenters' slides are available online at the event webpage[1]. At the end of this document, we provide a list of areas of important research identified at the meeting that will contribute to advancing the state-of-art and -practice in probabilistic fault displacement hazard assessment.

Current PFDHA Models and Applications

An overview of current PFDHA models was presented by Dr. Bob Youngs. The general basis for current PFDHA methods and models was developed in the 1990s as part of the Yucca Mountain study, which evaluated the site as potential permanent storage for spent nuclear fuel and radioactive waste (Stepp et al., 2001; Youngs et al., 2003). While these early models only considered normal faulting on well-located

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[1] SCEC's webpage for the workshop: *https://www.scec.org/workshops/2019/fault-displacement*

primary faults, subsequent models have considered other styles of faulting (Moss & Ross, 2011; Petersen et al., 2011) and primary fault location uncertainty (Petersen et al., 2011). More recently, Lavrentiadis and Abrahamson (2019) developed a method that simulates surface slip along rupture length using wavenumber model. The method is similar to physics-based approaches used in kinematic rupture modeling.

Stepp et al. (2001) and Youngs et al. (2003) developed two methods for computing fault rupture hazard: a displacement-based approach and an earthquake-based approach. The displacement approach uses site-specific information on the rate and distribution of displacement at the site. The probability of slip occurring is one (100%), and the mechanism (primary faulting, secondary slip, etc.) is not considered. This approach is applicable for sites with paleoseismic information to inform or bound estimates on the rate and amplitude of displacement. Many site-specific applications lack the necessary data to apply the displacement approach and must use the earthquake approach. This method is similar to Probabilistic Seismic Hazard Analysis (PSHA) for ground motions, except the PFDHA application considers the probability of a displacement exceeding a specified value given by a Fault Displacement Model, instead of the ground motion probability distribution given by a Ground Motion Model. The earthquake approach is used in the Moss and Ross (2011) and Petersen et al. (2011) models.

The Youngs et al. (2003) and Petersen et al. (2011) earthquake approach models consider both principal fault displacements and distributed slip. Both models follow Coppersmith and Youngs (1992) in defining principal faulting as the slip occurring on the key tectonic/seismogenic feature responsible for the earthquake, and distributed faulting as the secondary slip that occurs on other faults, fractures, or shears near the principal fault. Importantly, both definitions refer to discrete, localized deformation and do not explicitly address continuous, nonbrittle deformation. Discussions at the workshop identified the challenges in classifying faults/structures both before and after an earthquake as either strictly principal or distributed.

To ensure new PFDHA models adequately address end-user needs, the workshop included a presentation by Dr. Chris Madugo with examples of how site-specific PFDHA is currently used to assess displacement hazard for different types of infrastructure and common issues or shortcomings with existing models. While deterministic analyses are still widely used, probabilistic hazard and risk assessments are becoming increasingly common. PFDHA is typically performed for critical facilities (e.g., nuclear and hydroelectric facilities) and linear infrastructure (e.g., water, gas, and transportation lines). Prior to computing the hazard, site-specific geologic studies aimed at locating primary and secondary faults and characterizing fault parameters (e.g., strike, dip, rake, sense of slip, complexity) are typically performed. The level of effort varies depending on the facility, potential hazard, and potential consequence of failure. In addition to site-specific applications, new models ideally could also be used supplement zoning guidelines for California's regulatory Alquist-Priolo Earthquake Fault Zone maps.

Key limitations of the current models include generally broad uncertainties and lack of guidance on the following:

- Probability of rupture and slip partitioning on (sub)parallel faults, including step-overs, reverse splay faults, and other structural complexities
- Probability of rupture and slip partitioning on known secondary fault and unknown geologic structures (e.g., potential faults that have not been identified)

- Methods to differentiate between slip at surface and slip at depth (e.g., tunneling applications and gas field wells)
- Methods to incorporate geologic conditions (e.g., bedrock, granular alluvium, cohesive alluvium) in slip estimates
- Probability, amplitude, and spatial deformation caused by broad warping or tilting

Development of New Database and Models

The FDHI database is being compiled to support the development of next-generation fault displacement models, which aim to estimate the spatial distribution and amplitude of coseismic displacements. Key advantages of the new database include two-dimensional geospatial control for slip measurements and mapped ruptures (e.g., latitude and longitude coordinates), local event coordinate system ordinates, and back-end development in Structured Query Language (SQL). A unique feature of the FDHI database is the inclusion of an event-specific local coordinate system for each earthquake in the database. The event coordinate system (ECS) provides a framework for converting the two-dimensional database into one-dimensional along-strike ordinates to be compatible with existing models that evaluate on- and off-fault slip as a function of distance along strike. The ECS algorithm is being developed as part of the new Lavrentiadis and Abrahamson PFDHA model and is based on the Generalized Coordinate System, version 2 (Spudich and Chiou, 2015) that was used to compute the distance metrics in the Next-Generation Attenuation West2 (NGA West2) models and database.

The workshop included presentations on PFDHA model approaches from several model development teams. Most of the models are in the initial stages of development and will be refined significantly in the next year. The Kuehn et al. model team plans to use the Lavrentiadis and Abrahamson (2019) method to estimate the total slip and variability along the fault and apply a Dirichlet process mixture model to partition slip on subparallel segments. Lavrentiadis and Abrahamson will also use their 2019 method to estimate the total slip, as well as develop additional models for the number/location of parallel fault segments and distributing slip onto the parallel segments. The Chen et al. model development will begin with an assessment of the performance of their earlier Petersen et al. (2011) model against the new database, and then update or redevelop the model as needed. They will also explicitly consider pixel-based strain measurements (e.g., optical image correlation; Milliner et al., 2016) to address probabilistic hazard from distributed or off-fault deformation. Lastly, the Nurminen et al. reverse/thrust fault model development is in progress as part of PhD studies at Università degli Studi "G. d'Annunzio" Chieti - Pescara (UniCH) in Pescara, Italy. Their model is based on the Boncio et al. (2018) database and will provide probabilistic displacements on principal faults and distributed (secondary) faults, and the methodology is expected to be extended to develop new models for normal and strike-slip faulting.

Fault Rupture and Slip Simulations

The afternoon sessions of the workshop included presentations on simulations by Drs. Rob Graves, Kyle Withers, and Yongfei Wang. Kinematic and dynamic fault rupture simulations have been used to varying extents in ground motion model development. Kinematic simulations are computationally efficient and have been well-validated for ground motion applications, such as extrapolating models beyond observational data. The along-fault spatial distribution of total slip can also be modeled using kinematic simulations; however, extensive calibration of the key inputs (coefficient of variation of slip and slip correlation length) is needed for fault displacement model development, and distributed or off-fault deformation is not explicitly generated in kinematic simulations. Dynamic simulations parametrize the underlying physics of fault rupture and are therefore more computationally demanding; however, dynamic models can capture off-fault deformation, fault branching/slip partitioning, fault maturity, and other complex geometries or properties. The key inputs (initial stresses, fault friction, and fault geometry at depth) are poorly constrained in dynamic simulations, and validation for fault displacement model development is in the early stages.

The results of recent studies presented at the workshop suggest along-strike variability, off-fault deformation, and fault zone width can be captured using dynamic simulations. Fault plane asperities have a first-order impact on the spatial distribution of surface displacement and can be modeled in dynamic simulations. Asperities effectively act as roughness along the fault and are related to fault system maturity. Perrin et al. (2016) showed asymmetrical along-strike slip distributions correspond to along-strike variations in fault system maturity, with the more mature end accommodating more surface slip. Roten et al. (2017) incorporated plasticity and nonlinearity in the friction law by using the Drucker-Prager yield criterion at each node in their finite difference model with the Hoek-Brown failure envelope. They systematically varied the yield stresses to approximate rock qualities ranging from poor to very good and showed the relative amount of off-fault deformation and fault zone width observed from optical image correlation (e.g., Milliner et al., 2015, 2016; Zinke et al., 2014) can be reproduced in dynamic simulations by approximating rock quality and including a low velocity zone along the fault.

To effectively apply dynamic rupture simulations to PFDHA model development, validation and verification studies are needed. Workshop participants identified four first-order validation metrics: (1) satisfaction of applicable scaling laws, such as magnitude vs. displacement or appropriate seismological constraints; (2) agreement with empirical observations of slip vs. along-strike distance; (3) ability to capture relative amount of off-fault deformation, as determined from optical image correlation or similar datasets; and (4) ability to generate reasonable ground motions while satisfying other criteria. Proposed verification metrics included spectral analysis (e.g., power spectrum) and fault zone width. Specific details of the validation and verification plan will need to be determined by a dedicated dynamic simulations working group.

Future Work

Workshop participants recognized the need for focused research to advance the state-of-the-art and practice in PFDHA. In addition to identifying the following areas of important research, there were multiple discussions bearing on the use of "principal" and "secondary" faults and a lack of consensus on the need for the distinction.

1. Development of dynamic rupture simulation validation and verification metrics to capture on-fault displacement, off-fault deformation, and fault zone width; application of dynamic rupture simulations to fill database gaps for use in PFDHA model development.
2. Testing of kinematic rupture simulations against new database to improve estimates of slip coefficient of variation and slip correlation length.

3. Develop updated regressions/models using the new empirical database (e.g., magnitude-displacement, magnitude-probability of surface rupture).
4. “Fault box” studies to constrain off-fault deformation in granular vs. cohesive materials for potential use in PFDHA model development.
5. Compilation or development of pre-earthquake fault maps from aerial photograph analysis for use in, or testing of, PFDHA models.
6. Parametric evaluation of the impact of judgment as commonly applied in the current state-of-practice of PFDHA, including slip partitioning, horizontal-to-vertical ratios, etc. and/or guidance on applying PFDHA results to site-specific fault geometries.
7. Development of best-practice guidelines for measuring and documenting displacements in the field and using differential remote sensing.

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