Fault Displacement Hazard Analysis Workshop in Menlo Park, USGS facility- Synthesis and Perspectives – 8 and 9 December 2016

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Fault Displacement Hazard Analysis (FDHA) plays an important role in the risk assessment and design of both new and existing infrastructure located across and near active and potentially active faults. The primary objective of FDHA is to quantify the spatial distribution and magnitude of surface displacements and deformation caused by tectonic faulting and the hazard for structures impacted by this deformation.

Lessons learned from recent earthquakes, new research, and implementation of FDHA methodologies in projects, as well as recent guidance documents (e.g. American Nuclear Society - Criteria for Assessing Tectonic Surface Fault Rupture and Deformation at Nuclear Facilities) provide the current perspective on FDHA in the assessment of tectonic surface deformation of engineering concern. However, compared to other types of seismic hazard analysis (ground motion, liquefaction, slope failure), this field is still considered by many to be in its early stages of development.

After a kick-off meeting in Paris (October 2015), sponsored by IRSN, this Menlo Park workshop, organized by USGS, CGS, INGV and IRSN, aimed at bringing together researchers, practitioners, and stakeholders interested in the topic of fault displacement, to discuss issues pertaining to FDHA, and to develop a plan for moving FDHA research forward. The workshop was very successful in terms of the quality of presentations and discussions, as well as in attendance. It attracted more than 100 participants from 8 countries, 8 major infrastructure stakeholders, 11 universities, 12 government agencies and laboratories, and 17 geologic engineering consulting companies. One of the primary motivations of this workshop was to develop a community-sourced, worldwide, unified database of surface rupturing earthquakes with a rich list of parameters for the basis of empirical regressions used in FDHA. This database is currently in development within the framework of an International Union for Quaternary Research (INQUA) project (Surface Rupture during Earthquakes Database - SURE) and IAEA working group.

Schedule

The workshop included talks on "*Lessons Learned from Recent Earthquakes*" (6 talks), "*Observational Data for the Surface Rupture during Earthquakes (SURE) Database*" (6 talks), the "*Application and Advances in Deterministic and Probabilistic Fault Displacement Hazard Analysis*" (10 talks)" and possible ways for "*Moving Forward*" (2 talks). Time was also allotted to some attendees to present surface faulting cases or their top lessons learned in the applications of FDHA during 2-4' flash-talks. Some scientists could also share their experience thanks to discussion around posters.

Lessons learned from recent earthquakes

1. Francesca Cinti (INGV): Surface rupture in the 2016 Earthquake Sequence in Central Italy

2. Shinji Toda (IRIDes - Tohoku University): Widespread complex surface rupture associated the Mw 7.0 16 April 2016 Kumamoto, Japan, earthquake

3. Dan Clark (Geoscience Australia): Variation in earthquake surface rupture characteristics across intraplate Australia

4. Greg dePascale (University of Chile): Fault rupture observations from the most recent and prior events along New Zealand's Alpine Fault and Greendale Fault

5. Pilar Villamor (GNS Science) : Last minute addition: Briefing on the 2016 Kaikoura, New Zealand Earthquake

6. Ben Brooks (USGS): Constraining Co- and Post-Seismic Shallow Fault Slip with Near-Field Geodesy and Mechanical Modeling Executive Summary

Observational data for the Surface Rupture during Earthquakes (SURE) Database

7. Tim Dawson (California Geological Survey): Perspectives from California

8. Xiwei Xu (China Earthquake Administration): Issues associated with setback distance from active fault in China: What we have learned from the 2008 Wenchuan Earthquake

9. Chris Milliner (U.C. Berkeley): Quantifying Co-seismic Distributed Deformation Using Optical Image Correlation: Implications for Empirical Earthquake Scaling Laws and Safeguarding the Built Environment

10. Austin Elliot (COMET/ University of Oxford): A new technique to measure 3D slip vectors from high-resolution topography, applied to photogrammetry of historic ruptures

11. David Schwartz (USGS): 50 or 500? Current Issues in Estimating Fault Rupture Length

12. Stéphane Baize (IRSN): Towards a unified database of Surface Ruptures (SURE): Objectives and perspectives

Application and Advances in Deterministic and Probabilistic Fault Displacement Hazard Analysis

13. Thomas Davis (Geologic Maps Foundation, Inc): Fault displacement hazard at natural gas storage fields-a future research and regulatory direction

14. Ivan Wong (Lettis Consultants International): U.S. criteria for assessing tectonic surface fault rupture and deformation at nuclear facilities

15. Mark Petersen (USGS) and Rui Chen (CGS): Surface Rupture Data and Location Uncertainty in Probabilistic Fault Displacement Hazard Analyses

16. Steve Thompson (Lettis Consultants International): Deterministic and probabilistic fault displacement hazard methodologies for gas pipeline crossings in California: applications and data needs

17. Keith Kelson (U.S. Army Corps of Engineers): Risk Characterization and Dam Safety Modifications to Address Active Fault Rupture Beneath an Embankment Dam

18. Naoto Inoue (Geo-Research Institute – Japan): Framework of probabilistic and deterministic methods for evaluating near-fault displacement

19. Donald Wells (Amec – Foster Wheeler): Application or Mis-Application of PFDHA. What Relationships are Appropriate and Is the Displacement Result Reasonable?

20. Glenn Biasi (University of Nevada, Reno): Performance-Based PFDHA Using the Third Uniform California Earthquake Rupture Forecast

21. James Gingery (Kleinfelder): Case study of the Analysis and Design of Bridge Foundations Intersected by Active Faulting

22. Jonathan Bray (U.C. Berkeley): Engineering Implementation of the Results of a Fault Displacement Hazards Analysis

Moving forward

23. Norm Abrahamson (Pacific Gas and Electric): The Path Forward: Research Directions and Plans for a PEER Research Project

24. Jeff Bachhuber (PG&E), Yousef Bozorgnia (PEER): Collaborative Opportunities and Coordination of Research Efforts

Synthesis

The workshop was successful in the sense that it assembled a large community interested in earthquake surface ruptures. Academic scientists, governmental and institutional agencies' members, consultant engineers and geologists were gathered to attend relevant presentations and related discussions.

The earthquake geologists presented the recent cases' ruptures and the lessons learned. In Italy (2016 Amatrice & Norcia: Francesca Cinti), Japan (2016 Kumamoto: Shinji Toda) and New Zealand (2016 Kaikoura: Pilar Villamor), the rupture complexity has been emphasized, with significant distributed and/or triggered deformation and with main ruptures occurring on generally previously mapped fault traces. In the Japanese case, surface rupture follows the mapped fault when examined at 1/50,000 scale, but small scale ruptures show unpredictable patterns (multiple scale en echelon step-overs, conjugate segments). A striking counter-example is given by the 2010 Darfield earthquake, New Zealand (Gregory De Pascale) which caused rupture and surface faulting on previously unknown faults. In Australia, fault rupture displacement hazard might only be meaningfully defined in non-cratonic areas, where earthquake recurrence could be inferred from classical surface geology (Dan Clark). Talkers and audience noticed the significance of site-effects (local geology) in the rupture pattern at the surface. Several talks focused on the huge contribution provided by new observational geodetic techniques in order to 1) quantify the geomorphic fault displacements and related uncertainties in complex cases with oblique slip and steep slopes (Austin Elliott) or estimate the distributed deformation off the major ruptured faults (Chris Milliner) 2) understand the shallow faulting mechanics and influence of mechanical properties on deformation distribution (Ben Brooks), 3) evidence the secondary displacements of low amplitude or slow active faults (Gregory De Pascale). The influence of surface geology, shallow fault geometry or earthquake mechanism (including the "hanging wall effect" for dip slip faults) has been emphasized by field observations (e.g. Christopher Milliner, Xiwei Xu), but also confirmed by modelling (Naoto Inoue).

For most industrial and conventional buildings, fault displacement is a hazard that is considered in the design stage, with the exception of deep gas storage in earthquake-prone areas of USA (Thomas Davis) which needs regulation guidelines. In the current practice, Fault Displacement Hazard is estimated by the engineering/consultancy community for building planning on a pure deterministic way in California (Alquist-Priolo Act), using local data from paleoseimology to assess the potential surface faulting threat at a site (Timothy Dawson). Numerical modelling, complementing field findings, deterministic or probabilistic analyses, allow the identification of strategies to mitigate surface faulting at facilities like bridges (James Gingery) or house buildings (Jonathan Bray) or dams (Keith Kelson). For its large pipeline network, the Californian electrical operator (PG&E) has developed a deterministic approach exploring the uncertainties on magnitude determined from "length to M" scaling relationships, and estimating the corresponding displacement, etc (Stephen Thompson). Probabilistic approach to estimate the surface displacement hazard is the recommended way to assess the safety of nuclear facilities, accounting for the return period of events, calling for empirical relationships supported by worldwide databases (Ivan Wong, Naoto Inoue) and at the end estimating the annual rate of exceedance of displacement values and associated uncertainties (Mark Petersen and Rui Chen). The last release of the probabilistic earthquake forecast model for California (UCERF3) could be used to quantify surface displacement offsets and their uncertainties across the major faults of California, in order to evaluate the risk for lifelines such as aqueducts and pipelines (Glenn Biasi). A key issue in FDHA is to estimate the maximum earthquake that can be caused by a fault, and a common technique is to use fault length: however, estimating "extreme" events by considering multiple fault segment ruptures' scenarios should be given more attention, considering physical factors rather than a collection of rules, as presently done in UCERF3 (David Schwartz). In a broader sense, sensitivity tests illustrate that, in the PFDHA approach, choices on input parameters (selected fault models, scenarios of ruptures, rupture probability functions) must be informed by as much knowledge of the site setting as possible (Donald Wells). In addition, a significant issue in PFDHA is also to assess the uncertainties of future location of rupture with respect to known mapped faults (Mark Petersen and Rui Chen): whether epistemic (mapping inaccuracy) or aleatory (natural variability of rupture location), uncertainty quantification can be improved by upgrading fault mapping and analyzing the scattering of ruptures in the prehistoric recordings.

There is clearly a variability in the current practice, from deterministic to probabilistic approaches, following or not the ergodic hypothesis (= i.e. we can gather the samples of similar seismotectonic regions to replace the lack of local information) or using modelling. There is a large use of field data, either at local scale with high level of accuracy for specific studies (e. g. paleoseismological trenches, geodetical measurements of coseismic slip), or at global scale with compilation of worldwide surface rupture information (e.g. empirical relationships between magnitude and fault parameters, displacement attenuation). Both are the purpose of the current INQUA project dedicated to improve the worldwide dataset of surface ruptures (SURFACE: http://www.earthquakegeology.com/materials/projects/1620R.pdf). The US earthquake-related community is clearly starting to build up a concrete project for improving the surface faulting hazard assessment as demonstrated in the concluding session by the talk "Moving forward" of Norm Abrahamson and Jeff Bachhuber from PG&E. The US project, as proposed by PEER and PG&E, will focus on compiling and acquiring data in the western USA. The database for the whole area will probably be significantly upgraded with respect to the existing one. The "international" community (i.e. non-US people) has already started to progress in this direction with a special focus on gathering worldwide cases to set up the unified SURE database (Stéphane Baize).

Take away points

- There is broad interest, worldwide, in probabilistic estimates of the amount of slip and its distribution during future earthquakes for engineering design of infrastructure. Distributed deformation is a key concern, particularly for long baseline structures such as a pipelines, tunnels, and bridges.
- Worldwide researchers, especially from the US, Europe, Japan and New Zealand, are currently updating and compiling existing fault rupture data that will be incorporated into the SURE database.
- Following the Menlo Park meeting and the project dissemination, new fault rupture data from recent earthquakes have been provided by some of the participants, to feed the SURE database.
- The Database structure as well as additional fault parameters needed (like surface geology or structural complexity) for its implementation that were discussed in Paris at the first SURE database meeting were validated at the Menlo Park meeting.
- The US stakeholder community has identified potential funding partners (currently PEER [Pacific Earthquake Engineering Research Center] and PG&E [Pacific Gas and Electric Company]) for improving the Database with western US observations. The US initiative will soon nominate an Executive committee to guide and manage this research effort. The International community will participate in this as much as possible and, in parallel, will identify sources and request funding for its own activities.