**Workshop on Fragile Geologic Features (FGFs) & PSHA**
Mark Stirling & Mike Oskin
Palm Springs Hilton
11 Sept 2022; 9.00am to 12.30pm Pacific Standard Time

SCEC Award #22154
$12,000

## Introduction

In the last year, fragile geologic features (FGFs) studies have "come of age," being used to constrain design loadings for a major engineering application in New Zealand. This milestone has been accompanied by key studies of FGFs and probabilistic seismic hazard assessment (PSHA) in North America. On 11 September we held a half day workshop involving participants currently involved in research on FGFs and PSHA. The workshop came exactly three years after the last SCEC workshop on this topic, and provided an opportunity for researchers to discuss the latest work, unresolved issues, and future directions. The following sections provide a summary of the workshop.

**Mark Stirling and Mike Oskin** opened the workshop with welcomes and introductory comments. The message conveyed was that there had been milestones achieved in the last two years with FGFs being used to set the design motions for a large dam site in New Zealand, and in informing hazard for the Diablo Canyon power plant. These two workstreams could be viewed as FGF-PSHA research "coming of age", through making the transition from science to practise. The main topics discussed at the workshop were: FGF fragility; FGF populations; completion of a major 15 year-long regional study of FGF ages and fragility in southern California; regional studies in the Pacific Northwest, eastern USA; Trona Pinnacles case study; and methods for using FGFs in PSHA. Workshop highlights are described in the sections below.

Figure 1: The Clyde Dam site, where FGFs were used for the first time to set the design motions for a major engineered structure. The inset shows one of the schist FGFs focused on in the study. Images from Mark Stirling and Julian Thomson.

Regional/topical studies

**Ramon Arrowsmith** began the presentations with one on FGF populations and fragility. He described evolutionary models for FGFs, with a focus on precariously balanced rocks (PBRs). He discussed two end-members of PBR formation: a gradual increase in fragility (e.g. hoodoos), and the instantaneous model of formation by PBR emplacement (e.g. glacial erratics). He also showed how newly-developed robotic UAVs could be used to efficiently collect PBR data, automatically identifying and documenting PBRs as part of a survey. Also discussed was the quantification of fragility from simulations, and the use of 3D printed PBRs atop mini shake table.

**Devan McPhillips** provided an overview of his work on Oregon/Washington coastal sea stacks. In fragility analysis, seastacks are treated as elastic beams with a fixed base that has to be broken. The ages of the seastacks are estimated by way of the distance from seastack to coast and the estimated retreat rate of the coastal cliff. The comparison of seastack ages and fragilities to the simulated motions from Mw9 Cascadia megaquakes showed generally good agreement. Furthermore, the use of landslides to estimate minimum-bound motions tended to be in good agreement with the maximum-bound motions from the seastacks. These studies therefore suggest that the national seismic hazard estimates are not over-cooking the hazard in this part of the world.

**Tom Pratt** provided an overview of his compilation and first-order analysis of FGFs in the eastern USA. His sources of information and images were obtained from hobbyists interested in FGFs as aesthetic landscape features. Tom showed most of these features in the northeastern USA to be glacial erratics left behind from deglaciation around 15-20 kyrs ago. Tom has used structure-from-motion photogrammetry to develop point cloud 3D models of the PBRs, including the detailed geometry and rock pedestal contact area. He also placed seismometers on top of PBRs to measure the resonant frequencies of the rocks. Finally, Tom showed how he was able to map potential exclusion zones, where hypothetical large earthquakes may have toppled PBRs. This work shows great promise for estimating shaking hazard in the eastern USA, where earthquake sources do not slip frequently enough to be revealed by traditional fault-mapping and paleoseismic approaches.

**Christine Wittich** gave a virtual presentation on her work on the details of fragility estimation. Christine showed that the parameters of cumulative absolute velocity (velocity over a time history) and peak ground acceleration (PGA) are both favourable predictors of PBR toppling. The parameters are certainly as favourable as the ratio of peak ground acceleration to PGA versus PGA approach developed by Matt Purvance over a decade ago. Christine further showed that FGF interface geometry with the pedestal had a very significant influence on fragility.

Regional/topical (continued) & application to PSHA

**Anna and Dylan Rood** gave a joint virtual presentation on a regional PBR study in southern California, currently in press at the Bulletin of the Geological Society of America. The study started some 15 years earlier with the work of Lisa Grant Ludwig and Jim Brune, and SCEC was a major supporter of the effort in these early days. The study combines PBR fragility and cosmogenic age estimates for sites across southern California. The authors used OpenQuake and UCERF3 to compare PBRs fragility to site-specific hazard estimates. Part of this work was a very thorough documentation of the PBR sites and associated analyses, summarised for each site in the supplementary information. The presenters used joint toppling probabilities for multiple PBRs at a single site, rather than focusing on the most fragile PBR. The overall study shows that the PBRs can be used to reduce the hazard estimates by 65-72%, which may have significant implications for hazard estimates across southern California.

**Christine Goulet & Xiaofeng Meng** gave an update on efforts to thoroughly document all of the fragile elements of Trona Pinnacles, located near the 2019 Ridgecrest earthquake sequence, to produce an interactive database. This is being combined with the existing SCEC PBR database. The issues still remain as to how FGF information in general should be managed, given that they are ancient, delicate features that could easily be vandalised. Guidance from the American Geological Institute was suggested by Lisa Grant-Ludwig as a way forward towards protecting such scientifically precious features.

**Norm Abrahamson & Albert Kottke** presented their latest work on how best to use PBRs to constrain probabilistic seismic hazard models. Their suggestion was to not base logic tree branch weights on PBRs, but instead identify logic tree branches that are inconsistent with the PBRs, and remove them. They also suggested that fully ergodic hazard doesn't produce enough epistemic uncertainty to allow any of the percentiles of hazard to be compatible with the most fragile PBR at the Double Rock site near the Diablo Canyon power plant, thus down-weighting or removal of logic-tree does not improve the compatibility of hazard estimates. The only way to achieve compatibility is to use a non-ergodic approach, which produces a larger range of potential hazards that overlap with most fragile PBR. Norm and Albert also showed that the Double Rock PBRs seem to: (1) favor larger magnitudes on Hosgri and Shoreline faults due to recurrence intervals being longer; (2) be inconsisistent with some frequently-used ground motion models, leading them to suggest that these models should be looked at first when trying to understand PBR-PSHA discrepancies. Finally, Norm and Albert made the following series of conclusions:

- Non ergodic uncertainty treatment, and the use of non-Poissonian source models are the most favourable approaches to doing PSHA. The non-ergodic hazard curves tend to be steeper, and allow for more compatibility with the PBRs.
- Fragility models need to incorporate epistemic uncertainties.
- There is a need to adequately address spatial correlation issues with respect to PBR populations.
- Rejection of hazard curves should avoid using a specific probability level. Use of Bayesian methods is a more favourable approach.

Following the presentations, a general discussion focused on the following:

- The lack of fragility age control on the Trona Pinnacles provides no ability to gauge how useful they are for constraining major prehistoric earthquakes in the area. We note however that the age of the pinnacles, which were formed underwater, is well constrained from the age of pluvial Trona lake.
- The use of the ensemble approach to fragility estimation was generally seen as the preferable way to advance FGF applications to PSHA.
- Further detailed studies of fragility and age need to be done in order to get a true understanding of these two parameters. There is still work to do at the Double Rock site, for instance.
- The concept of time-dependent fragility has not been fully addressed as yet, and needs more focus. Time-dependent damage to PBR bases, and gradual weathering, are not adequately understood.

<u>Participants physically present:</u>
Albert Kottke
Chris Madugo
Tom Pratt
Devin McPhillips
Ramon Arrowsmith

Lisa Grant Ludwig
Christine Goulet
Xiaofeng Meng
Malinda Zuckerman
Zhiang Chen
Mike Oskin
Mark Stirling
Glenn Biasi
Martin Mai

Participants attending virtually:
Norm Abrahamson
Christine Wittich
Anna Rood
Dylan Rood