Impact of Contact and Interface Modeling on Precarious Rock Fragilities
Final Technical Report, SCEC Award #19113

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Project Objectives

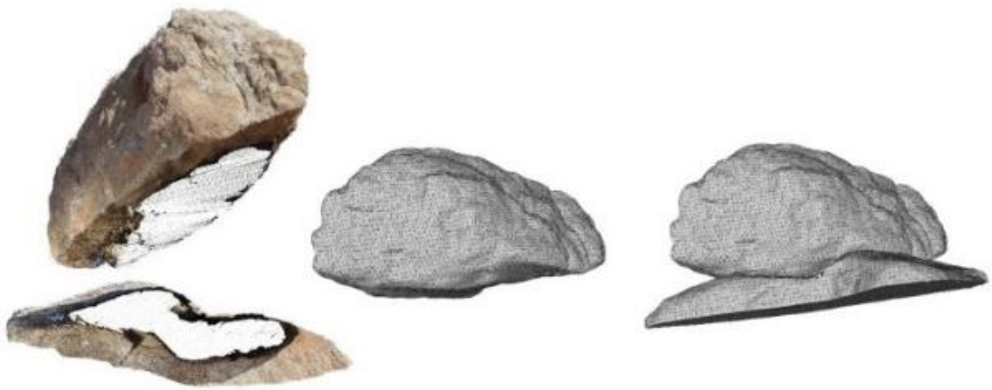
Figure 1. Sample precariously balanced rock in Jacumba, CA.

Reliable estimates of seismic hazard are essential for the development of resilient communities; however, estimates of rare, yet high-intensity earthquakes are highly uncertain due to a lack of observations and recordings [1]. For example, nuclear power plants and nuclear waste repositories must be designed to survive extremely rare seismic events; however, there is a knowledge gap regarding the ground motion amplitudes resulting from such an infrequent event. In the absence of significant earthquake observations, the existence of certain precariously balanced rocks and other fragile geologic features provide a means to deduce the maximum possible ground motion at a site over the lifetime of the rock – i.e., that which precludes overturning or toppling [2]. A precariously balanced rock is an individual or group of rocks that has eroded into an unstable configuration – see **Figure 1**. Given that the ages of many of these features have been established to be in excess of 10 – 30 ka [3], precarious rocks and other fragile geologic features are one of the only available means to validate seismic hazard associated with long return periods.

Current state-of-the-art methods for predicting overturning of a precarious rock include detailed surveying of the rock's geometry followed by numerical simulations and ultimately fragility analysis, in which the probability of overturning is related to a measure of earthquake intensity (e.g., peak ground acceleration) [e.g., 4]. However, there are significant sources of uncertainty at each analysis stage of the precarious rock, which impact the resulting probabilities of overturning to unknown extents. For example, recent field surveys of precarious rocks have highlighted the potential for complex interface conditions that are not readily captured by traditional surveying techniques [5]. Therefore, a precarious rock may appear that is in uniform contact with a rock pedestal; however, the base of the rock may have eroded into a configuration where it is in contact at only a few discrete points on the pedestal. Recent analytical studies have highlighted the potentially significant impact of interface geometry on the dynamic rocking response of two-dimensional rigid bodies, which is likely to translate to the dynamic response of precarious rocks [6 -7]. As a result, the overall objective of this project was to quantify and assess the impact of interface geometric variations on the probabilistic overturning predictions of precarious rocks. This was conducted through a numerical case study on a representative precariously balanced rock, that was previously surveyed in Jacumba, CA [7].

Methodology

In this study, the rocks were documented with a combination of laser scanning and structure-from-motion (or photogrammetry) due to noted nonlinearities with respect to geometry. This documentation strategy combined the accuracy of laser scanning with respect to geometry and orientation with the surface detail of the image-based structure-from-motion. This produced excellent coverage of the rock and pedestal as well as a detailed outline of the interface. This data was augmented by detailed manual measurements and documentation of the interface to identify the regions in contact. A unique scheme previously developed by the PI and others interpolates data points along the occluded interface using the detailed three-dimensional outline of the interface and guided by the manual interface measurements [7]. Provided these dense point clouds of the individual rocks, watertight triangulated surface meshes could be generated via the Poisson Surface Reconstruction algorithm [8], to obtain high-resolution geometric models for numerical analysis. A representative PBR with the interpolated interface and final mesh of both rock and pedestal are shown in **Figure 2**.



(a) (b) (c)

Figure 2. (a) Point cloud of PBR and pedestal with interpolated interface points; (b) triangulated surface mesh of PBR; and, (c) surface mesh of PBR atop pedestal.

The 3D surface meshes of the PBRs were imported into a distinct element program, 3DEC [9], which was developed based on Cundall's pioneering efforts on distinct element method [10]. Given the nature of the problem being studied, the distinct element approach is preferred over other techniques (such as finite element method) as it allows large rotation and complete detachment in addition to its versatility in contact detection. In this type of modeling strategy, the individual PBR and pedestal are modeled as distinct rigid entities that are free to displace, rotate, and impact with one another. Forces are transferred within a system of rigid bodies, such as this, through penalty-based contact algorithms, in which the penetration of one body into another yields a reactionary force. These contact forces are then used in the determination of the displacement and rotation of the rigid body at the next time step. This numerical modeling scheme handles the fully three-dimensional motion of arbitrary shapes, and accounts for the range of likely failure modes including overturning, excessive sliding, and combination modes. The 3D surface meshes were converted into actual volumetric models by utilizing a material density of 162 lb/ft^3 (2600 kg/m^3) to reflect rock-like material. The pedestal rock was modeled within the program with the same material. As the geometrical interfaces in a distinct element program are characterized by joint normal and shear stiffnesses, a typical stiffness value of 1 GPa/m was used for this purpose.

The ground motion records for the numerical simulations were predominantly near-fault records taken from PEER NGA-West2 database [11]. The only exceptions are the 2015 Gorkha-Nepal earthquake records, which were retrieved from Center for Engineering Strong Motion Data (CESMD) [12]. The two orthogonal horizontal components of the ground motion were combined to obtain a single representative intensity measure that is independent of the orientation. The intensity measures $RotD_{50}$ PGV/PGA and $RotD_{50}$ PGA are calculated using the procedure presented by Boore [13]. $RotD_{50}$ is the median amplitude or 50^{th} percentile of response spectra over all non-redundant rotations of a given pair of horizontal components of ground motion [13]. The median amplitude of the spectra at period of 0 s corresponds to $RotD_{50}$ PGA. As the numerical analyses were performed under horizontal bidirectional excitation, the as-recorded ground motion time series were rotated to North and East to align the input time series along two orthogonal directions of the model. A total of 70 bidirectional records, covering a range of $RotD_{50}$ PGV/PGA values, were selected for the analyses. Each horizontal component of the selected records was normalized by $RotD_{50}$ PGA and multiplied with a range of scale factors (i.e. 0.2 g to 1.0 g) to obtain 9 intensity levels of PGA, which, in turn, results in 630 analyses for each PBR model.

Results

Seismic fragility analyses were performed by using the numerical outcomes from the PBRs analyses. Due to the dichotomous nature of the outcome (i.e. overturning or no overturning), a bivariate logistic regression is adopted to study the combined relation of $RotD_{50}$ PGA and $RotD_{50}$ PGV/PGA with the probability of overturning. In other words, it is a way to estimate the probability of overturning with vector-valued ground motion intensity measures. A bivariate logistic regression is similar to univariate logistic regression as it deals with binary outcomes considering two covariates (or independent variables) instead of one covariate. The logit function or log-odds can be expressed in the form of Eq. (1), while, the probabilities of overturning given the two covariates, can be calculated using Eq. (2):

$$logit\left[P\left\{O|PGA = x_1, \frac{PGV}{PGA} = x_2\right\}\right] = \beta_o + \beta_1 x_1 + \beta_2 x_2 \qquad (1)$$

$$P\left(O \,\middle|\, PGA = x_1, \frac{PGV}{PGA} = x_2\right) = \frac{e^{\beta_o + \beta_1 x_1 + \beta_2 x_2}}{1 + e^{\beta_o + \beta_1 x_1 + \beta_2 x_2}} \qquad (2)$$

where $P(O)$ represents probability of overturning, x_1 and x_2 are the covariates, and β_o, β_1, β_2 are regression coefficients. As the distribution associated with the logistic regression is a binomial distribution, the maximization of the likelihood function is necessary to estimate the unknown regression coefficients. The likelihood function, L, in its compact form is presented in Eq. (3):

$$L(\beta_o, \beta_1, \beta_2) = \prod_{i=1}^{n} P(x_i)^{y^i} (1 - P(x_i))^{1-y^i} \qquad (3)$$

where y^i is the binomial distribution variable, which equals unity if overturning occurs and is null otherwise. $P(x_i)$ is the probability of overturning given the two intensity measures PGA and PGV/PGA. Usually, the maximum likelihood estimates are found by employing the log-likelihood of this equation, differentiated with respect to the parameters (β_o, β_1, β_2). The derivatives are then set equal to zero and solved numerically since the closed-form solution is not possible.

The probabilities of overturning were then obtained at the intensity levels of interest, which are transformed into a fragility surface by plotting with the corresponding intensity measures. These fragility surfaces provide valuable information regarding the (probabilistic) vulnerability of the structure at various vector-valued intensities. The fragility surfaces for two PBR models developed using the aforementioned procedure are shown in Fig. 3. In this figure, Model 1 represents the "baseline" geometry of the surveyed rock and Model 2 represents the same rock with a 10% increase in the perimeter of the rock at the interface. This second model more closely represents the geometry that would be obtained using strictly remote sensing (lidar or SfM); however, the first model includes the detailed manual measurements of the interface. The fragility surfaces for both models are presented in Fig. 3, where the darker magenta shade represents lower probabilities of overturning and the lighter yellow shade approaches a 100% probability of overturning. As expected, lower values of PGA and PGV/PGA yield lower probabilities of overturning. In order to facilitate a more direct comparison of the two models, fragility contours at select probabilities of overturning are plotted in Fig. 3c (i.e., 16%, 50%, 84%, and 95%). With a 10% increase in the contact area at the base of the PBR (Model 2), the same probability of overturning is achieved, in general, at a lower PGV/PGA value when compared with Model 1. Specifically, at a PGA of 0.2 g, Model 2 has a 95% probability of overturning at a PGV/PGA of 0.58 s, while Model 1 has a 95% probability of overturning at a PGV/PGA of 0.70 s. Considering each of the contours, the probability of overturning can be underestimated by as much as 20% due to inaccurate interface measurements. Given the substantial differences observed in the probabilistic overturning for these two PBR models, further investigation is warranted to study the effect of the interface shape on the rate of overturning.

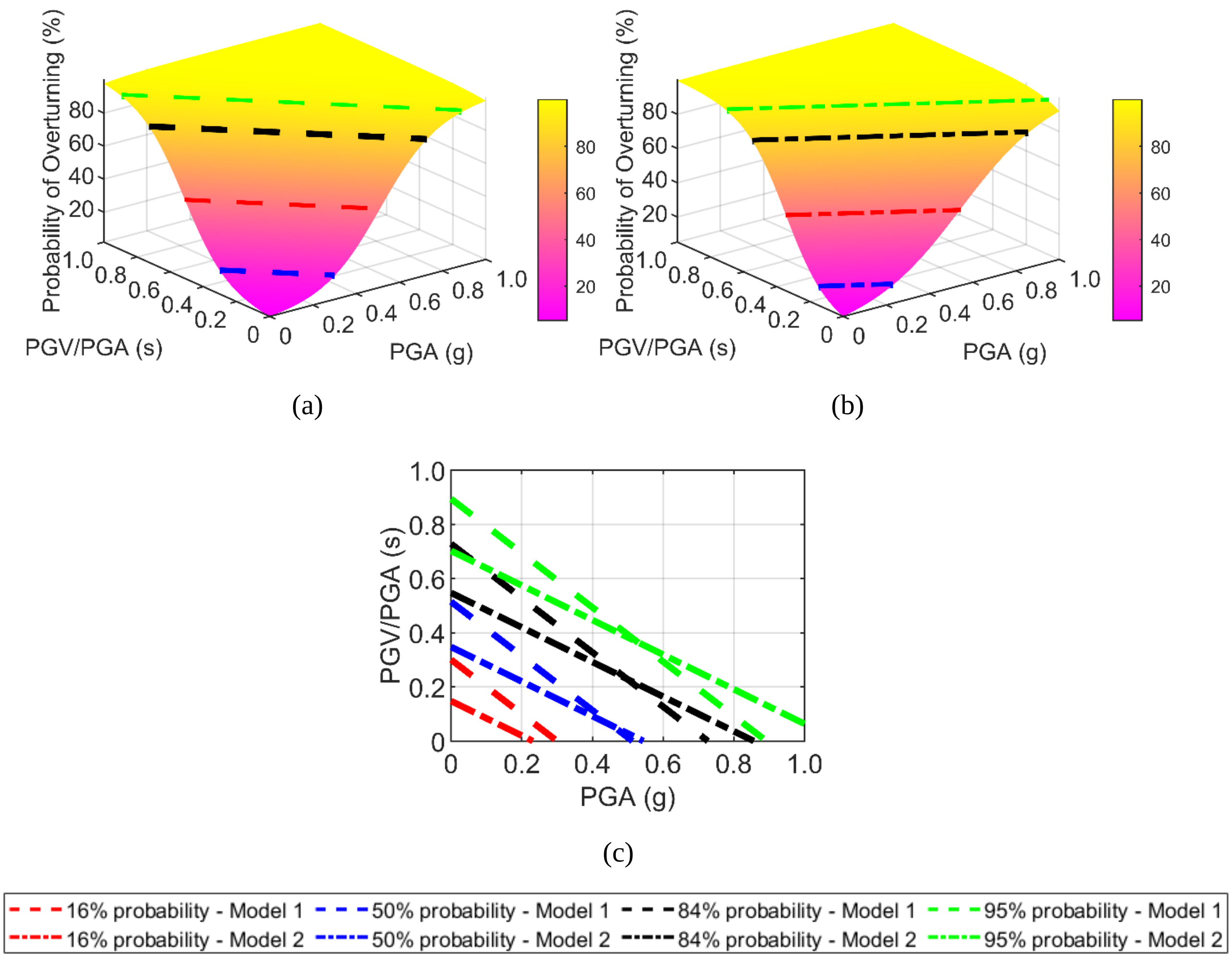


Fig. 3 – Fragility analyses of: a) Model 1, and b) Model 2, as well as c) cross-sections at different probability levels.

Significance and Future Work

This project aligns with the objectives and priorities of the Earthquake Geology disciplinary committee, which aims in part to foster research in outstanding seismic hazard issues and in the earthquake history of southern California. To this end, the analysis of precarious rocks and fragile geologic features has been identified as a particular strategy to evaluate ground motion hazard and inform seismic hazard methodologies. While precarious rocks are recognized as a means to evaluate hazard, it is also understood that existing analysis techniques carry potentially significant uncertainty and the development of analysis techniques is a noted research priority of this particular disciplinary committee. This project aimed, in part, to address this research priority through the analysis and quantification of uncertainty associated with the interface geometry of precarious rocks and the impact that this may have on subsequent fragility analyses. This project may also have an indirect impact on the ongoing research objectives and priorities of the San Andreas Fault System (SAFS) interdisciplinary working group. While this working group aims to develop projects that investigate the Cajon Pass Earthquake Gate Area, it is also a research priority to incorporate precariously balanced rock studies to aid in understanding the paleoseismology and related ground motion history. While this project did not incorporate precariously balanced rocks in the vicinity of the Cajon Pass Earthquake Gate Area, this project highlights the importance of interface geometry for future applications.

While results of this project highlight that the interface geometry of preciously balanced rocks is substantial in the overturning probabilities, there are numerous other factors that can impact the fragilities. Specifically, this project utilized a single value of the contact stiffnesses in the numerical model. The response to an individual ground motion was observed to be sensitive to this parameter, however a detailed treatment was unable to be incorporated into this particular project. The combined impact of both the interface geometry (and shape) along with the contact stiffnesses is warranted for future study, which must be experimentally validated using full-scale PBR specimens under realistic interface conditions. Given that the overturning fragilities are critical for the utilization of precariously balanced rocks as rare seismic hazard constraints, these sources of epistemic uncertainty must be adequately understood and quantified.

Publications

The following publication based on this project has been submitted for publication:

1. Saifullah, M.K., Barnard, A., and Wittich, C.E. (2020). Impact of interface geometry on the seismic response of freestanding structures. *17th World Conference on Earthquake Engineering*, Sendai Japan, September 13-18. (Abstract Accepted, Paper Pending).

The following presentations based on this project have been given:

1. Barnard, A., Saifullah, M.K., and Wittich, C.E. (2019). Scaled shake table tests: free-standing structures with varying footprint geometry. *American Geophysical Union Virtual Poster Showcase*, Poster Presentation, Virtual Conference (No Physical Location), November 6 – 19.

2. Wittich, C.E., Saifullah, M.K., and Barnard, A. (2019). Case study evaluation of interface geometry on fragility of precarious rock systems. *2019 Southern California Earthquake Center Annual Meeting*, Poster Presentation, Palm Springs, CA, September 9 – 11.

Additional publications and presentations based on this work will be added to the SCEC publications database.

References

1. Bommer JJ, Abrahamson NA, Strasser FO, Pecker A, Bard PY, Bungum H, Cotton F, Fah D, Sabetta F, Scherbaum F, Studer J. The challenge of defining upper bounds on earthquake ground motions. *Seismological Research Letters* 2004; 75(1): 82-95.
2. Brune JN, Whitney JW. Precariously balanced rocks with rock varnish – paleoindicators of maximum ground acceleration. *Seismological Research Letters* 1992; 63(1): 21.
3. Bell HW, Brune JN, Liu T, Zreda M, Yount JC. Dating precariously balanced rocks in seismically active parts of California and Nevada. *Geology* 1998; 26(6): 495-498.
4. Purvance MD, Anooshehpoor R, Brune JN. *Fragilities for Precarious Rocks at Yucca Mountain*. Pacific Earthquake Engineering Research Center, Report 2012/06, Berkeley, CA. 2012.
5. Brune JN, Brune R, Biasi GP, Anooshehpoor R, Purvance M. Accuracy of non-destructive testing of PBRs to estimate fragilities. *Proceedings of American Geophysical Union* 2011; S21A-2137.
6. Wittich CE, Hutchinson TC. Rocking bodies with arbitrary interface defects: analytical development and experimental verification. *Earthquake Engineering & Structural Dynamics* 2018; 47(1): 69-85.
7. Wittich CE, Hutchinson TC, DeSanto J, Sandwell D. 3-D reconstructions and numerical simulations of precarious rocks in southern California. *Proceedings of 11th National Conference on Earthquake Engineering* 2018, Earthquake Engineering Research Institute, Los Angeles, CA.
8. Kazhdan M, Bolitho M, Hoppe H. Poisson surface reconstruction. *Proceedings of the Symposium on Geometry Processing* 2006; ACM: 61-70.
9. Itasca Consulting Group, Inc. (2016): 3DEC — Three-Dimensional Distinct Element Code, Ver. 5.2. Minneapolis, Itasca.
10. Cundall PA, Strack ODL (1979): A discrete numerical model for granular assemblies. Géotechnique, 29 (1), 47–65.
11. Ancheta TD, Darragh RB, Stewart JP, Seyhan E, Silva WJ, Chiou BSJ, Wooddell KE, Graves RW, Kottke AR, Boore DM, Kishida T, Donahue JL (2013): PEER NGA-West2 Database. Technical Report PEER 2013/03, Pacific Earthquake Engineering Research, Berkeley, USA.
12. Center for Engineering Strong Motion Data (2015): Lamjung, Nepal Earthquake of 25 April 2015, CESMD. Retrieved from: <https://strongmotioncenter.org>
13. Boore, DM (2010): Orientation-Independent, Nongeometric-Mean Measures of Seismic Intensity from Two Horizontal Components of Motion. *Bulletin of the Seismological Society of America*, **100** (4), 1830–1835.