Impact of Contact and Interface Modeling on Precarious Rock Fragilities – Phase 3
Final Technical Report, SCEC Award #21058

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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 (PBR) 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. In addition, environmental conditions and erosion have likely introduced particulate material, soil, and other debris in these voids at the interface. These complex interface conditions require several assumptions to predict the overturning behavior of a precarious rock, which contributes to the prediction uncertainty. Prior SCEC Awards (#19113 and #20106) have highlighted that interface geometry and interface modeling parameters have a significant impact on the overturning of PBRs [6-8]. Therefore, the overall objective of this1-year continuation project was to quantify and assess the impact of interface material variations on probabilistic overturning predictions through experimental shake table testing. In the project, a single limestone rock specimen was obtained for testing. The specimen was later modified to induce small changes at the interface. The specimen was subjected to hundreds of excitations via shake table testing to generate a baseline overturning prediction model, which was then compared and statistically analyzed in light of numerical results to understand, quantify, and ultimately reduce the uncertainty due to modeling material variations.

Methodology

This research involved a comprehensive experimental and numerical study to understand the seismic behavior of precariously balanced rocks (PBRs), focusing on the combined effects of subtle interface changes and rock material. The methodology integrated experimental shake table testing with advanced three-dimensional numerical modeling using the Distinct Element Method (DEM) through the commercially available DEM platform 3DEC [9]. The experimental phase involved testing two limestone rock specimens (SP1 and SP2), with SP2 being a chiseled version of SP1, under 1164 earthquake simulations on a 7 ft x 7 ft shake table (see Figure 2). High-resolution LiDAR was used for precise geometric data acquisition, capturing the intricate geometry of the rocks at millimeter-level accuracy, essential for both generating the numerical model and tracking the evolution of the rock interface. The study also included a change detection analysis using CloudCompare to assess the evolution of the rock interface and the implications of chiseling. In the numerical phase, the DEM platform 3DEC was employed to represent complex failure modes such as rocking, sliding, and overturning. Volumetric meshes generated from the LiDAR-derived point clouds facilitated detailed analysis of the seismic response (see Figure 3). Simulations were aligned with experimental conditions based on achieved ground motions from the shake table tests. The methodology's comprehensive nature, combining experimental data with nuanced numerical modeling, provided a robust framework for analyzing the seismic behavior of PBRs. Results from this project are also compared with those of SCEC Award #20106, which tested and simulated a granite PBR, enabling conclusions to be drawn regarding the impacts of rock material combined with interface geometry.

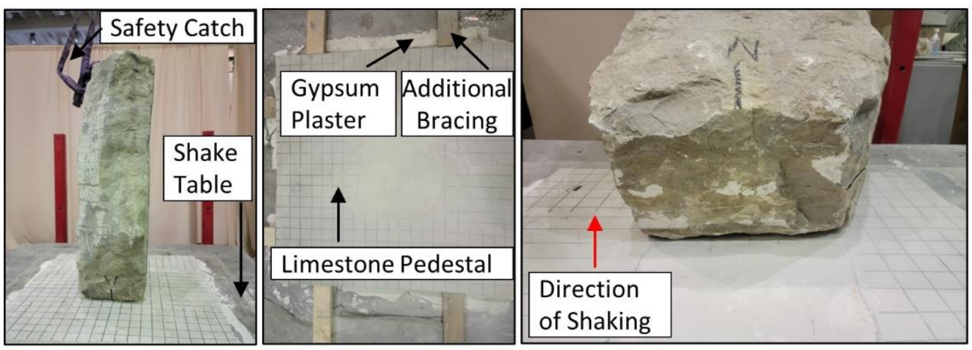

Figure 2. Experimental shake table setup.

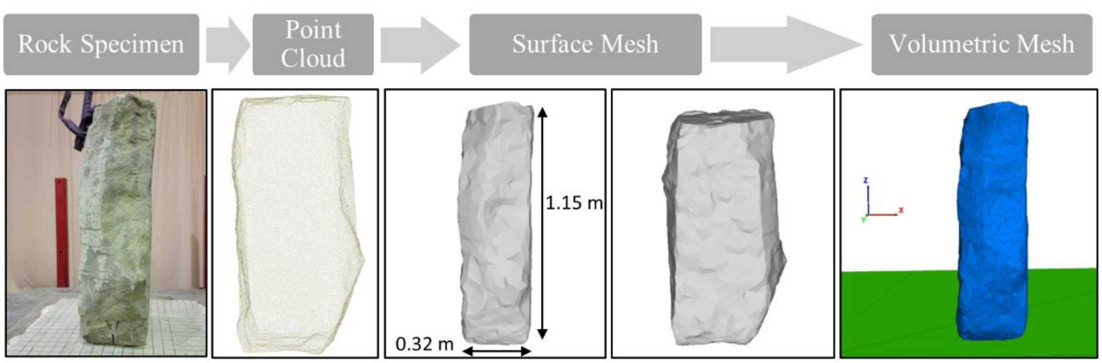

Figure 3 Steps involved in Geometric Modeling

Results

The shake table testing yielded insightful data on the seismic response of the limestone specimens. The experimental results, presented alongside vector intensity measures like PGA and PGV/PGA, showed that the chiseled specimen (SP2) exhibited more cases of overturning compared to the unchiseled specimen (SP1) (see Figure 4). The testing protocol, comprising 582 tests per specimen, elucidated the seismic behavior under varying conditions. Analysis of dominant modes, including rocking (R) and rock-twist (RT), revealed a shift in the distribution of these modes between SP1 and SP2, impacting their contribution to overturning. Additionally, the deterioration of the limestone slab on which the specimens rested was monitored, revealing significant changes that influenced the experimental outcomes (see Figure 5). Notably, placing SP2 on an undeteriorated part of the slab brought its results closer to SP1, indicating the impact of pedestal deterioration on overturning responses.

The numerical results, categorized into true positive (TP), true negative (TN), false negative (FN), and false positive (FP) cases, were compared with experimental data to assess model performance (see Figure 6). The numerical models demonstrated a clear influence of chiseling on the overturning behavior, with models of the chiseled specimen performing better than those of the unchiseled one. These findings were further corroborated through a fragility analysis comparing the numerical models of the limestone specimens with granite specimens, highlighting material-based differences in seismic response (see Figure 7).

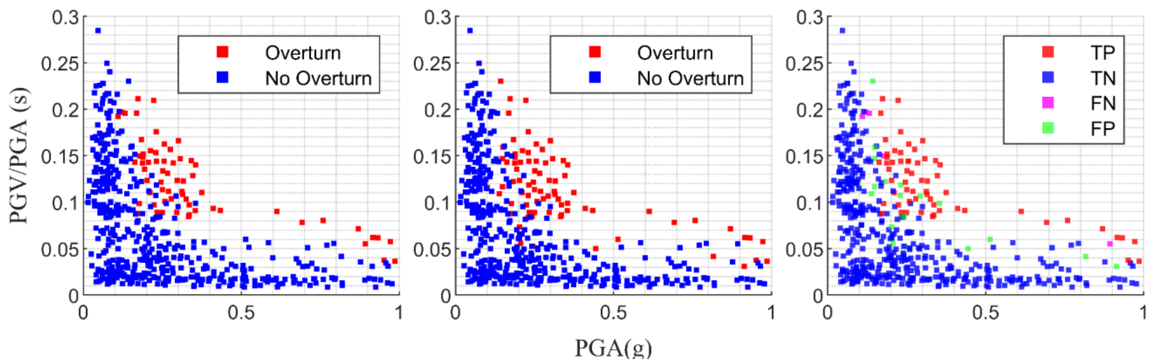

Figure 4 Raw results a) Unchiseled Specimen 1 (SP1) b) Chiseled Specimen (SP2) c) Difference in SP2 results w.r.t to SP1 results

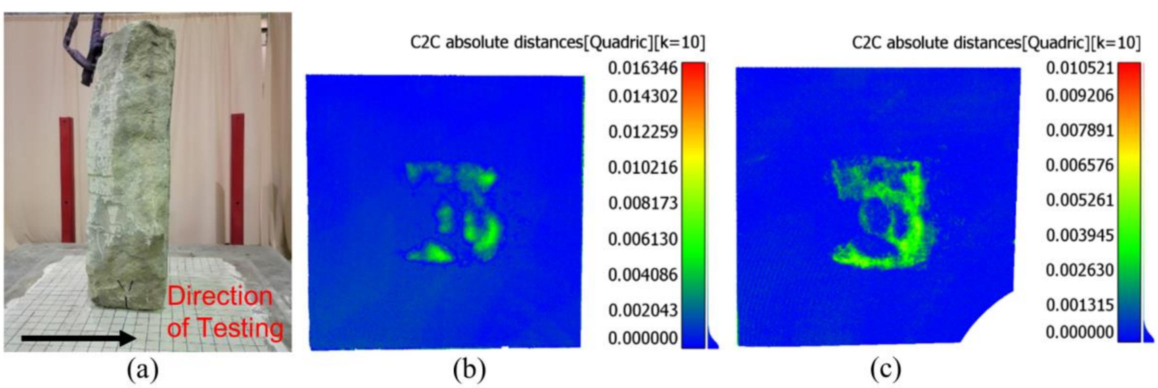

Figure 5 Limestone Slab a) Direction of excitation b) Change detection at the end of testing of Specimen 1 c) Change detection (relative to Specimen 1) at the end of testing of Specimen 2

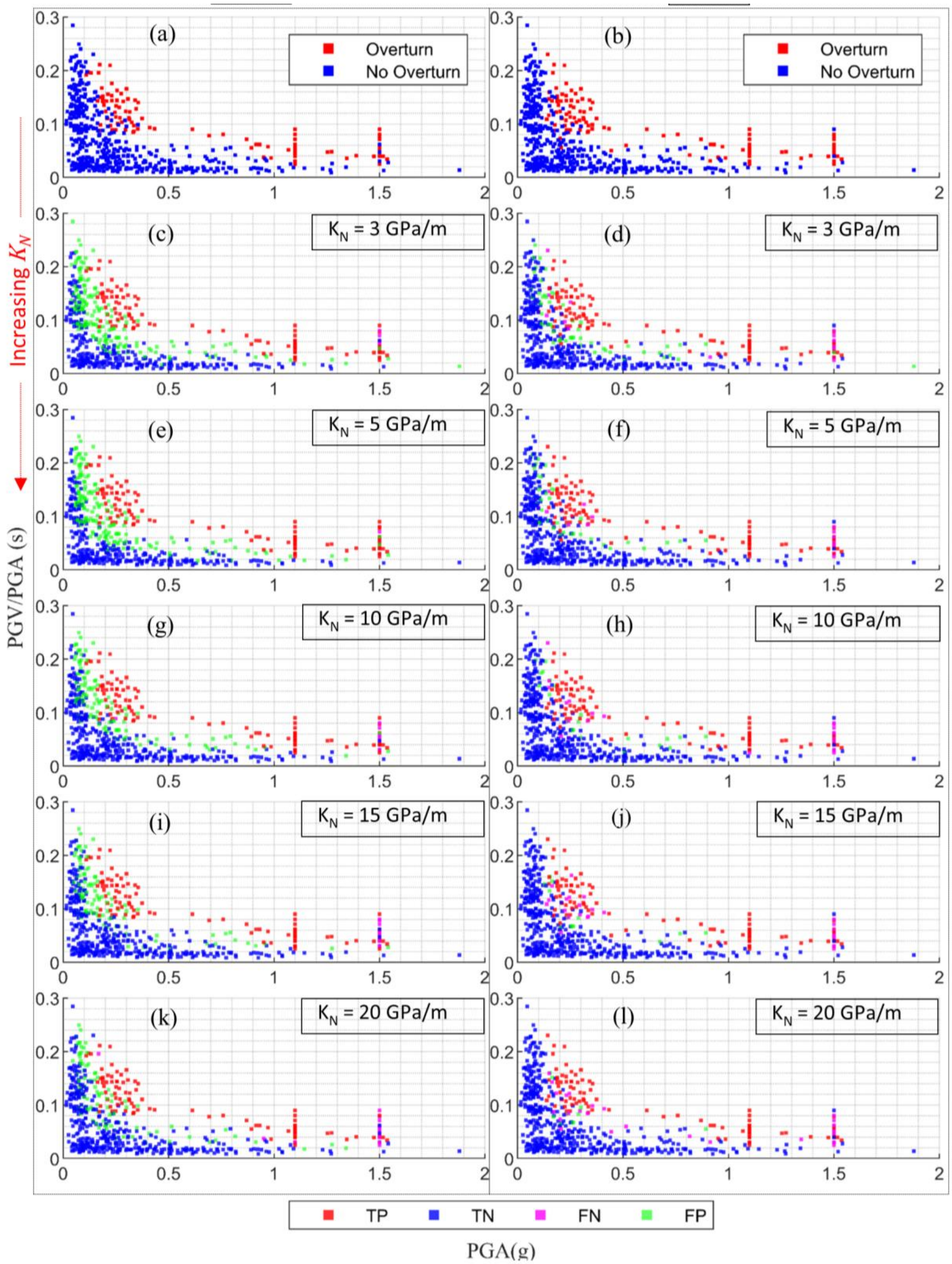

Figure 2 Raw data comparison a) Experimental SP1 b) Experimental SP2 c) SP1 3 GPa/m d) SP2 3 GPa/m e) SP1 5 GPa/m f) SP2 5 GPa/m g) SP1 10 GPa/m h) SP2 10 GPa/m i) SP1 15 GPa/m j) SP2 15 GPa/m k) SP1 20 GPa/m l) SP2 20 GPa/m

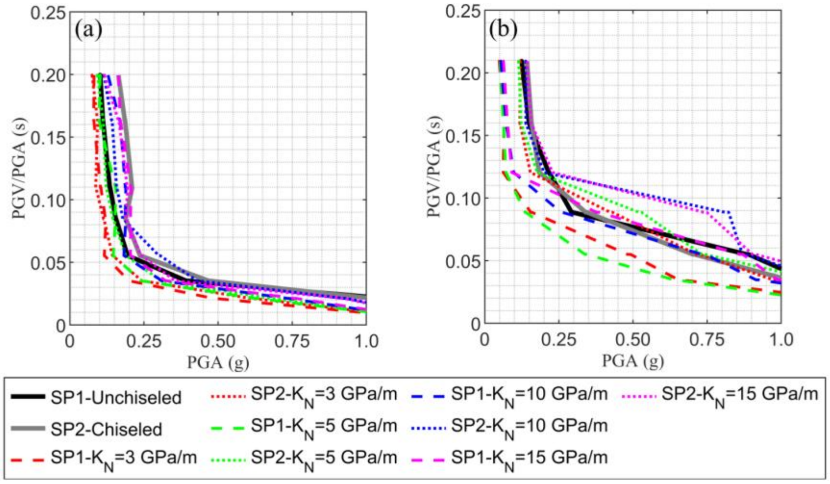

Figure 3 Comparison of numerical fragility contours at 50 percent probability of overturning a) Granite specimen b) Limestone specimen

Significance and Future Work

The study's findings are significant in advancing the understanding of PBRs' seismic behavior, particularly the influence of subtle interface changes and material properties. The experimental and numerical analyses have provided critical insights into how chiseling and rock material affect the stability and overturning of PBRs during seismic events. These results have implications for seismic hazard assessments, especially in regions with naturally occurring PBRs. The observed changes in dominant response modes due to interface modifications underscore the importance of detailed geometric modeling in PBR analysis. Additionally, the identified impact of pedestal deterioration highlights a critical aspect that must be considered in future PBR studies. The research outcomes contribute valuable knowledge to the field of earthquake engineering, enhancing the predictive modeling of PBRs and informing mitigation strategies against seismic risks. Future work should focus on extending the scope of study to rocks of different materials, further elucidating the role of interface conditions and material properties in the seismic stability of PBRs.

Publications

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

1. Saifullah, M. K. and Wittich, C.E. (202X). Combined influence of rock material and interface geometry on precariously balanced rock overturning via shake table testing and numerical modeling.

The following dissertation was based, in part, on this project:

1. Saifullah, M. K. (2022). *Uncertainty in the Seismic Response of Freestanding Structures*. Ph.D. Dissertation. University of Nebraska-Lincoln: Lincoln, NE.

The following presentations based on this project have been given:

1. Saifullah, M.K. and Wittich, C.E. (2022). Impact of rock material on precarious rock fragilities. *2022 Southern California Earthquake Center Annual Meeting*, Poster Presentation, Palm Springs, CA, September.

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

References

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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.
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6. Saifullah, MK, Wittich CE. (2024). Uncertainty in distinct element modeling of freestanding structures considering stiffness parameters. *Journal of Earthquake Engineering*. DOI: 10.1080/13632469.2024.2318630
7. Saifullah, M. K. and Wittich, C.E. (2023). "Uncertainty in overturning of precariously balanced rocks due to basal contact." *Earthquake Engineering & Structural Dynamics* 52.14: 4562-4581.
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9. Itasca Consulting Group, Inc. (2016): 3DEC — Three-Dimensional Distinct Element Code, Ver. 5.2. Minneapolis, Itasca.