3-D Reconstructions and Numerical Simulations of Precarious Rocks in Southern California

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Presentation Outline

Background & Motivation
Survey of Precarious Rocks
3-D Reconstructions
  ◦ Data Acquisition
  ◦ Surface Meshing
Fragility Analysis
Effect of Interface Variations
Conclusions & Future Work
Background & Motivation

Reliable seismic hazard estimates are essential for building resilience

- There is a lack of observation or measurement for many rare, high-magnitude earthquakes
- Estimates of rare seismic events are highly uncertain
Precariously Balanced Rocks (PBRs)

Individual or systems of slender, freestanding rocks that are free to topple, *if forced*

- Current precarious state is indicative of an unexceeded ground motion at its site and over its lifetime
- Widespread throughout greater California and Nevada regions
  - Nearly 2000 documented PBRs are archived by the Southern California Earthquake Center (SCEC)
  - Including in areas near to known and active faults

Images from: 2016 SCEC Archive of Precariously Balanced Rocks
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*How long has the rock system been in its current state?*
Precariously Balanced Rocks (PBRs)

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*What ground motion would it take to topple?*
Precariously Balanced Rocks (PBRs)

What ground motion would it take to topple?

- Dynamic behavior of a rigid, freestanding structural system
- Likely to have a significant rocking response:
  - Nonlinear with respect to geometry
  - Piecewise with respect to orientation

Equation of motion for rotation, $\theta$, subject to horizontal ground acceleration, $\ddot{x}_g$:

$$(I + mR^2)\ddot{\theta} = m\ddot{x}_g R \cos(\alpha - |\theta|) - \text{sgn}(\theta)mRg \sin(\alpha - |\theta|)$$

Coefficient of restitution at impact:

$$r = 1 - \frac{3}{2} \sin^2 \alpha$$

From Housner (1963)
Survey: Scope

Survey of PBRs conducted in October 2016

- Location: Jacumba, CA
- Previously Identified PBRs: 2
- Proximity to:
  - Elsinore Fault
  - Laguna Salada Fault
- Goal: Study impact of geometric data acquisition methods
  - Laser scanning (lidar)
  - Aerial structure-from-motion (UAV)
Survey: Site Overview
Survey: Selected PBRs

(a) PBR-01 (R4_00262)
(b) PBR-02 (R4_00260)
(c) PBR-03
(d) PBR-04
(e) PBR-05
(f) PBR-06
3D Reconstructions: Data Acquisition

Laser Scanning (Lidar)
- Based on time-of-flight or phase of laser light reflections
- Multiple scans required to reduce occlusion
- Ground-based on tripod
- Scale and orientation is automatic

Structure-from-Motion (SfM)
- Based on corresponding pixel features in multiple images
- Multiple images required
- Aerial-based on UAV
- Required GPS targets for scale and orientation
3D Reconstructions: Results

Point clouds via lidar and SfM compared:

- Similar point densities (2.4 – 2.7 million points)
- Difference in scale < 1% between two methods
- Noticeable occlusion, particularly near the interface
  - Lidar resulted in occlusion near the top and interface of rocks
  - SfM shows superior coverage due to larger number of imaging locations
3D Reconstructions:

Interface is occluded, but necessary for analysis

- Point generation scheme devised based on perimeter of interface:
  1. Extract perimeter of interface within the point cloud
  2. Data points generated in linear segments
  3. Discretization variable, but kept consistent with rest of PBR cloud

- Poisson surface reconstruction generates a watertight triangulated mesh
Fragility Analysis

Given geometric data, PBRs are compared to current estimated seismic hazard through a points-in-hazard-space approach:

- **Seismic Hazard**: From USGS (2014) at PBR site
- **Overturning PGA**: From Dimitrakopoulos and Paraskeva (2015) for 50 – 99% probability of overturning
- **Frequency of Exceedance**: From Bell et al. (1998) in which PBRs in this region determined to be 10 – 30 k years old

**Limitations**:
- Slip not permitted
- Motion direction
- Two-dimensional geometry with two points
Interface Effects: Development

Probability of overturning is limited by the rocking model

- Rocking model assumes two-points for rocking in the two-dimensional body
- Realistic PBRs have complex interfaces with multiple potential points of rocking
- Two-dimensional model was extended to account for this situation
Interface Effects: Overturning

Impact of multiple rocking points studied via overturning spectra

- Input: Sinusoidal pulse of amplitude $A_p$ and frequency $\omega_p$
- Output: Maximum rocking rotation ($\theta$)

- Significant increase in overturning observed due to multiple rocking points
Concluding Remarks

Conclusions

- Lidar points clouds are more accurate than SfM point clouds
- Due to rocky terrain and tripod mounting, SfM via UAV is recommended
- Preliminary analyses indicate that PBRs in the Jacumba cluster may indicate an inconsistency with current seismic hazard

Future Work

- Probabilistic overturning analyses accounting for:
  - Slip and uplift motions
  - Three-dimensional response
  - Site-specific motions including direction of PBR with respect to faults
Acknowledgments

Funding for this project was provided by:

University of California, San Diego’s Frontiers of Innovation Scholars Program

Access to the SCEC PBR database was provided by:

Dr. Glenn Biasi
University of Nevada Reno

Surveying equipment for the PBR survey was provided:

Cultural Heritage Engineering Initiative
University of California, San Diego
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