2013 SCEC Annual Report

PBR SCIENCE FOR SCEC4:
VALIDATION OF GROUND MOTION PREDICTION AND SIMULATIONS

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Summary
Precariously balanced rocks (PBRs) provide unique physical constraints on unexceeded ground motions at return times of centuries to 1000's of years. As such they play an important role in evaluating predictions of physics-based ground motion efforts including CyberShake (Graves et al., 2011). This project continues development of PBR constraints in support of CyberShake. The goal of this project is to develop vector-valued survival probabilities (e.g., in joint PGA, PGV space) where PBR's constrain ground motions of interest to CyberShake and southern California hazard estimation. To achieve this and to extend the scientific utility of PBRs, we have made great advances in compiling rock locations, dimensions, and fragilities. Over 9,000 images have been added. Over 1,900 distinct PBR and geologic features are included, doubling the resource during this year. New maps show the spatial extent of quantitative ground motion constraints. Structures in the map patterns include a ~25x25 km region between the northern San Jacinto and Elsinore faults within which ground motions are apparently rarely or never above about 0.7 g. Elsewhere PBRs occur in linear arrays, or locally, in islands of apparently low ground motions. A simple viewing mechanism is now available to display rock images on the basis of rock ID, locale, or static overturning angles.

Intellectual Merit
Research progress this year with the precariously balanced rock photo collection has enabled us to identify areas and approximate maximum ground motion limits not exceeded in the past few thousand to perhaps 10,000 years. No similar data are available within SCEC community.

Broader Impact
Seismic hazard estimation is a fundamental societal benefit of SCEC research. This project compliments that research by providing data with which to constrain physics-based ground motion simulations. New data may also lead to new understandings of seismic wave propagation in southern California.

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Introduction

This project continues development of PBR constraints in support of CyberShake. The goal of this project is to develop vector-valued survival probabilities (e.g., in joint PGA, PGV space) where PBR’s constrain ground motions of interest to CyberShake and southern California hazard estimation. Precariously balanced rocks (PBRs) provide unique physical constraints on unexceeded ground motions because they have survived for centuries to 1000’s of years (Anderson et al., 2011). This makes them empirical tests of ground motion predictions with long return times, such as the 2% in 50 year U.S.G.S National Seismic Hazard maps. PBRs also play an important role in evaluating predictions of physics-based ground motion efforts including CyberShake (Graves et al., 2011).

Two basic measurements are made on precariously balanced rocks (PBRs) relevant to constraining ground motions. The force sufficient to topple the rock can be estimated from the rock geometry alone as \( F_r = Mg \tan(\alpha) \), where \( M \) is the rock mass, \( g \) is the acceleration due to gravity, and \( \alpha \) is the angle from vertical of a line connecting the rock center of mass to the rocking point over which it would topple (Anooshehpoor et al., 2004). The static overturning acceleration \( F_r / M = g \tan(\alpha) \) is an upper limit on ground acceleration allowable for the rock to survive. \( \tan(\alpha) \) is thus the fraction of \( g \) for static overturning, and can be approximated by \( \alpha \) in radians over the useful range of PBR angles. The frequency at which the rock is most sensitive to ground motion is proportional to the square-root of the distance \( R \) from the rock center of mass to the rocking point. Rocks less than 2-3 meters in height are most relevant for ground motion constraint.

We have focused on two main elements in this project year. First has been to work with research assistant Jessica Donovan to consolidate information about selected rocks near CyberShake grid points and field points added for additional CyberShake constraint. These include about 50 rocks at about 20 CyberShake locations in southern California. Collaborator Dr. J. Brune, and R. Brune and L. Grant-Ludwig at U.C. Irvine, have been developing photogrammetric quasi-static overturning accelerations, adding orientations, and working to complete the table of constraints. PBR age dating efforts are also being pursued at U.C. Irvine (J. Brune et al., 2012).

The second effort, at UNR, has pushed to gather and consolidate rock location, height, and broader photo evidence, and to move the resource from a collection of photos to a useable archive. We have been able to accelerate the work by using dedicated archive help and UNR funds contributed as part of the SCEC core institutional membership match.
The archive has increased by a factor of 6 in terms of images under management to now number over 10,000. Dr. Brune was enlisted to provide locations for over 1000 rocks that previously could not otherwise be included in the archive. At the beginning of the project year only about ~100 rocks had sizes integrated into their analyses. This has increased by over seven fold, again by successfully soliciting the data from Dr. Brune. In continuing work, Dr. Brune is confirming all 2-D analyses with small alphas and providing pedestal heights, which can be used to estimate pedestal exposure times (J. Brune et al., 2012; Grant-Ludwig et al., 2009).

Results

As a result of efforts in this SCEC project year, locations and fragilities can now be evaluated together. Figure 1 provides a visual summary of the map distribution of PBRs potentially useful for constraining ground motions in southern California. Figure 2 is a more detailed view of the same data. Symbol colors communicate a rough upper limit of peak ground acceleration (PGA) at the PBR site, with warmer colors increasingly fragile. Green symbols show rocks with at least one alpha less than 30 degrees corresponding to a static overturning estimate of about 0.5 g. Regression testing of shake-table results indicate that the dynamic PGA for toppling is ~1.3 times greater, so these rocks would be inconsistent with recurring PGAs above 0.7g. Yellow symbols indicate rocks with one alpha < 25 degrees and PGA < 0.55 g. Orange have both alphas < 20 and <0.45 g PGA, and red has both angles <15 degrees and a 0.35 g PGA.

Interesting patterns emerge in Figures 1 and 2. First, spatial patterns appear to be internally consistent. The most fragile features (orange, red) generally occur inside “islands” with lower limits. This suggests that ground motions responsible for toppling these rocks are coming from the faults, and that some decay with distance from the fault is responsible for the gradient. In discussions of how wide a fault zone may be, the PBRs show that at return times relevant for hazard maps, the San Andreas, Elsinore, and San Jacinto faults are relatively narrow and well defined. The spatial distribution of PBRs also bears on how “background” seismicity is distributed in hazard mapping applications (Brune et al., 2010).

A second observation from Figures 1 and 2 is that bounds on PGA indicated from the PBR data have a significant spatial extent along faults. This means that whatever the process is that modulates ground motions such that the PBRs survive, the process apparently has a similar spatial extent. PBRs are apparently not preserved only at special or isolated places along faults such as step-overs where ground motions may be lower.

Thirdly, Figures 1 and 2 show that at most sites multiple rocks can contribute to ground motion limits. Rock toppling limits on ground motion are probabilistic in nature (Purvance et al., 2008a, 2008b). Therefore, ground motion limits based on individual rocks in most cases might be strengthened by the joint probability of exceedance formed with nearby rocks. The exact nature of the joint probability constraint also depends on rock sizes and ages. Developing these constraints will be a focus of future research.
Figure 1. Map distribution of precariously balanced rocks potentially suitable for ground motion constraint. Green: one alpha < 30 degrees; yellow: one alpha < 25 degrees; orange: both alphas < 20 degrees; red: both alphas < 15 degrees. These correspond to estimated PGA limits of 0.70, 0.55, 0.45, and 0.35 g, respectively. Red lines are principal faults. Many PBR sites are nearly co-located such that the total number far exceeds the visible number of dots.

Figure 2. Detail from Figure 1 showing the spatial relationship among PBR overturning angle. Fine gray lines are major roads added for reference. Most fragile PBRs occur within zones outlined by rocks with lesser potential for toppling. In most cases an offset distance is observed from the faults to the PBRs. The quasi-uniform distribution of rocks in a ~25x25 km field centered on 33.8, -117.25 between the northern Elsinore and San Jacinto faults compares markedly with the linear array farther south and suggests different rupture patterns or earthquake sizes. The presence of several very fragile rocks very near the Pinto Mountain fault suggests that fault activity there is extremely low.
By far the preponderance of data from PBRs comes from an idealized 2D analysis of rock photos (Biasi et al., 2011, 2012). This raises the question of how accurate these estimates are compared to more sophisticated photogrammetric analysis (J. Brune et al, 2012) and rock testing (Brune et al., 2011). Figure 3 gives a preliminary comparison of 2D analyses to photogrammetric estimates of alphas as developed by R. Brune at U.C. Irvine. With the 2-D analyses $\alpha_1$ values are found to be, on average, about 7.8 degrees smaller than from photogrammetry. This was not entirely expected because 2D analysis alphas can more easily be overestimated by, for example, having the photo line of view be rotated relative to the most slender direction. It appears that the difference traces to the assumption that rock is a polygonal cylinder in and out of the axis of view. Rocks that are rounded on top (say, bullet-shaped) violate the 3-D shape assumption of the 2D analysis method. Also, mass distributions out of view to the 2D analysis can cause differences, usually to show that the true rock center of mass is lower than it appears, and that the alpha estimates should be larger. A rock-by-rock comparison is planned to better understand the
differences and develop a correction suitable for use with the larger archive. In addition, a collaborative effort at U.C. Irvine will be extending the photogrammetric data set.

Conclusions

PBR constraints on ground motion for use in CyberShake have been developed in a collaboration between UNR, U.C. Irvine, research assistant J. Donovan at USC. We do not show them here, but vector-valued toppling probabilities can (and will) be developed for rocks with alphas less than about 40 degrees. Useful spatial constraints on upper limit ground motions are emerging from the larger archive. PBRs indicate that ground shaking hazard varies significantly across Southern California. New understandings and applications of PBRs for SCEC earthquake system science are coming into view.

![Figure 3](image-url)

**Figure 3.** Comparison of alphas from 2D analysis versus a more thorough photogrammetric analysis of the rock shape. Estimates are standardized so that the smaller alphas from each method are considered to be $\alpha_1$. On average the 2D analysis underestimates alpha by 7.8 degrees in $\alpha_1$ and 1.2 degrees in $\alpha_2$. Plot courtesy of J. Anderson, UNR.
References