2013 SCEC ANNUAL REPORT

PBR STUDIES IMPORTANT FOR TESTING CYBERSHAKE, NGA, AND HAZARD MAPS

Submitted by Lisa Grant Ludwig (UC Irvine) and James Brune (UNR, UCI)
with contributions from Richard Brune, Glenn Biasi (UNR)
Jessica Donovan (USC) and Tom Jordan (USC)

ABSTRACT

We have been conducting research to develop, refine, and implement the use of precariously balanced rocks (PBRs) for validation of ground motion studies and seismic hazard analysis. Currently, the only tool available to empirically test unexceeded earthquake ground motions over timescales of 10 ky-1 My is the use of fragile geologic features, including PBRs. The age of PBRs together with their aerial distribution and mechanical stability ("fragility") provide constraints for probabilistic seismic hazard analysis (PSHA) over long timescales, including USGS National Seismic Hazard Maps (NSHM), and validation of ground motion models such as Cybershake. SCEC has previously supported research to identify and document locations of PBRs in S. California, and to develop methods of analyzing fragility and estimating ages. A database at UNR contains locations of thousands of PBRs in S. California. With prior funding, we identified important PBRs, collected samples for a feasibility dating study, and used the samples to develop a numerical modeling method of dating PBRs in the granitic terrains of southern California with cosmogenic ^{10}Be. In FY2013, we focused on measuring fragility of PBRs that are important for validation of Cybershake calculations. We used photogrammetry to construct 3D models of 17 PBRs at 16 distinct sites, and measured fragility parameters such as rocking angles and azimuths, to derive quasi-static toppling acceleration and toppling direction at each location. Fragilities range from 0.1 g to > 0.5 g.

INTELLECTUAL MERIT

Earthquake rupture forecasting methodology has improved significantly in recent years (e.g. WGCEP, 2008, 2013). Concurrently, the numerical power for calculating seismic ground motion, based on various types of modeling and assumed input parameters, has also improved. The weak link in proceeding to estimates of seismic hazard is validation of inputs and modeling procedures. Current models require assumptions about source parameters (e.g., rupture rise time, slip weakening distance, rupture velocity, direction of rupture, background stress, frictional stress, dynamic stress history) but there are not enough near-source data from large earthquakes to validate or constrain the programs and assumed source parameterizations. The study of precariously balanced rocks (PBRs) provides critical insights. Analysis of apparent discrepancies between PBRs and seismic hazard maps (Brune et al., 2010a, 2010b, 2011), suggests that PBRs may be important in testing the ergodic assumption, attenuation relationships, random background earthquake assumptions, directions of rupture propagation (Weiser et al., 2007), relative hanging wall-foot wall ground motions, step-over ground motions, frequency of supersonic ruptures, and other assumptions such as fault activity and fault geometry (Anderson et al., 2011). For example, orientations of PBRs between the Elsinore an San Jacinto faults suggest supersonic rupture velocities (Brune et al., 2006). PBRs at Silverwood Lake and Grass valley in the San Bernardino mountains, seem incompatible with the NW to SE rupture commonly assumed for the 1857 Fort Tejon earthquake, raise questions about whether ruptures have propagated between the San Andreas and San Jacinto fault in Cajon Pass, and suggest that the Cleghorn fault and Pinto Mountain faults are not as active as assumed in UCERF2 (Schlom et al., 2007; Grant Ludwig and Brune, 2010; Brune et al., 2010a).

BROADER IMPACTS

Seismic hazard maps are essential tools for regional planning and development of earthquake resilient infrastructure in seismically active regions. Seismic hazard maps are derived from two basic components: fault rupture probability and ground motion probability. Precariously balanced rocks (PBRs) provide important insights and data for each component. PBRs provide the only source of data for constraining maximum ground motions over long periods of time needed for seismic hazard assessment. By providing constraints on maximum ground motions over hundreds to thousands of years, PBR data also provide implicit constraints on rupture probability of nearby faults. Thus PBR data are important for assessing seismic hazard and designing earthquake-safe buildings.

PROJECT BACKGROUND AND OBJECTIVES

To make full use of the rocks for Cybershake waveform validation and seismic hazard applications we need to determine the timescale and mechanisms for creating and exposing PBRs, along with the nature of earthquake ground motions which could topple them. Early attempts to date PBRs in California and Nevada (Bell et al., 1998) suggested that the rocks have been exposed and fragile for > 10 ka. SCEC has supported research to identify and document locations of PBRs in S. California, and to develop methods of analyzing fragility and estimating ages.

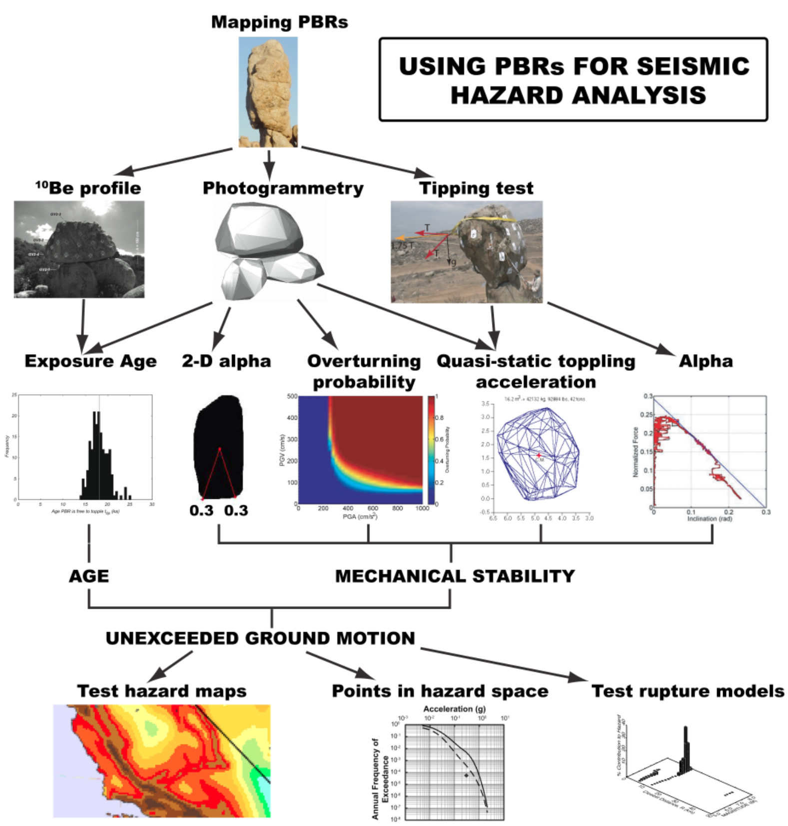

Figure 1: Summary of methodology for using PBRs in seismic hazard analysis. Photogrammetry and shape modeling is useful for understanding exposure age (Balco et al. 2011) and fragility. See Andersen et al. (2011) for summary of applications to seismic hazard.

A database at UNR contains locations of thousands of PBRs in S. California. With SCEC3 funding, we identified important PBRs, collected samples for a feasibility dating study, and used the samples to develop a numerical modeling method of dating PBRs in the granitic terrains of southern California with cosmogenic ^{10}Be. The methodology for using PBRs in seismic hazard analysis is illustrated in Figure 1 (from Rood et al., 2012 and Grant Ludwig et al., 2012). Questions persist about the age, evolution, fragility and survival of PBRs in seismically active regions (Andersen et al., 2011; O'Connell et al., 2007).

In FY13 we conducted a targeted study of PBR fragility rocks for comparison with Cybershake (Graves et al., 2011) broad band seismograms in southern California (Donovan et al., 2012; Graves and Pitarka, 2010). PBRs will only constrain hazard for solid rock sites, but the broad-band Cybershake modeling effort will provide extrapolations to soft rock and sediment sites. Relevant PBR sites are shown on Figure 3. We proposed to analyze 10-12 rocks. To date, we have completed analysis of 16 PBRs, highlighted in yellow in Figure 2 caption. In this report we describe the methods for analyzing the rocks, and present results (fragility parameters) in Table 1. Selected field photographs of the rocks, and images of resulting 3D models, are presented in Figure 3.

METHODS Each PBR was visited in the field and photographed, as shown in Figures 3a,3b. The digital photos provide documentation of the geomorphic context, and images for photogrammetry. Digital images are downloaded and processed with AutoCAD and Photomodeler photogrammetry software to construct oriented 3-D models, and determine fragility parameters (quasi-static toppling angles, alpha1 and alpha2). The results are described herein as “Photomodeled fragility” to distinguish from fragility that is estimated in the field, measured directly with a pull test, or a shake table (Purvance et al., 2008). As discussed by Andersen et al. (2011), pull testing is destructive (as well as dangerous), and should only be conducted in exceptional circumstances.

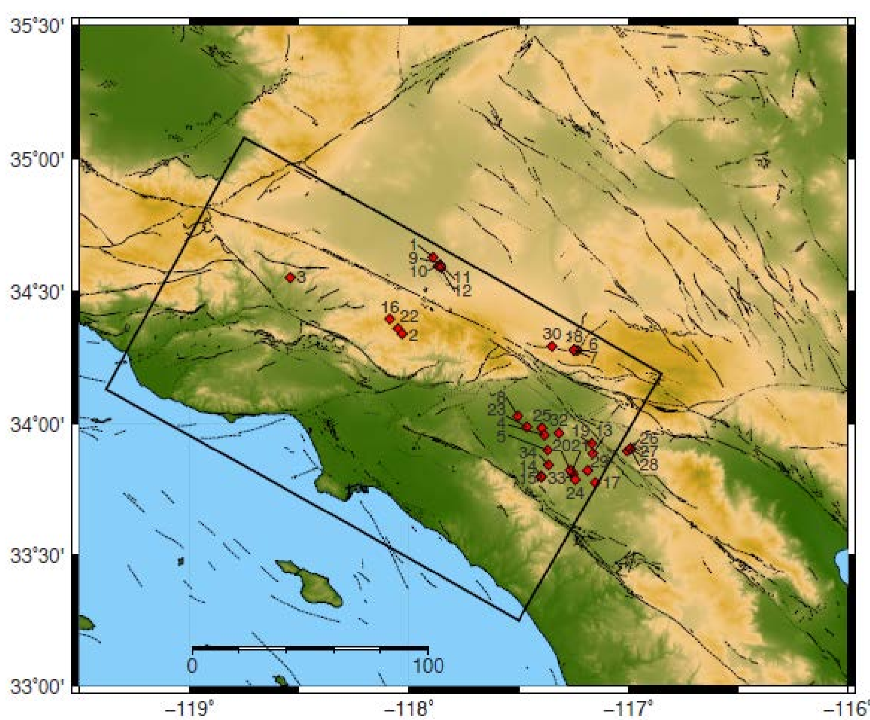

Figure 2 - Locations of PBRs (red diamonds) within or near the Cybershake grid (black box). PBR numbers and informal names highlighted in yellow were analyzed in FY13: 1 Alpine Butte; 2 Chilao; 3 Castaic Lake; 4 Gibraltar; 5 Gopher Gulch Small; 6 GV0; 7 GV01; 8 Jarupa; 9 LB05A; 10 Lovejoy Big; 11 LJB Dylan Small; 12 LJB08A; 13 Lake Perris; 14 Mathews Matt; 15 Mathews Matt2; 16 Mill Creek Summit; 17 Menifee; 18 Marie Louise Across; 19 Moreno Valley; 20 Mead Vlly Mushroom; 21 Mead Vlly Tipped; 22 Pacifico; 23 Pedley Small Low; 24 Perris; 25 Rubidoux; 26 SJ02; 27 SJ04; 28 SJ05; 29 S of Perris Dam; 30 Silverwood; 31 Santa Ynez; 32 UCR-3; 33 UCR Motte (Enchanted); 34 Water Tank. See TABLE 1 for PBR Fragility data.

Figure 3a: Photo of PBR "UCR Motte Enchanted", or "Motte 1". See text for explanation. Photo by R. Brune.

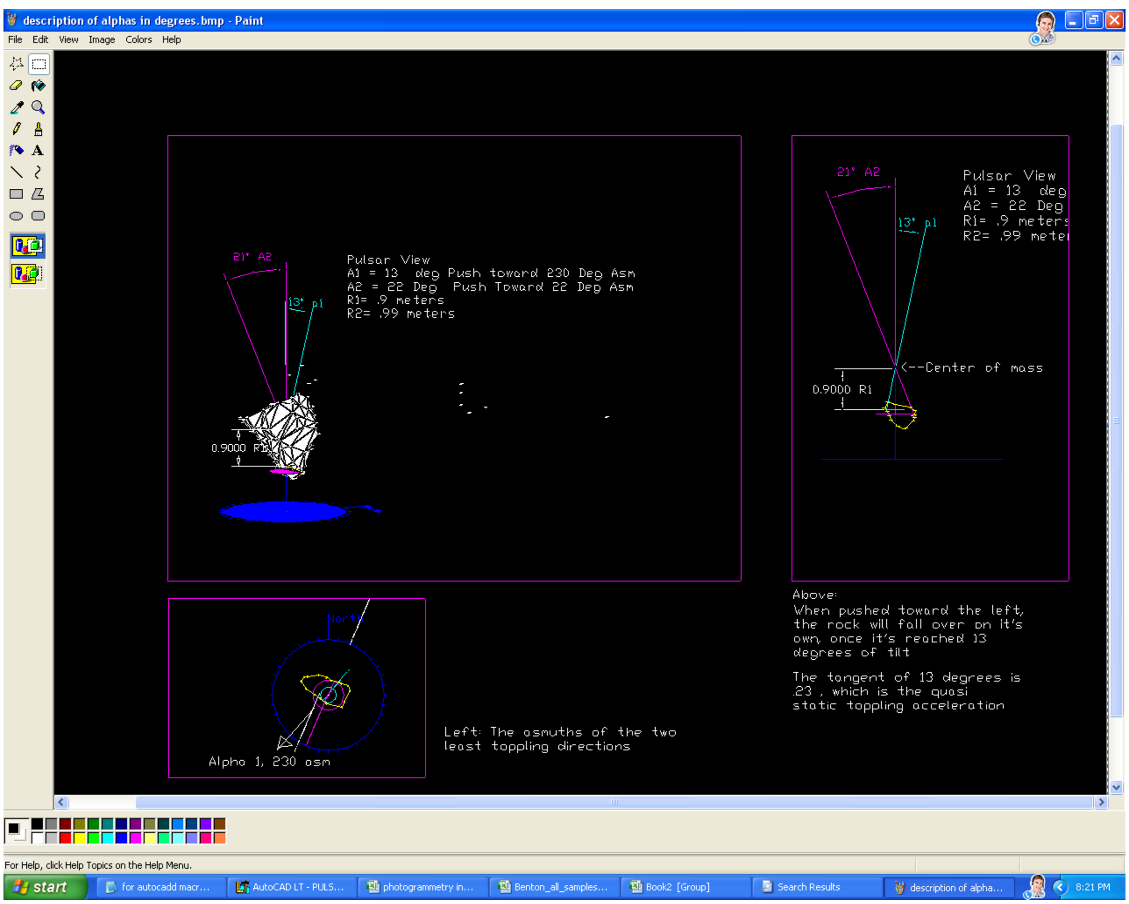

Figure 3b – See text for explanation

RESULTS

Table 1 shows the fragility of PBRs derived from photomodelling in FY2013.

TABLE 1 Results: PBR Fragility

Rock Name	**Location (lat/lon)**	**Least Quasi Static Toppling accel (g)**	**Alpha 1 toppling angle, degrees**	**Alpha1 azimuth**	**Alpha2, degrees**	**Alpha2 azimuth**
Mead Valley Tipped	33.817369,-117.259952	**0.532**	29.00	45	28.00	225
motte1, UCR Motte Enchanted	33.8103,-117.2553	**0.141**	8.00	150	17.00	340
MAT2 Lake mathews	33.799361,-117.397301	**0.488**	26.00	90	28.00	235
lj05 (lb05) LB05A	34.5973,-117.86720	**0.364**	20.00	220	23.00	40
lj08 lb08 LB15a	34.588520,-117.85350	**0.268**	15.00	270	20.00	130
Mill Creek summit	34.397228,-118.086417	**0.466**	25.00	170	36.00	360
sw01 Silverwood	34.29679,-117.33984	**0.268**	15.00	38		
MAT1 lake mathews S of	33.7989,-117.3972	**0.384**	21.00	45	44.00	225
LJB2 ljb Dylan Small	34.60255,-117.859128	**0.171**	9.70	190	34.20	10
alp1 alpine butte	34.6434,-117.86694	**0.100**	5.69	78	22.52	200
alp2 alpine butte	34.641828,-117.868505	**0.168**	9.51	260	53.52	105
S. of Perris Dam	33.82201,-117.18759	**0.268**	15.00	3	46.10	170
Mead Valley Mushroom	33.82333,-117.26491	**0.402**	21.88	45	23.37	270
Castaic Lake	34.55644,-118.53751	**0.149**	8.47	338	20.14	158
Pedley Small Low	33.9875,-117.46217	**0.443**	23.90	273	25.94	87
Jarupa	34.02939,-117.50433	**0.577**	30.00	2	40.00	185
Golfer Gulch	33.89935,-117.36438	**0.420**	22.79	320	24.58	200

The fragility of PBRs is derived from rocking angles “alpha1” and alpha2, expressed in degrees or radians. The quasi-static toppling acceleration is derived from tangent alpha. Sustained acceleration applied toward the direction of a toppling azimuth will result in toppling. Each alpha is associated with at least one toppling direction, given in degrees azimuth, as measured in the field. Figure 3a shows methods for measuring toppling azimuth in the field, and photographing the rocks to develop a 3D model for determining alphas. Prior to photography, colored targets (removable tape) are affixed to each rock. Geographically oriented tripods are set up to provide coordinate system reference and azimuth for 3D model. Figure 3b shows the photogrammetry-derived 3-D model. The center of mass is inside the tock, at the point of the alpha angles. The yellow line is the pedestal footprint, drawn for purpose of calculating the horizontal distance of the tangent alpha.

DISCUSSION

Comparison with 2008 USGS Seismic Hazard maps (Petersen et al.)

Using the methods described above, results for PBR Motte1 (Figure 3a) show it is most fragile PBR in a line of PBRs between the Elsinore and San Jacinto fault, first described by Brune et al. (2006). PBR Motte1 is located in a small canyon draining off of a relatively flat, stable, erosional surface near at Perris. Its height is about 1.2 m. The pedestal height on the upstream side is about 1 m and on the down-hill side about 2 m. Using methods of Purvance et al. (2008a,b), J. N. Brune estimates the probability of toppling Motte1 by an earthquake with the USGS 2008 2% in 50 yr values for PGA and Sa1 is 90 % (>90% for 1% in 50 yr hazard,). Because of its height, Motte1 is not as fragile as some smaller rocks in the Elsinore-San Jacinto line, but is well suited for cosmogenic sampling for erosion rate. It has been sampled for 10Be by Dylan Rood, but results are not yet available. Because it is in a small erosional canyon we can't be confident about the age without further study, but based on other results (Brune et al., SSA 2014 abstract) we estimate it is a few thousand years old. Thus the fragility of PBR Motte1 appears to be only marginally consistent with the USGS hazard maps. Final conclusions await better age control.

Another interesting result is the fragility of PBRs at Alpine Butte. PBR "alp2 Alpine Butte" is the most fragile rock Photomodeled in the Mojave Desert near the San Andreas fault. It is located on a large granite outcrop for this area. Its height is approx 0.8 m. The pedestal height is about 1 m. Using methods of Purvance et al. (2008a,b), J.N. Brune estimates the probability of toppling by an earthquake with the USGS 2008 2% in 50 yr values for PGA and Sa1 is 90 % (>90% for 1% in 50 yr hazard,). Its height and fragility are typical of numerous smaller rocks in the Alpine Buttes area, and at Lovejoy Buttes and Black Butte. We have not studied the age cosmogenically, but numerous rock faces here and on adjacent buttes have varnish microlamination (VML) dates of about 10 ka (Purvance, written communication) and thus we feel it is very likely several thousand years old. Thus we consider it to be inconsistent with the USGS hazard maps (Petersen et al., 2008).

Preliminary comparison with Cybershake

A major objective of our work was to accurately document PBR fragilities and geomorphic conditions for comparison with Cybershake predictions. Cybershake produces hazard curves for Sa1. PBRs are susceptible to toppling by relatively high frequency ground motions. The higher frequencies for broadband waveforms are still in development. Here, for discussion, we make a preliminary comparison between Sa1 hazard curves and PBR fragility curves. Peter Powers kindly provided us with preliminary Sa1 hazard curves for a number of our "Photomodeled" PBR sites. Since the sites are specified and Cybershake takes into account structure, for a given structure model the only input parameters that are free to adjust are related to the source.

Perhaps surprisingly the preliminary Cybershake Sa1 hazard points for 2% in 50 yrs are very close to the corresponding curves for the 2008 USGS hazard maps even though the 2008 USGS maps make the ergodic assumption, including aleatory site and path effects, which tends to increase Sigma and thus ground motion at low probabilities. The USGS hazard estimates also include random background earthquakes which tend to increase the hazard, whereas the Cybershake results do not. Thus at first glance it appears that the randomness in source parameters for Cybershake compensates for not using the ergodic assumption and for not using background earthquakes.

These preliminary indications of discrepancies between Cybershake Sa1 hazard and the Photomodeled PBR fragility results suggest that too much variability has been introduced into the source parameters in Cybershake. The main sources of Cybershake source variability are the directivity introduced by assuming a large range of rupture directions and nucleation points for given rupture lengths, variability of average stress drop on these ruptures, and variability of the spectrum of fault slip on the fault plane (phase and amplitude). In this preliminary report, we do not attempt to decide on the appropriateness of these variables, but wait for further analysis by others.

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