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Towards Validation of a Petascale Cyberfacility for Physics-Based Hazard Estimates: Precariously Balanced Rocks in the Vicinity of San Bernardino

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Introduction

A recent article in the Los Angeles Times discussed the vulnerability of structures, especially unreinforced masonry buildings, in San Bernardino. Sally McGill of Cal State San Bernardino noted that "no point in San Bernardino is more than four miles from an active fault" (Bernstein 2007), highlighting the substantial seismic hazards faced by this city of over 200,000. In the same article, Lucy Jones of the USGS stated more flatly, "if you're San Bernardino, you're toast" and that "San Bernardino is on two faults, and those [unreinforced masonry] buildings will fall down." (Bernstein 2007). The risks associated with weak structures are exacerbated by the relatively shallow groundwater aquifer leading to a strong liquefaction potential. These combined conditions may be a recipe for a "perfect storm" in the words of Lucy Jones (Bernstein 2007). The economic and human costs of a large earthquake on either the San Andreas or San Jacinto faults will likely be dramatic in San Bernardino and the surrounding areas. As ground motions from a large, local earthquake ($M \geq 7$) have never been recorded in this region, hazard assessments must rely on ground motion simulations and/or extrapolations based on existing data to assess impacts on the lives and properties of residents. An alternate approach to assessing ground motions from such events is to investigate the unexceeded ground motion constraints provided by precariously balanced rocks (PBRs). In 2008 we undertook field investigations of PBRs near to San Bernardino (Figure 1) in order to refine their fragilities. Subsequently these data have been utilized to compare the PBR constraints with probabilistic seismic hazard estimates for the region based on the UCERF 2 (Field et al. 2008) earthquake rupture forecast (ERF) and the Campbell and Bozorgnia (2008) ground motion prediction equations (GMPEs). The existences of these PBRs strongly suggests that either the recurrence intervals of some earthquakes as indicated in the UCERF 2 ERF are unrealistically short or that the Campbell and Bozorgnia (2008) GMPE predicts unrealistically large ground motions amplitudes in the near field of large earthquakes.

PBR Constraints / Comparisons with Seismic Hazard Estimates

Figure 1 documents the locations of PBRs chosen for this analysis. These include PBRs at sites very close to the Cleghorn and North Frontal Thrust Faults (sites SW at Silverwood Lakes and GV at Grass Valley) along with sites near to the San Jacinto Valley section of the San Jacinto Fault and between the San Jacinto and San Andreas Faults (sites SJ). Pictures of the PBRs at these sites are also presented with targets affixed which are utilized for accurate shape determination via photogrammetry. These PBRs have all be field tested via forced tilting tests as outlined in Purvance et al. (2008) in an effort to more accurately delineate their fragilities. Rood et al. (2008) presents the only residence time study (e.g., duration over which the PBRs have resided in their current fragile configurations) of PBRs in this region. That studied detailed initial residence time estimates of 23-28 ka for Grass Valley PBR pedestals and 50 ka for one PBR at that site based on ^{10}BE cosmogenic isotope estimates. Thus there is evidence that the Grass Valley PBRs have resided in their current positions for many earthquake cycles. These exposure time estimates are consistent with the results of Bell et al. (1998) for PBRs in the Mojave and Southern California.

The estimated PBR fragility models have been exposed to suites of ground motions produced by ensembles of earthquakes taken from the UCERF 2 ERF. UCERF 2 represents the most up to date knowledge of earthquake recurrence in California. The GMPE of Abrahamson and Silva (1997) (referred to subsequently as AS97) and the NGA relation of Campbell and Bozorgnia (2008) (referred to subsequently as CB08) have been used in these analyses. Note that background seismicity has not been included due to the fact that the largest earthquakes on known faults control the hazard at these near fault sites. Monte Carlo simulations have been undertaken using the recurrence intervals and maximum magnitudes of events, sampling the GMPE for the magnitude/distance pairs. Since the PBR overturning fragilities depend on both the high- and lower-frequency ground motion amplitudes, we have utilized PGA and spectral acceleration at 1 Hz to estimate the overturning probabilities (see Purvance et al. 2008 for the fragility relations). Based on the results of Pullammanappallil et al. (2006), we have utilized Vs30 = 760 m/s for all analyses.

Figure 2 presents the overturning probabilities for each PBR shown in Figure 1 when exposed to the UCERF 2 ERF where the ground motions have been estimated based on the CB08 and AS97 GMPE. The ground motions are assumed to be statistically independent from earthquake to earthquake in these analyses and 10,000 year residence times have been assumed ubiquitously. As shown in Figure 2, the AS97 GMPE produces significantly higher rates of overturning when compared with the CB08. In both cases, a number of the PBRs should have overturned with high probability if exposed to the earthquakes represented by the UCERF 2 ERF, though. Thus the NGA GMPE does not remedy the inconsistencies between the PBRs and the UCERF 2 ERF at these sites.

In order to ascertain which earthquakes contribute the most to these high overturning probabilities, disaggregated lists of overturning probabilities are presented in Figure 3 for the PBRs with median overturning probabilities greater than 95%. The CB08 GMPE is investigated in Figure 3 as it represents the most up to date ground motion catalog available. It is clear that for PBRs near to the Cleghorn Fault (either SW or GV sites), the presumed M 6.7 which occurs every 1,245 years on that fault is the primary contributor to the overturning probability. Is the Cleghorn this active? Is the maximum magnitude much less than 6.7? Does the ground shake less within 1 km of the Cleghorn Fault than suggested by the CB08 GMPE? In addition, the very fragile PBR GV08 would also be overturned with high probability by earthquakes on the North Frontal Thrust (M 7.15, 1,758 yr recurrence interval - RI) and the San Andreas Fault (M 7.42, 1,131 yr RI; M 7.14, 881 yr RI; M7.56, 1,471 yr RI; M7.93, 2,597 yr RI). Thus the large magnitude events with recurrence intervals ¼ or less than the presumed PBR residence times produce significant overturning probabilities.

The PBR SJ08 is the most fragile PBR which resides in the vicinity of San Bernardino between the San Andreas and San Jacinto Faults. As shown in Figure 3, the San Andreas earthquakes do not contribute significantly to the overturning potential. Earthquakes on the San Jacinto Valley section (M 6.95, 2,225 yr RI; M 7.31, 2,247 yr RI; M 7.46, 2,245 yr RI; M 7.62, 2,235 yr RI; M 7.64, 2,225 yr RI, M 7.76, 2,247 yr RI) and the Anza section (M 7.49, 884 yr RI) of the San Jacinto Fault produce significant overturning probabilities. Again, the earthquakes with recurrence intervals less than ~ ¼ of the PBR residence times may produce significant overturning probabilities.

Conclusions

This report documents recent efforts to refine the unexceeded ground motion constraints provided by PBRs in the vicinity of San Bernardino. Detailed field investigations have led to improved fragility estimates based on the work of Purvance et al. (2008). The UCERF 2 ERF has been utilized as the preferred model for earthquake recurrence near these sites while the Campbell and Bozorgnia (2008) NGA GMPE has been used to estimate the ground motions resulting from these events. Monte Carlo simulations have been undertaken using 10,000 year PBR residence times and the maximum magnitude events on known faults. Thus background seismicity and Gutenberg-Richter magnitude distributions have been neglected in these analyses. A number of PBRs would overturn with high probability due to large magnitude earthquakes on the Cleghorn, North Frontal Thrust, San Jacinto, and San Andreas Faults. Detailed disaggregation of the overturning probability has assisted in identifying these events which contribute to the failure potential of the PBRs. The discrepancies may result from unrealistically high recurrence intervals for these events or unrealistically strong ground motions as predicted by the GMPE.

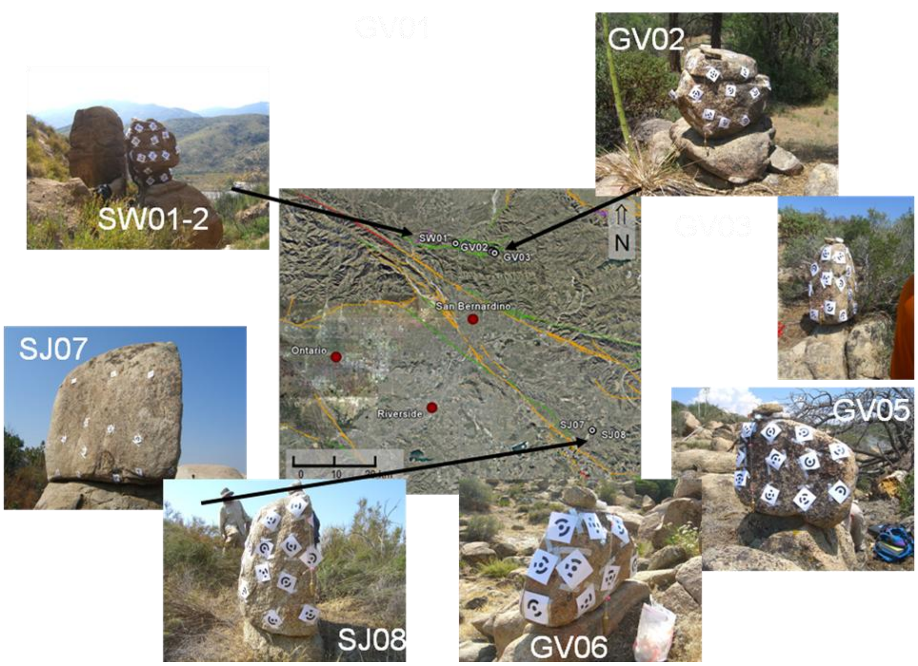

Figure 1. PBRs investigated in the vicinity of San Bernardino. The SW and GV sites lie very close to the Cleghorn, North Frontal Thrust, and San Andreas Faults while the SJ (San Jacinto) PBRs are very close to the San Jacinto Fault (within ~ 5 km).

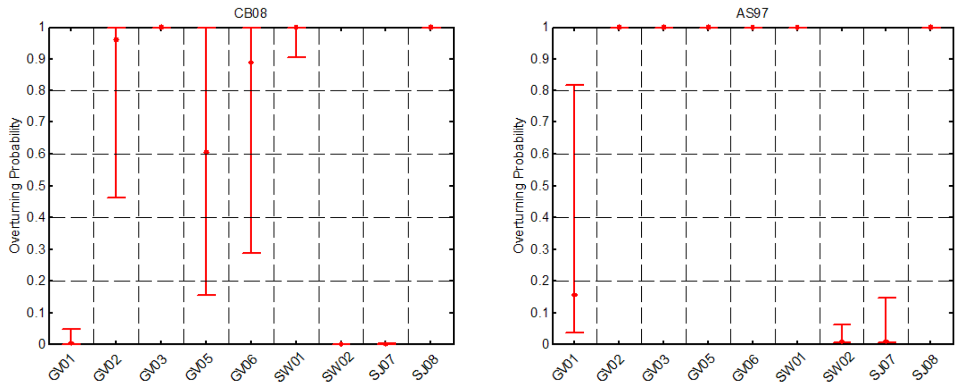

Figure 2. PBR overturning probabilities assuming 10,000 year residence times when exposed to the UCERF 2 (Field et al. 2008) earthquake rupture forecast. Results for the Campbell and Bozorgnia (2008) and Abrahamson and Silva (1997) GMPE are shown.

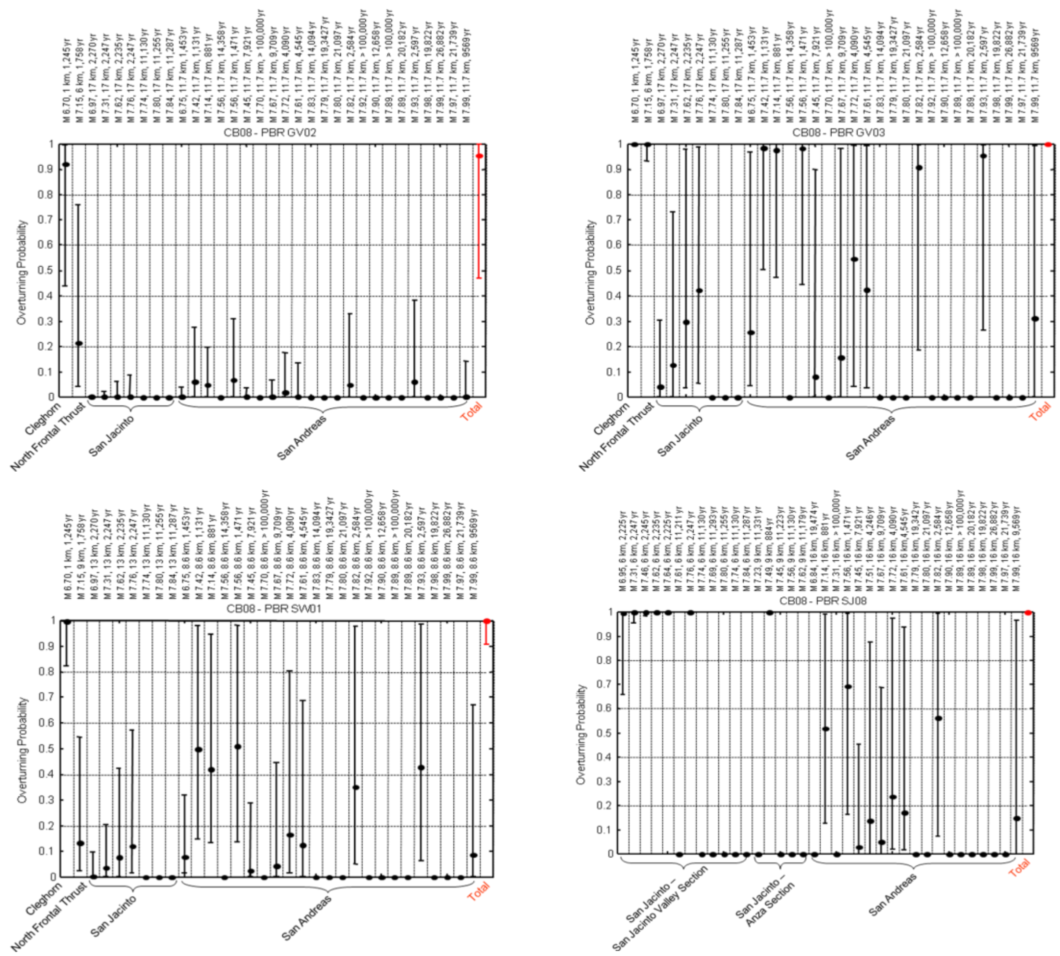

Figure 3. Disaggregations of the PBR overturning probabilities for the PBRs GV02, GV03, SW01, and SJ08. The Campbell and Bozorgnia (2008) (CB08) GMPE has been used in conjunction with 10,000 year residence times. Large magnitude earthquakes on nearby faults with recurrence intervals less than ~ ¼ of the PBR residence times may contribute substantially to the PBR overturning probabilities.

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