FINAL REPORT

Precarious Rock Constraints on Ground Accelerations Associated with Normal Faults

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Award Number: 07HQGR0028

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Research supported by the United States Geological Survey (USGS), Department of Interior, under USGS award number 07HQGR0028. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the United States Government.

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Abstract

We use results from field-tests of precariously balanced rocks (PBRs) in the vicinity of Carson City, Nevada, to provide constraints on the intensity of ground shaking during large earthquakes (M>7) on the Genoa fault. Field tests consist of accurate determination of the PBR shapes using photogrammetry, and quasi-static tilting tests of a subgroup of these PBRs to determine accurate restoring force versus tilt curves. These tests allow us to accurately estimate the PBR fragilities. These fragilities are utilized to determine the overturning probability of a PBR with a specified geometry as a function of the peak acceleration (PGA) and either the ratio of the peak ground velocity to the peak ground acceleration (PGV/PGA), the spectral acceleration at 1 second to the peak ground acceleration (S_a (1)/PGA), or S_a (2)/PGA.

In order to assess the constraints provided by generalized PBRs at sites near to the Genoa fault, the overturning probabilities for generalized symmetric PBRs that are 1 m tall were exposed to ground motions given by the ground motion prediction equations (GMPE) of Campbell and Bozorgnia (CB07), Atkinson and Boore (AB07), Abrahamson and Silva (AS97), and Spudich *et al*. (SEA99). 10000 Monte Carlo simulations were utilized to determine the overturning probability distributions where the earthquake magnitudes were taken from a uniform distribution ranging from 7.2 to 7.5 for Genoa fault earthquakes. For each earthquake realization the GMPE are queried for the medians and standard deviations and ground motion amplitudes are randomly chosen from lognormal distributions based on these values.

The survival probabilities of the PBR ensemble when exposed to the CB07, AB07, AS97, and SEA99 GMPE are 0.64%, 55%, 1.4e-5%, and 8.2e-4%, respectively. Thus the probability that the set of 6 PBRs studied in this initiative would all survive are less than 1% when the CB07, AS97, and SEA99 GMPE are utilized to estimate the ground motions. These results strongly suggest that these GMPE produce unrealistic ground motions when applied to these sites in the near field of large normal faulting earthquakes. Such inconsistencies may result from unrealistically elevated median ground motions or from an unrealistic spread in the predicted ground motions. Regardless, these PBRs present compelling evidence that a number of GMPE may not be appropriate for the near field of normal faulting earthquakes.

Introduction

Recent evidence from physical and numerical models has indicated that ground motions from normal faults may be much lower than for strike-slip faults with a large fault-normal tectonic stress component (Brune, 2000; Brune and Anooshehpoor, 1998, 1999; Oglesby *et al.*, 1998, 2000, Shi, 1999, Day and Ely 2000; Shi *et al.*, 1998, 2003). Data from trans-pressional strike-slip earthquakes and thrust faults dominate in the determination of regression curves for ground motions used in the USGS-CDMG PSHA maps. As a consequence, these maps may be too high for extensional regimes.

One of the main physical reasons for expecting low accelerations for normal faults and strike-slip faults in extensional regions is the fact that the fault normal component of fault stress must approach zero near the surface since the lithostatic stress approaches zero and the tectonic stress is extensional (Brune and Anooshehpoor, 1998; McGarr *et al*., 2000). As a result, relatively little elastic strain energy can be stored at shallow depth near the fault trace. Preliminary evidence from reconnaissance surveys of precariously balanced rocks (PBRs) provides support for such low ground accelerations.

Purvance (2005) has shown that PBRs overturn systematically when exposed to horizontal shaking. Overturning is found to be a function of block size, block shape, and excitation intensity. Purvance (2005) found that PBRs overturn as a result of both high peak ground acceleration (PGA) and higher low-frequency content (either peak ground velocity (PGV), spectral acceleration at 1 second ($S_a(1)$), or spectral acceleration at 2 seconds ($S_a(2)$). The derived formulation compares favorably with the results of shake table tests of simple blocks. Recently Purvance *et al*. (2008) refined this methodology via a simply realized physical experiment to better predict the overturning responses of complex stone boulders similar to actual PBRs. These results constitute an important enhancement in the ability to effectively quantify the overturning potential of PBRs. Purvance (2005) and Purvance *et al*. (in press) additionally demonstrated a methodology to compare the PBRs with ground motion models derived from PSHA calculations.

Evidence presented in Ramelli *et al*. (1999) strongly suggests that the Genoa fault has produced at least 2 large ($7.2 \leq M \leq 7.5$) normal faulting earthquakes in the last 2000 years. Such events constitute substantial seismic hazards to the Reno/Carson City urban corridor and to Lake Tahoe communities. This work utilizes the existence of fragile geological features in an effort to constrain the ground motions that have not been exceeded by large earthquakes on the Genoa fault. This is achieved by comparing predictions of ground shaking amplitudes with the failure propensities of select geological features. A number of PBRs exist within a few kilometers of the surface trace of the Genoa fault on the hanging wall side (Figure 1). Some of these PBRs also reside very close to the Carson City and Indian Hills faults, constraining ground motions that have not been exceeded by earthquakes on these faults as well. Note that this work does not consider earthquakes on these subsidiary fault systems.

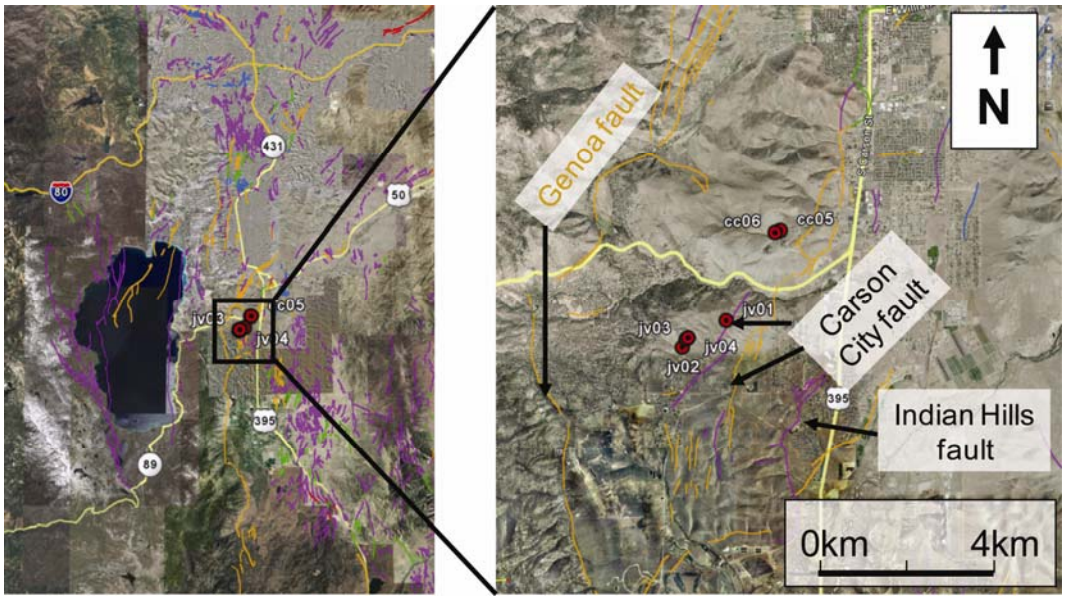

Figure 1: Map of the study area showing the PBR locations. The PBRs investigated in this study lie within ~ 4 km of the Genoa fault, the site of 2 M > 7.2 earthquakes in the past 2000 years.

PBR Methodology

Age of the PBRs

In order to utilize PBRs as ground motion constraints, it is vital that the times that the PBRs have resided in their current configurations be assessed. The ages of the specific PBRs used in this analysis have not been investigated. As outlined in Granger *et al*. (2001), bare granite rock erosion rates in northern Nevada may be very slow. That work found outcrop erosion rates in the Fort Sage Mountains of approximately 1.7 cm/ka in friable granite similar to the rock type of the PBRs investigated in this effort. This evidence strongly supports the conclusion that the PBR shapes have not changed significantly over the past 2000 years.

Could the PBRs have been exhumed from beneath the grussy soil horizon during the last 2000 years? Granger *et al*. (2001) found Fort Sage erosion rates depend strongly on the hillslope gradient. For gradients less than 0.4, these rates are less than 5 cm/ka. Thus PBRs with bases greater than ~ 10 cm above the current soil horizon would have likely survived the past two earthquakes without overturning due to ground shaking. These findings strongly suggest that PBRs such as those utilized in this work provide direct evidence of the level of ground shaking that has not been exceeded by the two earthquakes suggested by Ramelli *et al*. (1999). These slow erosion rates also suggest that the PBRs investigated in this study may provide ground motions constraints for more than two Genoa fault earthquakes depending on the most recent event prior to 2000 years before present. Future cosmogenic age dating initiatives could be utilized to assess the PBR ages more thoroughly.

Field Test of PBRs

The PBRs analyzed are shown in Figure 2. The PBR shapes have been determined via photogrammetry as outlined in Anooshehpoor *et al*. (2007). The digitized shapes are also shown in Figure 2. Anooshehpoor *et al*. (2007) demonstrated that the PBR volumes ascertained in this fashion are within 5-10% of the actual values, producing reasonably accurate representations of the PBR geometries including the center of mass locations. Figure 3 demonstrates the pertinent PBR geometrical parameters that will subsequently be used to determine the PBR fragilities. The parameterizations given in Purvance *et al*. (2008) are used subsequently to obtain ground motion constraints. Note that the Purvance *et al*. (2008) models correspond to 2-D rocking blocks while the PBR shapes are 3-D so that the smallest α_1 and α_2 values are utilized. The photogrammetry obtained geometrical parameters provide the least fragile configuration.

In addition to the analysis presented above, forced tilting tests have been undertaken where the tilting force and angle of tilt are simultaneously measured (Fig. 4). As shown in Purvance *et al*. (2008), such tests allow one to accurately estimate the PBR fragilities as these quantities depict the locations of the predominant rocking points. Geometrical parameters based on the forced tilting tests result in PBR fragilities that are at least as fragile as those based on photogrammetry alone. The fragility formulation of Purvance *et al*. (2008) are utilized to determine the overturning probability of a PBR with a specified geometry as a function of the peak acceleration (PGA) and either the ratio of the peak ground velocity to the peak ground acceleration (PGV/PGA), the spectral acceleration at 1 second to the peak ground acceleration (S_a (1)/PGA), or S_a (2)/PGA. Purvance *et al*. (2008) demonstrated that these fragilities, in conjunction with forced tilting tests, effectively represented overturning observations from a set of shake table experiments.

Analyses and Results

The important geometrical parameters, α_1, α_2, and p^2 ($p^2 = mgR/I$), for the PBRs analyzed near the Genoa fault are given in Table 1. Both the photogrammetry based and tilt test based α_1 and α_2 values are presented when available. Are these PBRs consistent with two 7.2 ≤ M ≤ 7.5 earthquakes in the past 2000 years? This question is investigated via Monte Carlo simulations utilizing the ground motion medians and standard deviations given by the ground motion prediction equations (GMPE) of Campbell and Bozorgnia (2007) (CB07), Atkinson and Boore (2007) (AB07), Abrahamson and Silva (1997) (AS97), and Spudich *et al*. (1999) (SEA99). The first two GMPE resulted from the PEER funded Next Generation of Attenuation (NGA) initiative and provide relations specific to normal faulting earthquakes. The SEA99 model is based on data from earthquakes in extensional environments; as a result, the SEA99 GMPE has widely been used for normal faults. The AS97 GMPE was commonly used as the standard GMPE for probabilistic seismic hazard analyses (PSHA) and is included for comparative purposes. Note that the ground motion parameters PGA and PGV are used to determine the fragilities for the CB07 and AB07 GMPE while PGA and $S_a(1)$ are used for the AS97 and SEA99 GMPE. The current analysis assumes rock or V_{s30} = 760 m/s site conditions. This assumption is based on ReMi measurements at granite PBR sites in Southern California that are similar to the Genoa PBR sites (Pullammanappallil *et al*. 2006). Additionally the Genoa fault is assumed to dip to the east at 60 degrees and the PBR sites are assumed to lie 4 km from the surface trace of the fault ubiquitously.

In order to assess the constraints provided by generalized PBRs at sites near to the Genoa fault, the overturning probabilities for symmetric PBRs that are 1 m tall are shown in Figure 5 when exposed to the CB07, AB07, AS97, and SEA99 GMPE. 10000 Monte Carlo simulations have been utilized to determine the overturning probability distributions. The earthquake magnitudes are taken from a uniform distribution ranging from 7.2 to 7.5 following the Ramelli *et al*. (1999) findings. The symbols correspond to the median (50th percentile) of the overturning probability distributions while the error bars correspond to the 16th and 84th percentiles of these distributions. The colors correspond to overturning when exposed to one (blue), two (green), and three (red) earthquakes. The overturning probabilities when exposed to each earthquake are assumed to be statistically independent in order to calculate the overturning probability when exposed to multiple Genoa fault earthquakes. As exposure to earthquakes increases, the median overturning probabilities increase. The spread from the 16th to 84th percentiles in overturning probability may be significant for PBRs with α in the range where the distribution transitions from overturning (overturning probability = 1) to survival (overturning probability = 0). NGA relations CB07 and AB07 produce lower median overturning probabilities than the previously used AS97 and SEA99 GMPE. The AB07 GMPE produces lower overturning probabilities as a function of α than the CB07 GMPE.

When exposed to two earthquakes, the α values for 1 m tall, symmetric PBRs with median overturning probabilities less than 5% are approximately 0.35 rad, 0.3 rad, 0.45 rad, and 0.45 rad for the CB07, AB07, AS97, and SEA99 GMPE, respectively. In other words 1 m tall, symmetric PBRs with α values greater than those outlined above would overturn with less than 5% probability on average when exposed to two earthquakes where 7.2 ≤ M ≤ 7.5. The α cutoff values with median overturning probabilities close to 50% are 0.25 rad, 0.2 rad, 0.3 rad, and 0.3 rad for the CB07, AB07, AS97, and SEA99 GMPE, respectively, while the α cutoff values with median overturning probabilities close to 95% are 0.2 rad, 0.15 rad, 0.25 rad, and 0.25 rad, respectively, when exposed to two Genoa earthquakes. In order for one symmetric, 1 m tall PBR to be very inconsistent (e.g., overturning probability > 95%), the PBR must be very slender with

α ~ 0.2 rad; this corresponds to a height-to-width ratio of ~ 5 or a symmetric PBR that is 5 times taller than wide.

As shown in Table 1, some PBRs near the Genoa fault are asymmetric ($\alpha_1 \neq \alpha_2$). For instance the α_2 of PBRs JV03 and JV04 are at least 1.5 times greater than the α_1 values. Purvance *et al.* (2008) also determined fragilities for asymmetric PBRs with $\alpha_2 \leq 0.45$ rad. Plots in Figures 6 are comparable with those in Figure 5 except that $\alpha_2 = 0.45$ rad in each case. Asymmetry of this degree greatly increases the PBR stability when compared to the symmetric PBR case (e.g., comparing α_1 with α above). For the asymmetric case with $\alpha_2 = 0.45$ rad, the α cutoff values with median overturning probabilities close to 95% are < 0.15 rad, < 0.15 rad, 0.25 rad, and 0.2 rad for the CB07, AB07, AS97, and SEA99 GMPE, respectively. Thus in order for a PBR to be very inconsistent with the CB07 GMPE, α_1 should be less than 0.15 rad when $\alpha_2 = 0.45$ rad.

Table 1: PBR identifiers and geometric parameters are listed. Parameters determined from photogrammerty analysis are given in columns 2-5. When tilt testing results are available those are shown in columns 6 and 7. The tilt test parameters are used in fragility determination when available.

PBR	**Photo**		**R (m)**	p^2 **(s^{-2})**	**Tilt Test**	
	α_1 (rad)	α_2 (rad)			α_1 (rad)	α_2 (rad)
JV01	0.334	0.371	0.520	14.10	0.227	0.256
JV02	0.406	0.419	0.749	9.80		
JV03	0.331	0.488	0.366	19.90	0.257	
JV04	0.084	0.649	0.657	11.10	0.059	
CC05	0.244	0.356	0.913	8.05		
CC06	0.442	0.540	0.621	11.80		

Figure 7 shows the calculated overturning probabilities for the specific PBRs investigated in this analysis. Note that when $\alpha_2 > 0.45$ rad, α_2 is set to 0.45 rad as in Purvance *et al.* (2008) parameterization does not exceed this value. When exposed to two earthquakes, the median overturning probabilities of at least one PBR exceed 95% for the CB07, AS97, and SEA99 GMPE. In fact 2 PBRs are inconsistent with the AS97 and SEA99 GMPE, namely the PBRs JV01 and JV04. No PBRs are inconsistent at the 95% level with the AB07 GMPE, though.

Suppose now that the overturning probabilities of each PBR when exposed to two earthquakes are statistically independent of one another. What is the probability that the set of these 6 PBRs remain in existence without any of them overturning? The survival probabilities of the PBR ensemble when exposed to the CB07, AB07, AS97, and SEA99 GMPE are 0.64%, 55%, 1.4e-5%, and 8.2e-4%, respectively. Thus the probability that the set of 6 PBRs studied in this initiative would all survive are less than 1% when the CB07, AS97, and SEA99 GMPE are utilized to estimate the ground motions. These results strongly suggest that these GMPE produce unrealistic ground motions when applied to these sites in the near field of large normal faulting earthquakes. Such inconsistencies may result from unrealistically elevated median ground motions or from an unrealistic spread in the predicted ground motions. Regardless these PBRs present compelling evidence that a number of GMPE may not be appropriate for the near field of normal faulting earthquakes.

Reconnaissance Survey for Potential New Normal fault PBR Sites

In anticipation of future studies of precarious rocks we have carried out reconnaissance studies for potential precarious rock sites which may constrain estimates of ground motion from Holocene normal fault earthquakes.

Foot Wall: Sand Springs Range, western Nevada; Granite Mountains, northern Nevada; Diamond Mountains, northeast California.

Hanging Wall: Owens River Canyon, eastern California; Mono Lakes tuff, eastern California; Bodie Junction, eastern California.

All of these sites have precarious or semi-precarious rocks within 15 km of large faults capable of near magnitude 7 earthquakes. Further field studies will be necessary to verify the usefulness of studying these rocks in detail.

Conclusions

The survival probabilities of generalized PBRs (1 m tall) at sites near Genoa fault when exposed to the CB07, AB07, AS97, and SEA99 GMPE are 0.64%, 55%, 1.4e-5%, and 8.2e-4%, respectively. Thus the probability that the set of 6 PBRs studied in this initiative would all survive are less than 1% when the CB07, AS97, and SEA99 GMPE are utilized to estimate the ground motions. These results strongly suggest that these GMPE produce unrealistic ground motions when applied to these sites in the near field of large normal faulting earthquakes. Such inconsistencies may result from unrealistically elevated median ground motions or from an unrealistic spread in the predicted ground motions. Regardless, these PBRs present compelling evidence that a number of GMPE may not be appropriate for the near field of normal faulting earthquakes.

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Figure 2: Photographs of the PBRs in Jacks Valley utilized in this analysis. The photogrammetry models of the rocks are also presented. The models are oriented to approximately match the corresponding photographs above them.

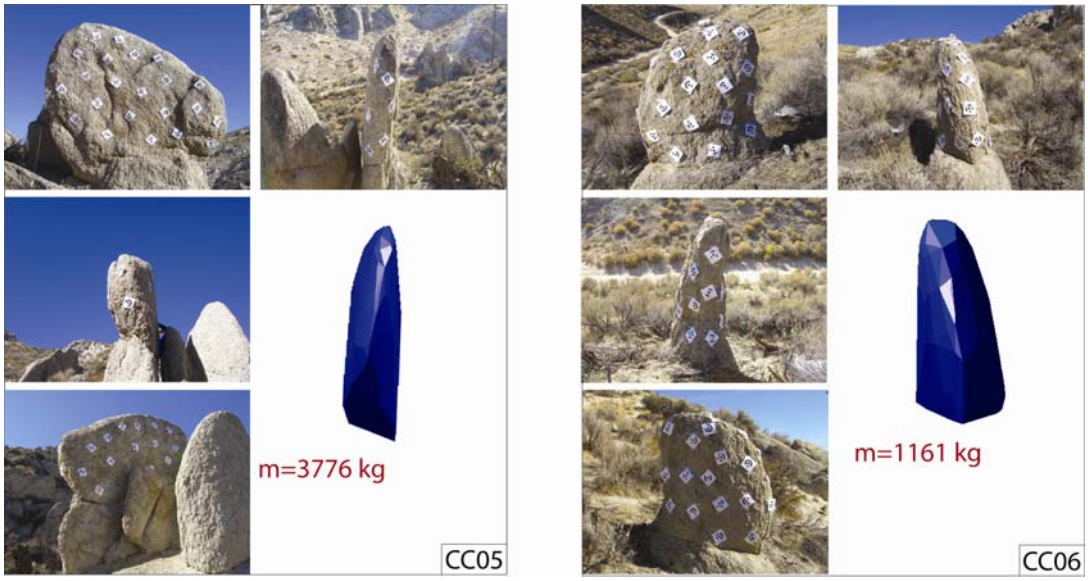

Figure 2 (cont.): Similar illustrations for PBRs CC05 and CC06.

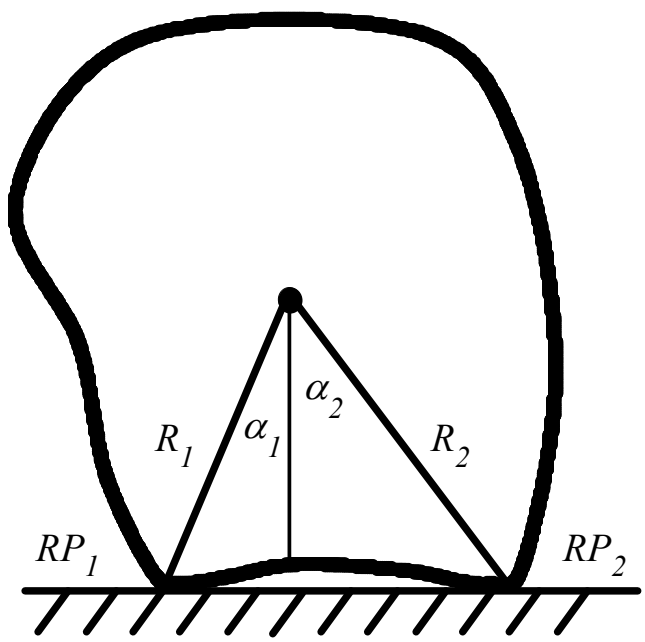

Figure 3: Geometric parameters used to determine the PBR fragilities. RP_1 and RP_2 are the rocking points, α_1 and α_2 are the angles from vertical to the lines connecting the center of mass to the rocking points, and R_1 and R_2 are the distances from the center of mass to the rocking points.

Figure 4: Setup for a typical field test of precarious rocks to determine the relation between the quasi-static tipping force and tilt. The force is measured by a load cell, and the tilt angle by an inclinometer. The nylon strap wrapped around the rock provides means to apply a horizontal force through the center of mass of the rock. The lower right photo shows the location of the inclinometer and the gap at the contact due to the tilt.

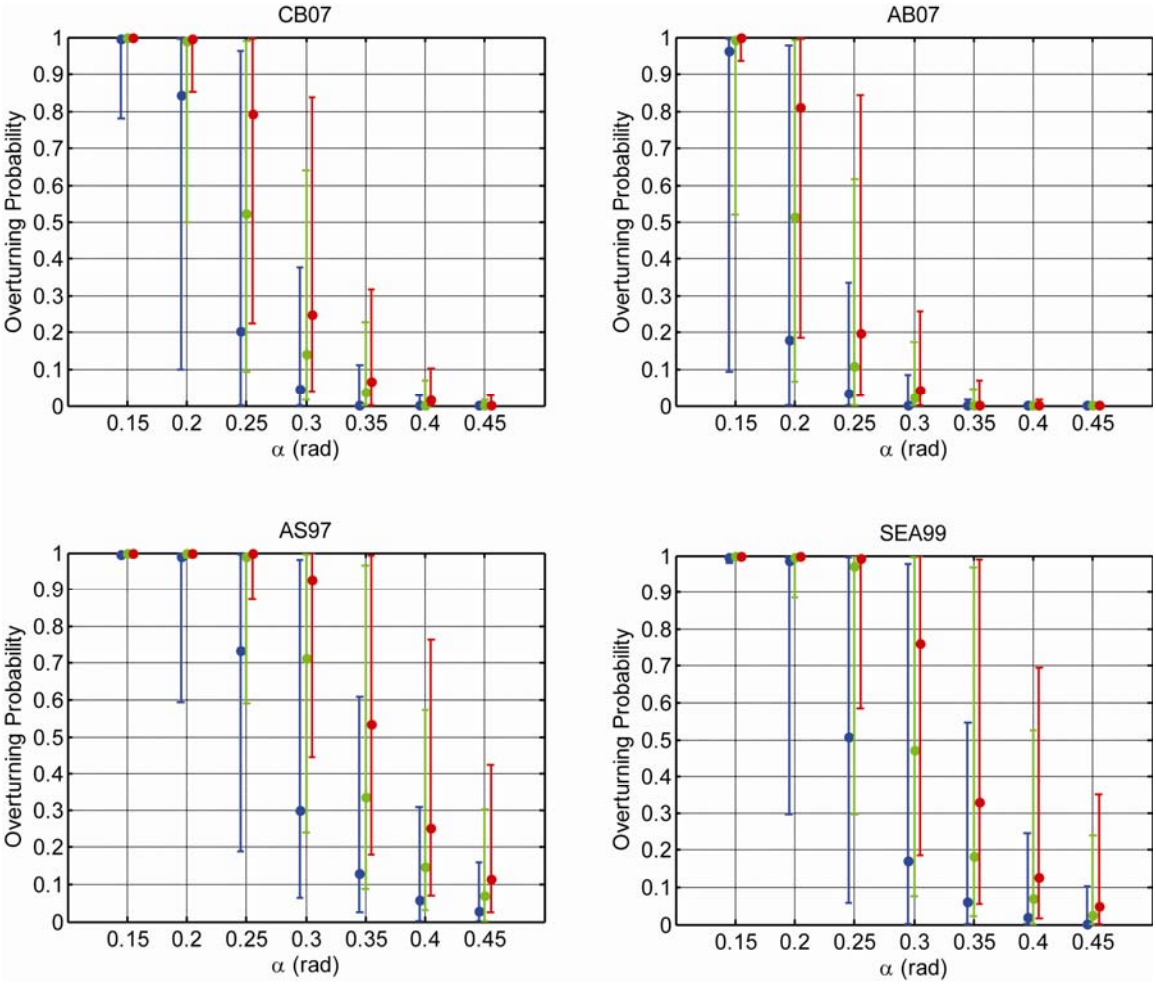

Figure 5: Overturning probabilities as a function of α for 1 m tall, symmetric PBRs exposed to 1 (blue), 2 (green), and 3 (red) Genoa fault earthquakes. The CB07, AB07, AS97 and SEA99 GMPEs were used in these analyses.

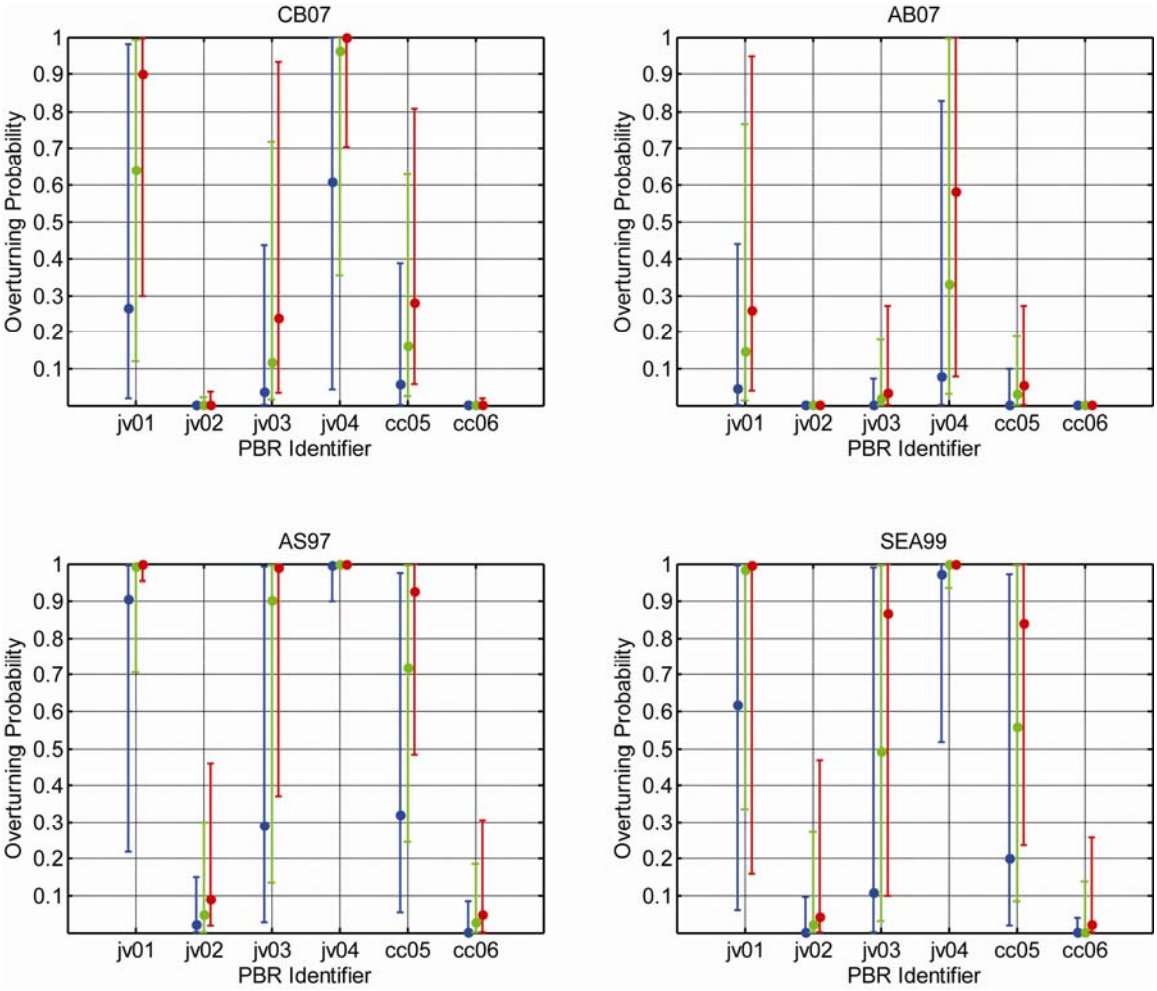

Figure 6: Overturning probabilities for the 6 PBRs investigated in this study exposed to 1 (blue), 2 (green), and 3 (red) Genoa fault earthquakes. The CB07, AB07, AS97 and SEA99 GMPEs were used in these analyses.

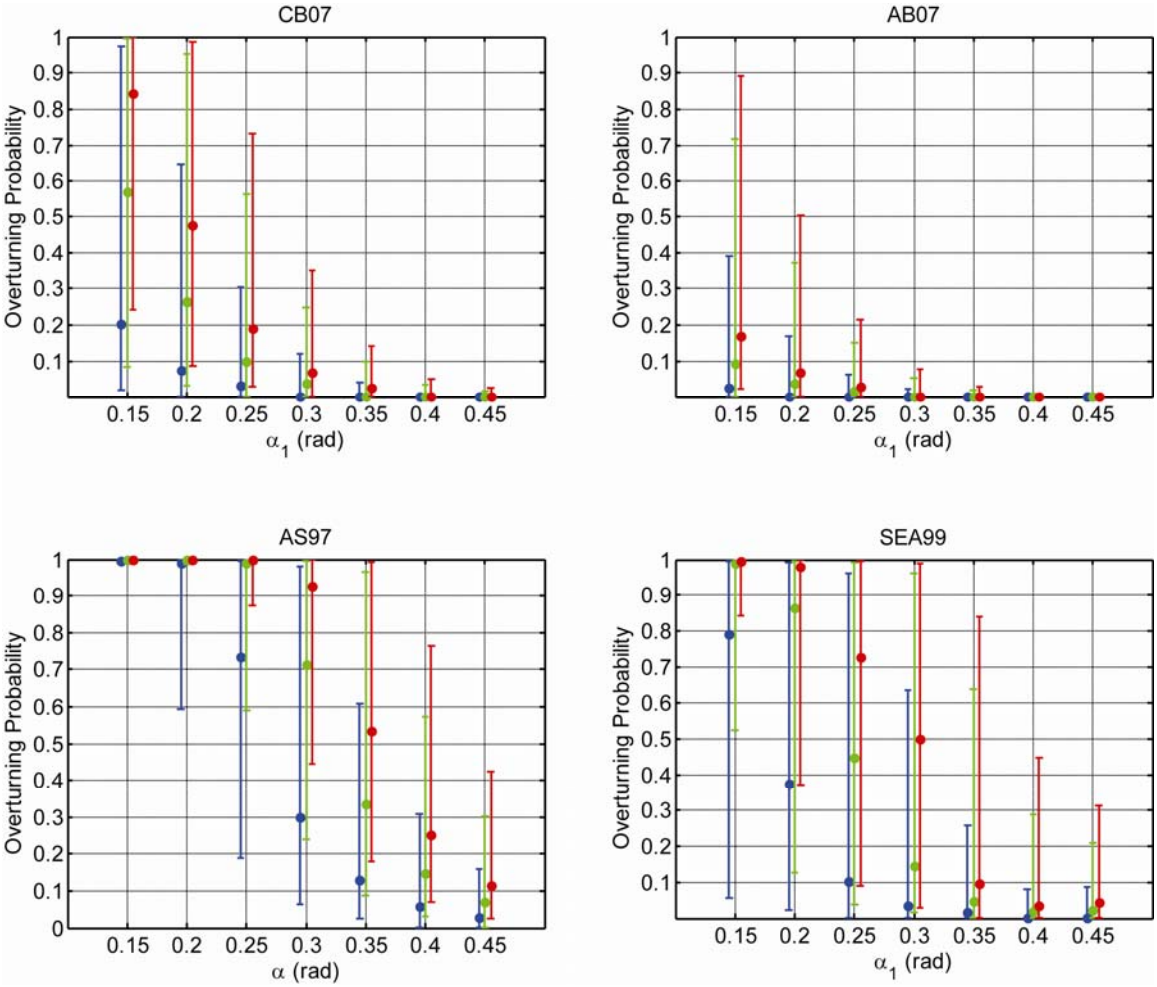

Figure 7: Overturning probabilities as a function of α_1 for 1 m tall, asymmetric PBRs with α_2 = 0.45 rad exposed to 1 (blue), 2 (green), and 3 (red) Genoa fault earthquakes. The CB07, AB07, AS97 and SEA99 GMPEs were used in these analyses.