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PRECARIOUS ROCKS AND DESIGN GROUND MOTIONS: FROM RESEARCH TO INDUSTRY APPLICATION

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Abstract

We summarise work undertaken to constrain the fragility of three precariously-balanced rocks (fragility = threshold peak ground accelerations, PGAs, for toppling failure) in the vicinity of Diablo Canyon Power Plant (DCPP), coastal California. The precariously-balanced rocks (PBRs) are found on two paleoseastacks (seastacks once actively eroded by the sea, but now uplifted well above sea level) at the Double Rock site, east of the power plant. We develop field-based fragility estimates from the geometries of the PBRs, as well as finite-element-code-based fragility estimates for one of the PBRs. Fragilities in the range of approximately 0.2-0.4g are obtained. These equate to the relatively short return periods of approximately 200-700 years on the DCPP hazard curve, and are consistent with 50th percentile PGAs for Hosgri Fault scenario earthquakes (large magnitude earthquakes at 5 km distance).

Our future work will verify the fragilities determined by field and finite-element-code-based methods, and determine the fragility age of at least one of the PBRs to ascertain whether the PBRs are old enough to provide meaningful constraints on the DCPP hazard estimates. Since the PBR fragilities equate to short return periods on the DCPP hazard curve, we consider that PBRs with ages of 1000 years or more would be useful for comparison to DCPP hazard estimates.

Keywords: precarious; fragility; Diablo; seismic; hazard

1. Introduction

Marginally-stable rock outcrops and precariously-balanced rocks (PBRs) are collectively termed ‘fragile geologic features’ (FGFs) and have potential application in seismic hazard assessment [1]. The strength of ground motions necessary to induce failure of a FGF (the fragility), and the length of time the FGF has remained fragile (the fragility age), can provide constraints on the past levels of ground motions that have occurred in the vicinity of the FGF site. Such information can then be used for evaluating probabilistic seismic hazard (PSH) models.

We report on work completed in 2015 to quantify the fragility of PBRs at the Double Rock paleoseastack site, in the vicinity of Diablo Canyon Power Plant (DCPP; Fig. 1; labelled DCNPP on the figure). The work is a follow up of recent reconnaissance work, in which PBRs were identified and a subset selected for further study [2]. Paleoseastacks are pillars or towers of rock that were originally formed by marine erosion, but have subsequently been uplifted above the sea. The Double Rock paleoseastacks rest on marine terraces with a 80,000-120,000 year estimated age range [3], and are composed of hard chert-rich lithologies of the Franciscan Assemblage [4], with a sub-vertical bedding dip.

The 2015 work comprised two days of fieldwork, follow up analysis, presentation of findings at Pacific Gas and Electric Company (PG&E), and reporting. The purpose of the two days of fieldwork was twofold: (1) to make field-based estimates of the quasi-static and dynamic toppling peak ground accelerations (PGAs) for failure of the PBRs at the site (fragilities), and; (2) to undertake photogrammetry to develop 3D models for the PBRs for 2D finite-element-based fragility analysis. If the fragilities from (1) and (2) were found to be low enough to be useful for constraining seismic hazard at DCPP (e.g. less than or equal to scenario motions for the Hosgri Fault, the major local fault source c. 5 km offshore; Fig. 1) then this would provide justification for further using the 3D models to obtain cosmogenic-based fragility ages for the PBRs.

Three PBRs were chosen for study from the two Double Rock paleoseastacks out of a total of seven at the site on the basis of accessibility and safety. DR1 was on the easternmost paleoseastack, and DR2 and 3 were on the westernmost seastack (Fig. 2). The paleoseastacks appear to have the same steep geomorphology, relief and geology as an active seastack located in the sea immediately northwest along bedding strike (“active” means actively eroding by sea wave action; Fig. 2), implying that the paleoseastacks have not been greatly modified since uplift from sea level. Furthermore, the relatively minor amount of observable debris on the 80,000-120,000 years old uplifted marine terrace [3] at the base of the paleoseastacks further implies slow rates of modification since uplift from the sea (Fig. 2). These assumptions are discussed in more depth later in the paper.

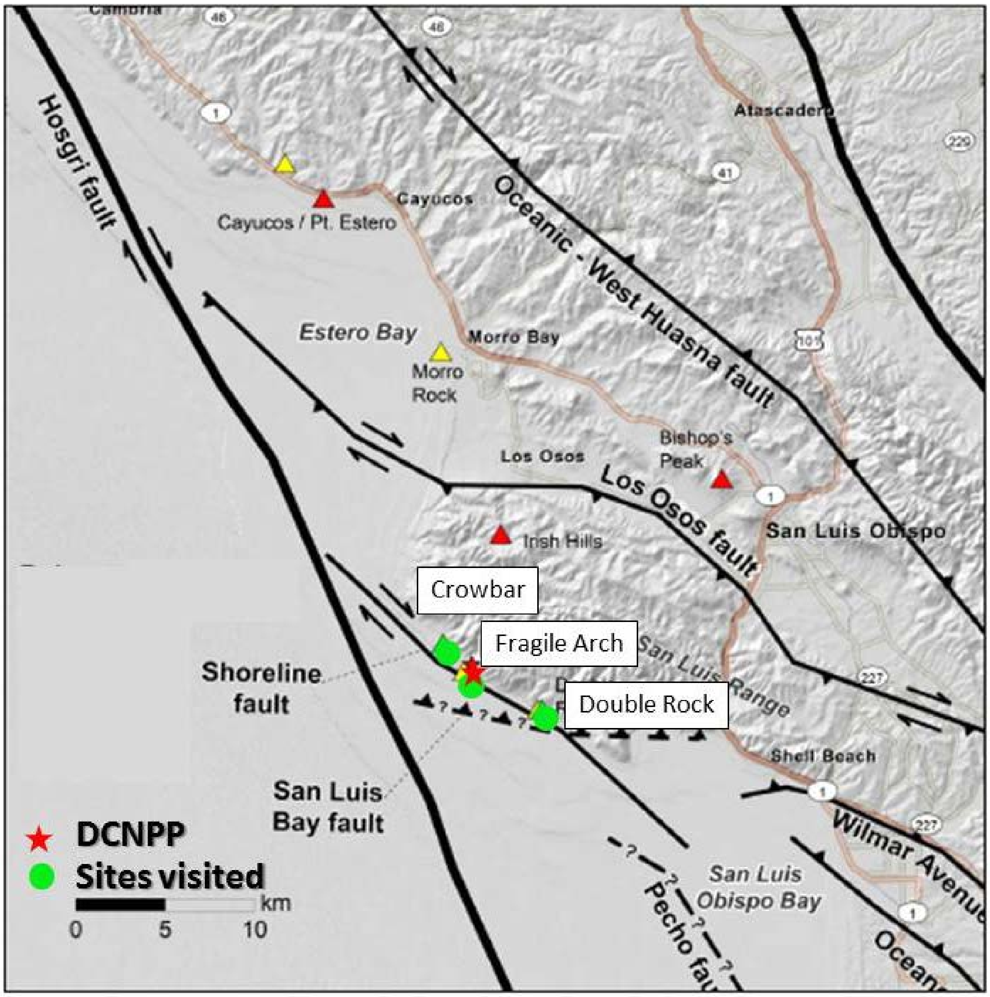

Fig. 1 - PBR sites near DCPP (power plant marked by the star labelled DCNPP). The Double Rock PBR site is the southeastern-most of the three sites shown by the large dots. Local faults are shown as dark lines.

Fig. 2 - The Double Rock PBR site, showing (clockwise from top-left): Double Rock paleoseastacks resting on uplifted marine terraces of 80,000-120,000 years age [3]; active seastack immediately west of the Double Rock paleoseastacks; DR2 and 3 PBRs on westernmost Double Rock paleoseastack, and; DR1 PBR on easternmost Double Rock paleoseastack.

2. Double Rock Fragilities

2.1 Methods

Field-based estimates of fragility are obtained for the three Double Rock PBRs (DR1-3), using the methods described by [5]. Specifically, the quasi-static toppling peak ground accelerations (PGAs) are based on the geometry and rocking points of the PBR (the tangent of the angle “alpha” between a PBR rocking point, PBR centre of mass, and the vertical is equal to the quasi static toppling acceleration; Fig. 3). However, shake table tests have shown that PBRs tend to topple when input PGAs are on average 30% higher than the quasi-static values. This 30% is added to the quasi-static values to give a dynamic estimate of fragility [5], which presumably accounts for additional factors influencing PBR toppling, such as the natural period of the PBR and the duration and frequency content of the earthquake motions.

We also use 2D finite element software to develop fragilities for one of the PBRs (DR1; Fig. 3). The software used is Rocscience Phase 2, (www.rocscience.com), a software suite that can be applied to a range of rock and soil applications, including excavation design, slope stability, groundwater seepage, probabilistic analysis consolidation, and dynamic analysis. We show in Figs. 4-6 cross sections taken through the 3D model of DR1 developed with the software photomodeler. These were required in order to use Rocscience Phase 2. The cross sections show the finite element net, along with the original resting position of the PBR (uncoloured outline), and a screen capture of the PBR in toppling failure mode (blue PBR). The original resting position of the PBR is on top of a bedrock ledge (blue area below PBR), and against a portion of the debris pile behind the PBR (small green area to right of PBR). The toppling failure of the PBR has been calculated according to each cross section and in terms of the quasi-static PGA required for failure.

2.2 Results

The field-based estimates of dynamic toppling acceleration range from 0.3g to 0.55g across DR1-3 (Fig. 3; Table 1).

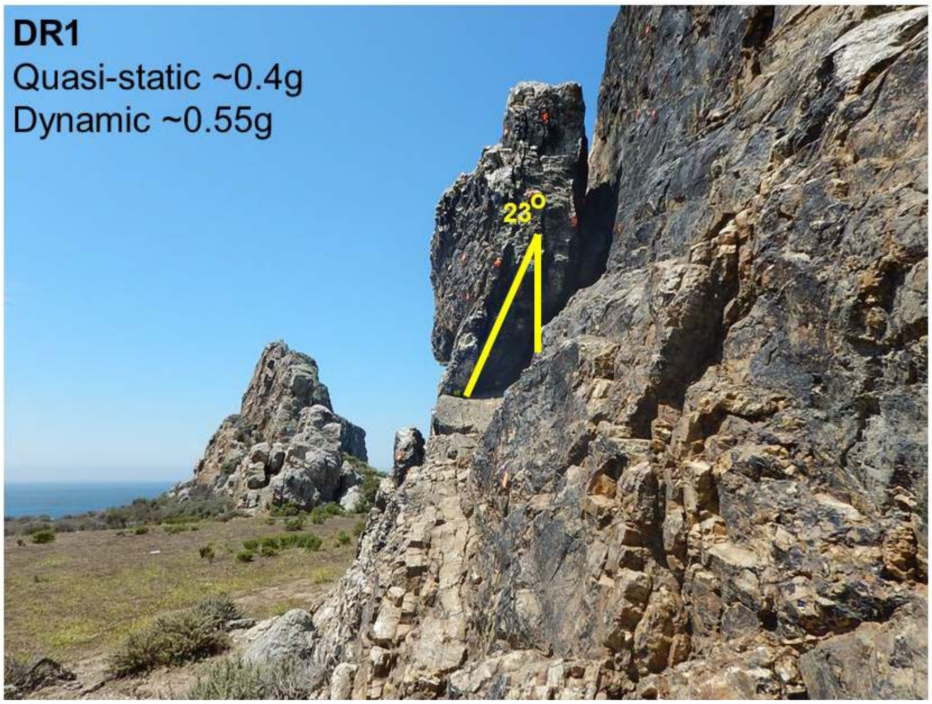

Fig. 3 - DR1 PBR, showing alpha angle (angle between the two yellow lines) on the eastern side of the PBR.

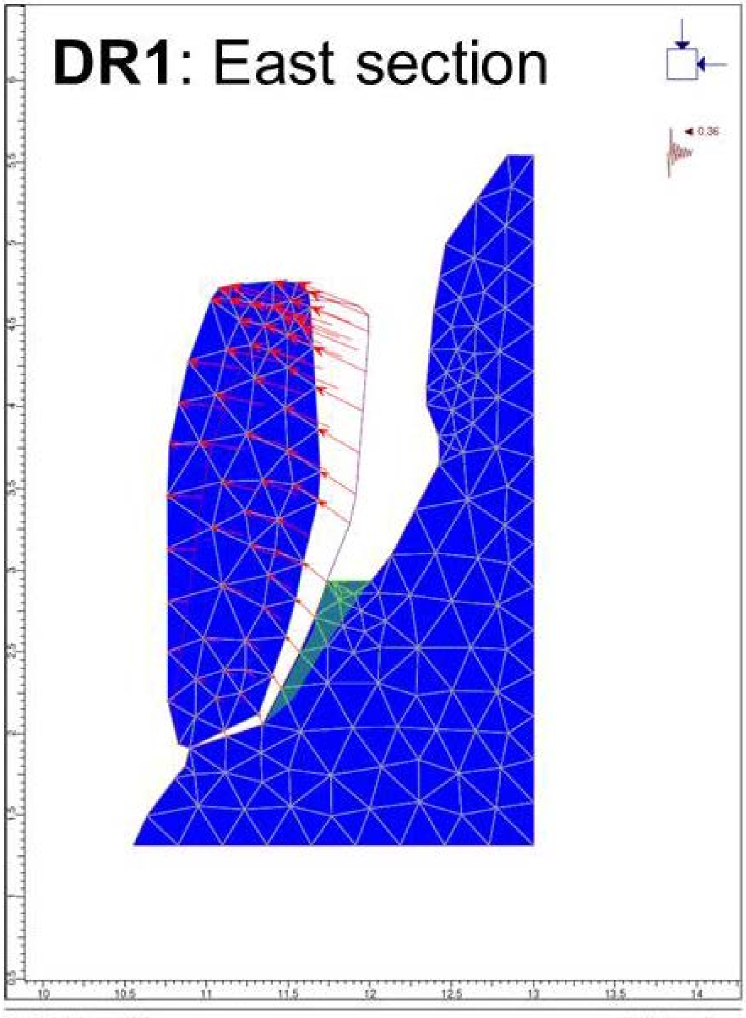

Fig. 4 - Easternmost cross section of DR1. Vertical and horizontal scales are labelled at 0.5 m intervals.

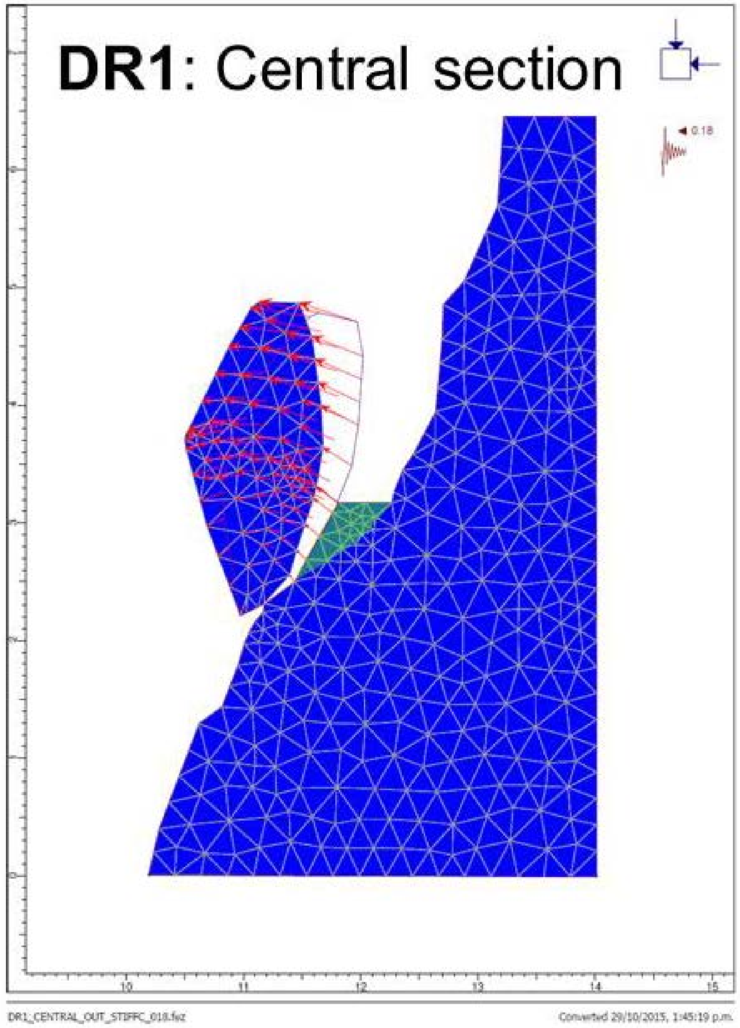

Fig. 5 - Middle cross section of DR1. Vertical and horizontal scales are labelled at 0.5 m intervals.

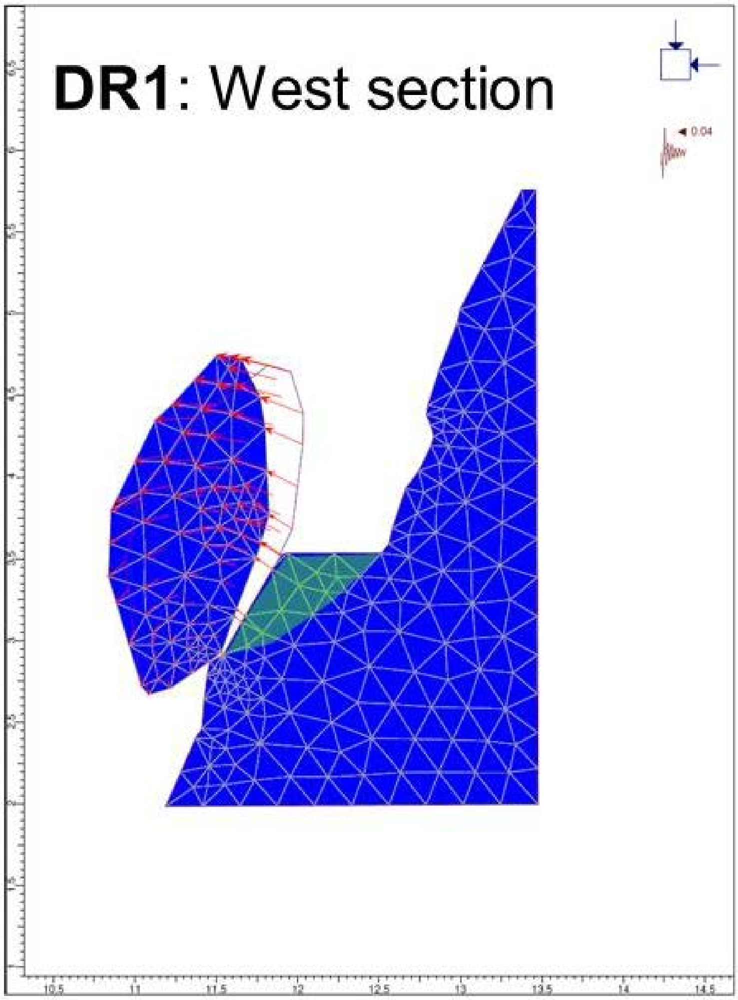

Fig. 6 - Westernmost cross section of DR1. Vertical and horizontal scales are labelled at 0.5 m intervals.

Fragilities derived from Rocscience Phase 2-based analysis of the three DR1 cross sections range from 0.04g (for the west section; Table 1) to 0.35g (for the east section). These are calculated by taking each cross section independently and estimating the threshold quasi-static PGA for failure. Since the PBR is strongly asymmetrical and sits irregularly on a sloping ledge, we do not consider the low fragility calculated for the westernmost cross section (Fig. 6) to be particularly representative of the entire PBR. In other words it is furthest removed from the centre of mass of the PBR. The central and eastern sections are closer to the centre of mass and more representative of the geometrical configuration. We therefore consider the range of fragilities derived from the central and eastern cross sections (0.17-0.35g; Figs. 4-5; Table 1) to be more representative of the stability of the PBR. Also, since the PBR has the largest dimensions at the eastern section, the fragility derived for that section (0.35g) is considered the most relevant for the PBR as a whole.

Table 1 - Fragilities (PGA in units of g) for the three PBRs DR1-3. "Field" denotes field-based fragility estimates (quasi-static increased by 30%), and "RS" denotes Rocscience Phase 2-based fragility estimates. The value for "RS West" is shown inside parentheses due to the questionable relevance of this fragility estimate.

PBR	Field	RS East	RS Central	RS West
DR1	0.3-0.55	0.35	0.17	(0.04)
DR2	0.3			
DR3	0.35			

3. Fragility – Hazard Comparisons

We show the PGA hazard curves developed for DCPP [6] in Fig. 7. The total hazard curve for the site is shown by the thick black line. Our fragility estimates for DR1-3 are in the range of approximately 0.2-0.4g (Table 1). These 0.2 and 0.4g PGA levels are shown by the vertical dotted lines. The intersection of the vertical dotted lines on the hazard curve and corresponding positions on the y-axis (horizontal dotted lines) give the annual frequency of exceedance for 0.2-0.4g according to the hazard curve. These correspond to annual frequencies of 0.0015-0.005, or return periods of approximately 200-670 years. This implies that the PGAs required to topple the PBRs will occur with relatively short return periods, especially considering the return periods of interest for the siting of critical facilities such as nuclear power plants (10,000 years or more).

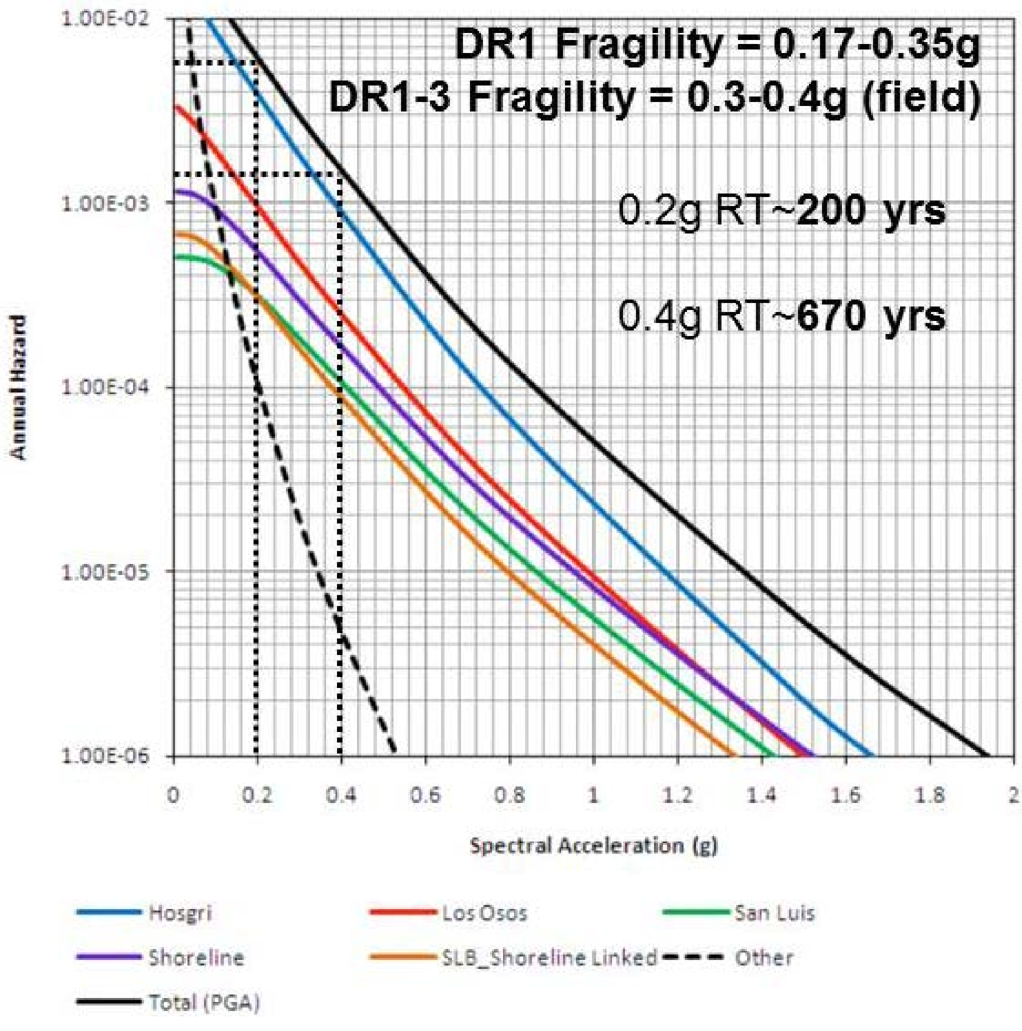

Fig. 7 - Hazard curves for DCPP ([6]; their Figure 6-20), showing PBR PGA fragility range is shown by the vertical dotted lines. See the text for further explanation.

A scenario (deterministic)-based comparison is shown in Fig. 8. The graph shows various response spectra for a Hosgri Fault scenario earthquake. The Hosgri Fault is a large earthquake source located at about 5 km offshore from the site, and is clearly the dominant source in the DCPP hazard model (hazard curve closest to the total hazard curve in Fig. 7). The spectra utilise a range of next generation attenuation (NGA) models, and the two groups of spectra represent 50th and 84th percentile spectra. The fragilities from DR1-3 are shown as crosses and circles on the left-hand-edge of the plot, where PGA is plotted on the spectra. The fragilities show a vertical spread of PGA that is controlled by the finite element stability analysis of DR1 at the lowest part of the range, and by the field-based fragilities at the highest part of the range. Collectively, the fragilities are consistent with the 50th percentile Hosgri Fault motions, and inconsistent with the 84th percentile motions. The implications are: (1) if Hosgri Fault earthquake motions have shaken the PBRs, then the motions have not exceeded the 50th percentile PGAs shown in Fig. 8 or the PBRs would have been shaken down, or; (2) that the PBRs are very young features and have not experienced any Hosgri Fault motions. Resolution of this issue is essential for determining whether the PBRs will be useful for constraining Hosgri Fault earthquake motions, but first requires the ages of the PBRs to be known. This is discussed in the next section. There is also the issue that the spectra-PBR comparisons do not consider the effect the topography has on the ground-motions experienced by the PBRs. As such, it is unclear whether the unadjusted NGA GMPEs are able to reliably predict the scenario ground motions at the PBR sites.

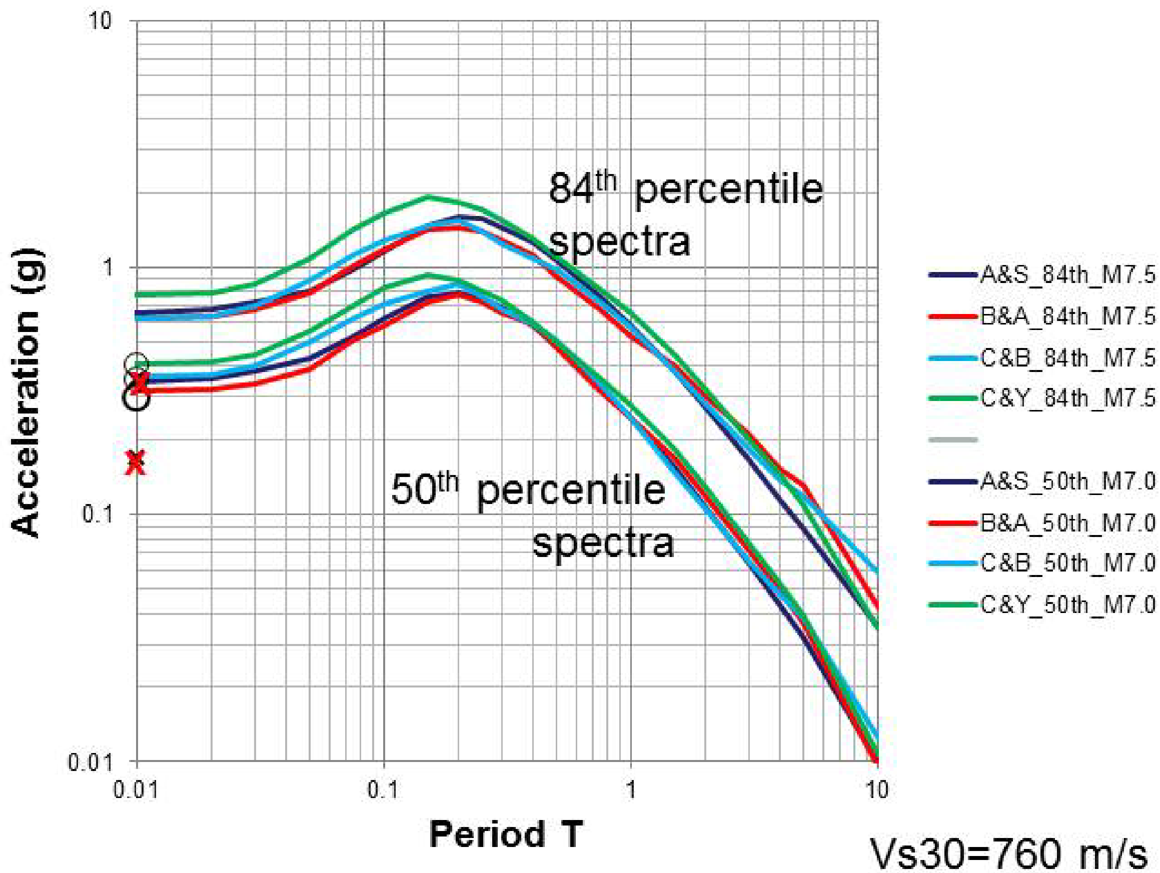

Fig. 8 - Scenario spectra for Hosgri Fault earthquake motions at the site, showing PBR fragilities as circles (field based) and crosses (Rocscience). NGA models used are as follows: A&S [7], B&A [8], C&B [9], and C&Y [10]. See the text for further explanation.

4. Likely Age of PBRs

While we do not have age control on the PBRs at Double Rock, we can make relevant observations of their morphology, and of the surrounding geomorphology. The PBRs are present as large slabby blocks balanced on narrow joint-controlled ledges. They appear to have been formed by slow exfoliation of the chert along the bedding planes and joints. The hardness of the lithologies, combined with the overall good preservation of the paleoseastack features (i.e. similar to a nearby actively eroding seastack; Fig. 2), and the general absence of boulder debris around the base of the paleoseastacks suggest that they have not been greatly modified since being uplifted from the sea. In short, the paleoseastacks still maintain near pristine seastack morphologies, despite being uplifted from the sea 80,000-120,000 years ago (Hanson et al., 1994). While there are some isolated rockfalls at the base of the Double Rock paleoseastacks (right side of the top left image in Fig. 2), the scarcity of them suggests that rockfalls are generally infrequent. Rockfalls may of course have been buried by more recent alluvial deposition across the area from local ephemeral streams, but the presence of an active gully of the order 10 m deep and only 20 m from the PBR site is more compatible with an erosional, rather than depositional environment. There is also the possibility that anthropogenic processes have resulted in removal of the boulders (farmers and Native Americans), but we are unaware of any information of this kind at the site. In short, the relatively minor amount of debris around the paleoseastacks and their relatively pristine seastack geomorphology is consistent with relatively minor modification over the last 80,000-120,000 years. If this is the case then the surfaces of the paleoseastacks and PBRs are likely to be of pre-historical age, possibly in the age range of 1000-10,000 years. 10,000 years is the end of Pleistocene cold climates, which is a time when rock weathering and erosion would have decreased significantly.

5. Conclusions and Future Work

The results of this study show that three of the approximately seven PBRs at the Double Rock site have PGA-based fragilities that are in the range of approximately 0.2-0.4g. These equate to the relatively short return periods of approximately 200-700 years on the DCPP hazard curve, and are consistent with 50th percentile PGAs for Hosgri Fault scenario earthquakes (large magnitude earthquakes at 5 km distance).

Follow up work will verify the fragilities determined by field and PGA based methods, and determine the fragility age of at least one of the PBRs to ascertain whether the PBRs are old enough to provide meaningful constraints on the DCPP hazard estimates. The PBR fragilities equate to short return periods on the DCPP PSH model (Fig. 7), so useful PBR-PSH comparisons will be possible if the PBRs are found to have ages of 1000 years or more. However, the more critical question is whether the PBRs are old enough to have experienced the last Hosgri Fault earthquake. Addressing this question will be critical for validating the level of aleatory variability in Hosgri Fault ground motion simulations at DCPP.

6. Acknowledgements

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7. References

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