Research and Development Program on Seismic Ground Motion

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Testing Site-Specific Hazard for the Diablo Canyon Power Plant Using Precarious Rocks

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Document history

DATE	VERSION	COMMENTS
2018/05/15	*1*	*Initial document*

Executive Summary

An initial application of hazard constraints from three precarious rocks near the Diablo Canyon Power Plant using the Baker et al (2013) methodology is shown. The three rocks have a similar age of being in a fragile state of about 17,000 years. Of the three rocks, rock DRW1 has the lowest fragility and provides the strongest constraint on the hazard. For a survival probability of at 1% or larger, DRW1 lies on the 25% fractile of the nonergodic hazard curves for the precarious rock sites, indicating that 75 percent of the weights for the end branches from the SSC and GMC logic tree are not consistent with the existance of DRW1. The other two rocks provide much weaker constraints: for a 1% survival probability, DRE falls near the 90th fractile and DW2 falls above the 99th fractile.

This initial application indicates that the precarious rocks have the potential to provide strong constraints on the seismic hazard at DCPP. Independent evaluations of the fragility curves and age dating are warrented. Nine additional candidate precarious rocks have been identified and initial data on the geometries and ages have been collected. If some of these additional rocks have estimated fragilties similar to DRW1, their ages and fragiltiies should be developed to provide additional constraints on the hazard at DCPP.

1. Introduction

Testing of hazard curves at a specific site requires a sufficiently long observation period. One way to get long observation periods is to use existence of fragile geologic features (FGS) to test the hazard. This requires developing fragility curves and ages for the FGS which can then be combined with the site-specific hazard curves to compute the probability that the FGS would not have failed during its lifetime.

As part of the DOE/PG&E extreme ground motion project (Hanks, 2013), Baker et al (2013) developed a methodology for testing site-specific hazard curves based on the existence of FGS at the site. Fragile geologic features near the Diablo Canyon Power Plant (DCPP) include precarious rocks. As part of the DCPP Long-Term Seismic Program (LTSP), data collection studies by Stirling and Rood in 2016 and 2017 were funded to characterize the fragilities and ages of precarious rocks near DCPP. This report describes the application of the Baker et al (2013) methodology to three precarious rocks near DCPP based on the fragility and age characterization given in Caklais (2017) and in Stirling et al (2017).

The Caklais (2017) master's thesis is given in appendix 1. It includes detailed descriptions of the precarious rocks, the cosmogenic age dating to determine the how long the rocks have been in their precarious geometry, the measure of the geometries of the rocks, and the development of fragility models for each rock. In this trial application, we used the fragility models and the ages of the precarious rocks given in Caklais (2017) with site-specific hazard curves for the precarious rocks. The Caklais (2017) report also includes comparisons with the hazard curves but they are not based on the updated hazard for the precarious rock sites and should not be used.

2. Precarious Rocks Near DCPP

The location of DCPP and the location of the three precarious rocks are shown in Figure 1. The precarious rocks are located about 5 km south of DCPP. The hazard at the precarious rock site shows that the same controlling sources contribute to the hazard at both DCPP and the rock site. Given the 5 km distance between the DCPP site and the precarious rock sites, the testing of the hazard will provide constraints on the local source model and on the ground motion model for the region. The spatial correlation lengths for the nonergodic source and path terms in the ground-motion models are about 15 km, so the rock site is close enough to DCPP to be useful for testing the source and path terms in the nonergodic GMPEs. The site terms have shorter correlation lengths, so the testing of the hazard at the rock sites will not provide constraints on the DCPP site terms.

The three precarious rocks evaluated by Caklais (2017) (called DRW1, DRW2, and DRE) are shown in Figure 2. The age of the rocks being in their precarious state was evaluated using cosmogenic age dating of the surfaces of the rocks and the base pedistal on which they stand. Caklais (2017) gives the ages as 17,000 to 62,000 years.

Caklais (2017) describes the evolution of the precarious rocks over the last 120,000 years. She assumes that the rocks have been in their current state since the the Holocene when the transition out of the last glacial period into a warmer, drier climate led to a reduction in the surface erosion rate. To avoid a time dependence of the fragility model, only the shorter age of 17,000 years is used for this trial application. Ongoing studies also show that the ages are more likely in the 20,000-year range.

To estimate the toppling probabilities (fragility) of the precarious rocks, a 3-D model was developed for each rock (Figure 3). Caklais (2017) shows two different fragility models: one based on PGA and SA(T=1) and one based on PGA and PGV/PGA. The fragility models given in Caklais (2017) have not yet been checked with independent estimates. There are some features in the PGA and SA(T=1) fragility model that are counter-intuitive (the probability of failure does not montonically increase with increasing PGA). The fragility model based on the PGA and PGV/PGA does not have this behavior. Therefore, for this trial application, only the fragility models based on PGA and the PGV/PGA ratio are used. The resulting fragility models are shown in Figure 4. Independent estimates of the fragilies are needed for QA of the Caklais (2017) fragility models.

3. Seismic Hazard at the Site of the Precarious Rocks

The seismic hazard was computed using the 2015 DCPP source characterization model for the five controlling sources (Hosgri fault, Shoreline fault, San Luis Bay Fault, Los Osos Fault, and the Irish Hills background zone. The 2015 ground-motion models were modified to include the nonergodic terms from Abrahamson et al (2018).

The precarious rocks on located on rock outcrops. Therefore, the site condition was assumed to VS30=1000 m/s. This site condition for the precarious rock sites should be verified by a site characterization study.

The PGA hazard for the precarious rock site is shown in Figure 5 and the deaggregation at a hazard level of 5E-5 is shown in Figure 6. This hazard level is similar to the inverse of the age of the precarious rocks.

In addition to the scalar hazard shown in Figure 5, a vector hazard was computed for PGA and PGV/PGA to facilitate the use of the two-parameter fragility curves. The mean vector hazard is shown in Figure 7.

4. Points in Hazard Space

Using the Baker et al (2013) approach, the probability of failure is computed using the mean vector hazard and the fragility curves. A scale factor for the mean hazard, called alpha, is found such that the probability of failure is either 1% or 5%. For example, for a 5% survival probability, the alpha value is given by

$$\alpha_{0.05} = \frac{1 - 0.05^{1/T}}{P_{\text{annual}}(G_{\text{fails}})}.$$

where Pannual(Gfails) is the annual probability of failure of the geologic feature G based on the mean hazard curve. The resulting values are listed in Table 1. The cumulative distribution of the PGA values leading to failure of each rock is shown in Figure 8. Following the Baker et al methodology, the constraint on the hazard is applied to the PGA corresponding the median from this CDF. These median PGA values are also listed in Table 1.

Table 1. PGA and alpha values for plotting the precarious rocks on the hazard curves

Rock	median PGA that leads to failure	Alpha for 1% probability of failure	Alpha for 5% probability of failure
DRW1	0.27g	0.50	0.32
DRW2	0.65g	6.1	4.0
DRE	0.47g	2.35	1.54

The three precarious rocks are compared to the fractiles of the PGA hazard in Figure 9. The DRW1 rock provides the strongest constraint on the hazard. Using the 1% failure point, the DRW1 rock falls along the 25th fractile, indicating that more than half of the weight of the end branches of the SSC and GMC logic trees are not consistent with DRW1. The other two rocks are more stable and provide only a weak constraint: DRE falls along the 90th fractile and DRW2 falls above the 99th fractile.

The next step is to identify which specific branches in the SSC and GMC logic trees lead to hazard curves that are inconsistent with DRW1. A program to compute the deaggregation on the inconsistent branches needs to be developed.

5. Additional Tasks Performed in 2017

A summary of the tasks, described in the Stirling et al (2017) memo, is given here.

1. Additional candidate precarious rocks

Nine additional precarious rocks were identified in the region. Initial photogrammetry and cosmogenic dating for a subset of these nine rocks was conducted (Rood et al, 2017). Figure 10 shows an example of one of the additional precarious rocks identified.

2. Testing of soils for age constraints

A sample of the soil on the uplifted marine terrace was collected to develop a soil chronosequence and for cosmogenic dating.

3. Testing of chert bedrock for age constraints

Samples of chert bedrock near the modern sea level to calibrate the cosmogenic ages for the precarious rocks and soil samples.

6. Conclusions

The preliminary application of the precarious rocks near DCPP shows that there is a potential for developing useful constraints on the hazard at DCPP. The main constraint is based on the single rock, DRW1. Showing results for additional rocks that also provide a strong constraint would greatly improve our confidence in modifying the weights on the logic tree based on the hazard testing feedback.

The following tasks should be considered for 2018:

1. Review the fragility and ages of DRW1, DRW2, and DRE

As part of the QA process, independently evaluate the fragilities and ages of the three precarious rocks studied in this report.

2. Estimate the fragilities for the nine additional precarious rock identified in 2017

Complete the 3-D modeling of the nine rocks and develop the fragility curves for these rocks. Identify the rocks with the lowest fragility curves (most precarious)

3. Estimate the ages for the best additional precarious rock identified in 2017

For the additional rocks with fragilities similar to DRW1, complete the age dating and estimate the age of the precarious rocks.

4. Site Characterization at the sites of the precarious rocks (DRW1, DRW2, and DRE)

To improve the hazard estimates, measure the VS profile for the marine terrace in the region of the three precarious rocks. Using the VS profile conduct a sire response analysis that can be included into the hazard curves for the precarious rocks.

5. Site Response at the sites of the precarious rocks (DRW1, DRW2, and DRE)

To improve the hazard estimates, install a seismic instrument on the marine terrace in the region of the three precarious rocks. Small earthquakes recorded at the site can be used to constrain the site-specific site term.

References

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Stirling, M., D. Rood, A. Caklais, and T. Gonzalez (2017). Overview of 2017 work on precarious rocks near DCPP, memo to PG&E.

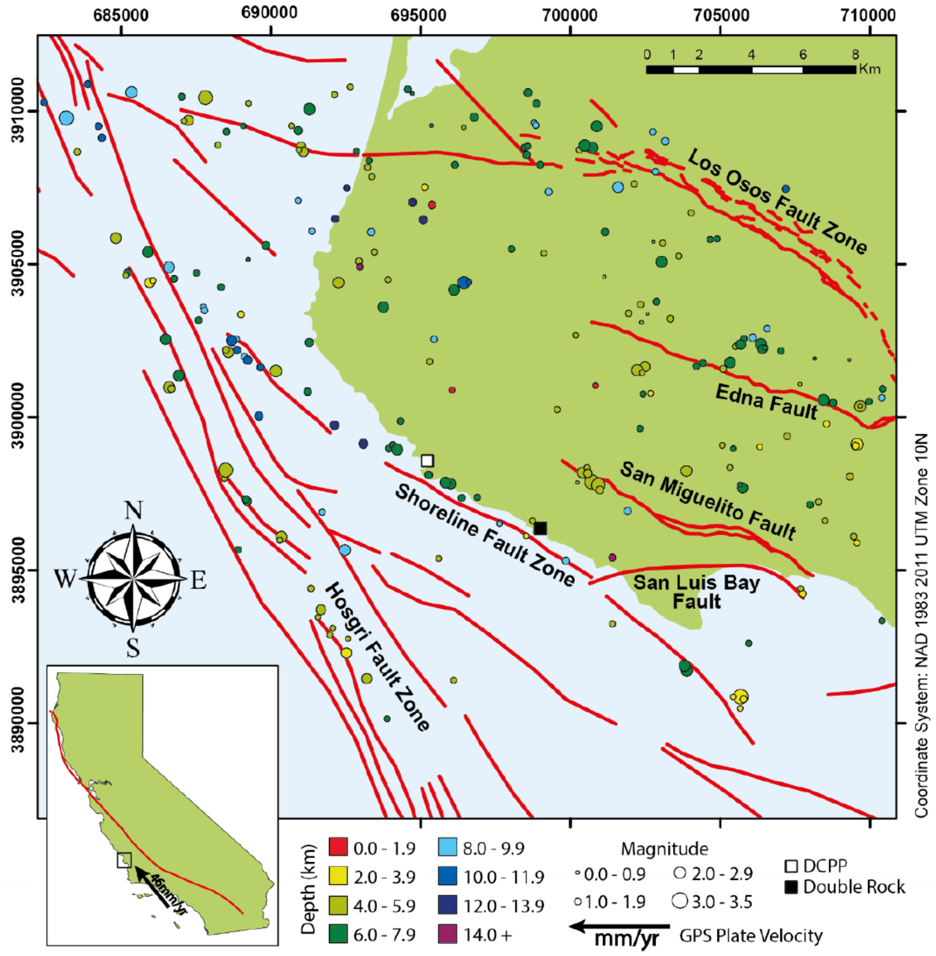

Figure 1. Location of DCPP (white square) and location of the precarious rocks (black square). From Caklais 2017.

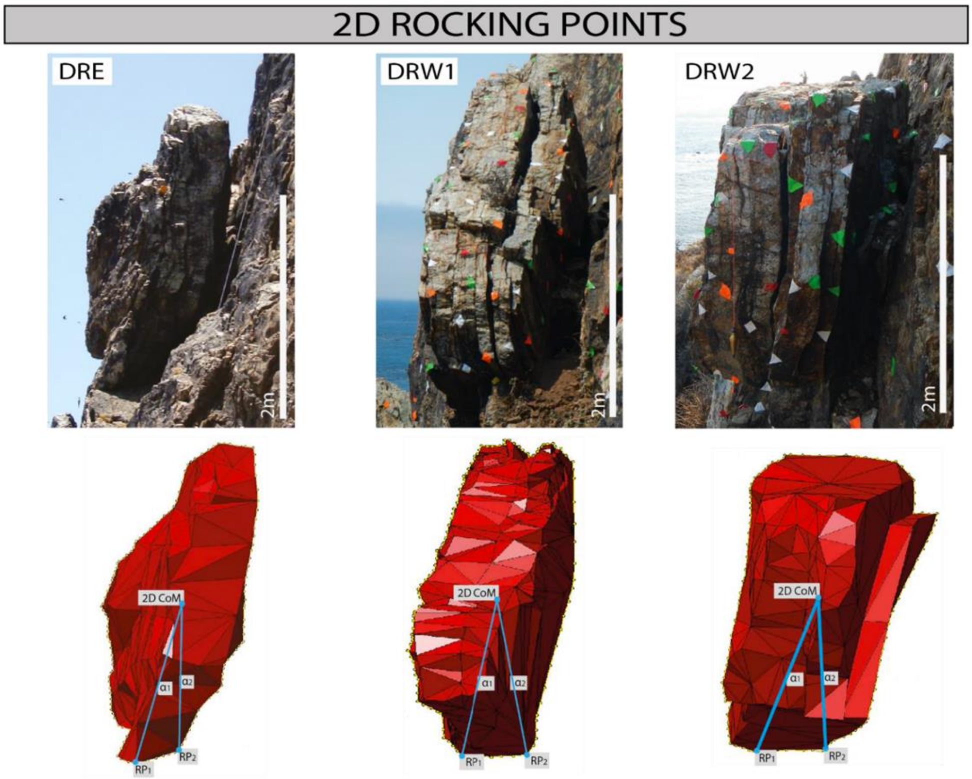

Figure 2. Precarious rocks used in this evaluation. From Caklais 2017.

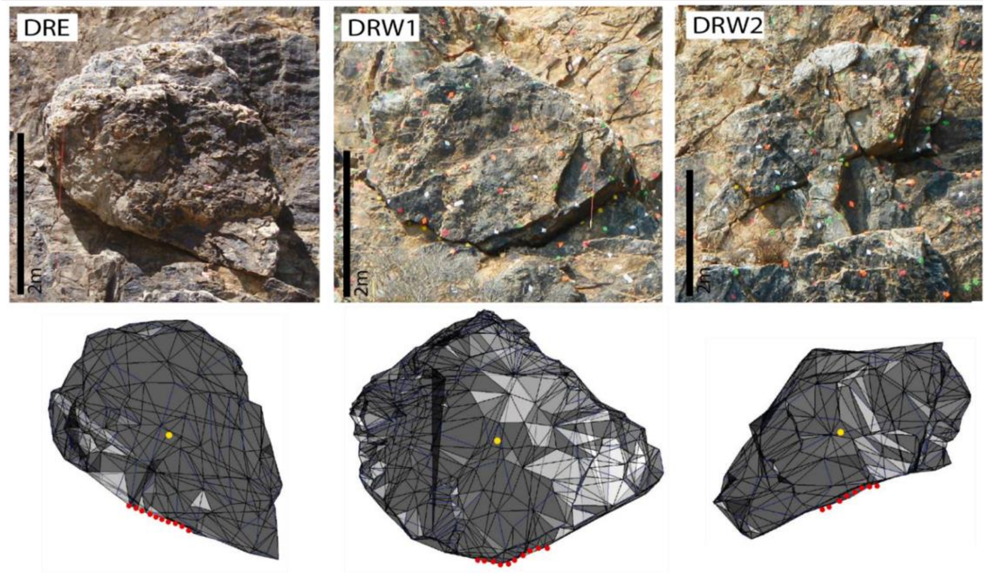

Figure 3. 3-D Geometries of the precarious rocks. From Caklais 2017.

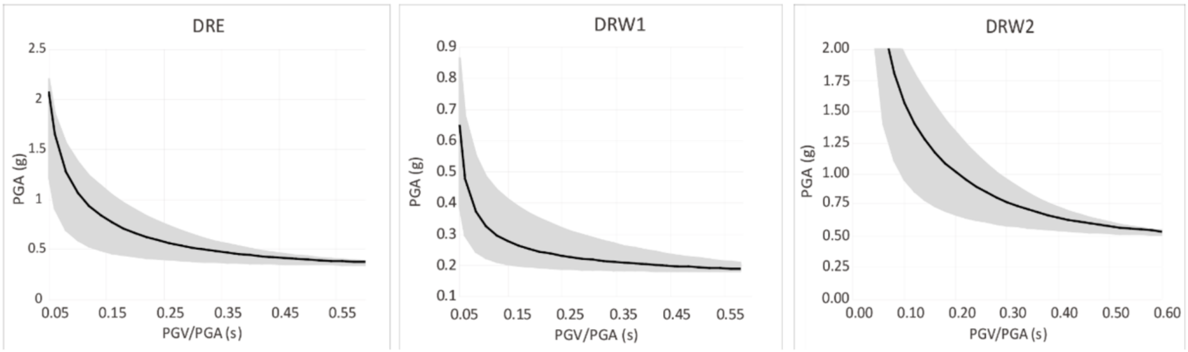

Figure 16: Overturning probability of each of the PBRs, calculated using equation of Purvance et al. 2008a. Grey shaded region shows the range of PGA vs. PGV/PGA in which there is a 5% to 95% probability of failure. The black line is at a 50% probability of overturning.

Figure 4. Fragilities for the three precarious rocks (From Caklais 2017).

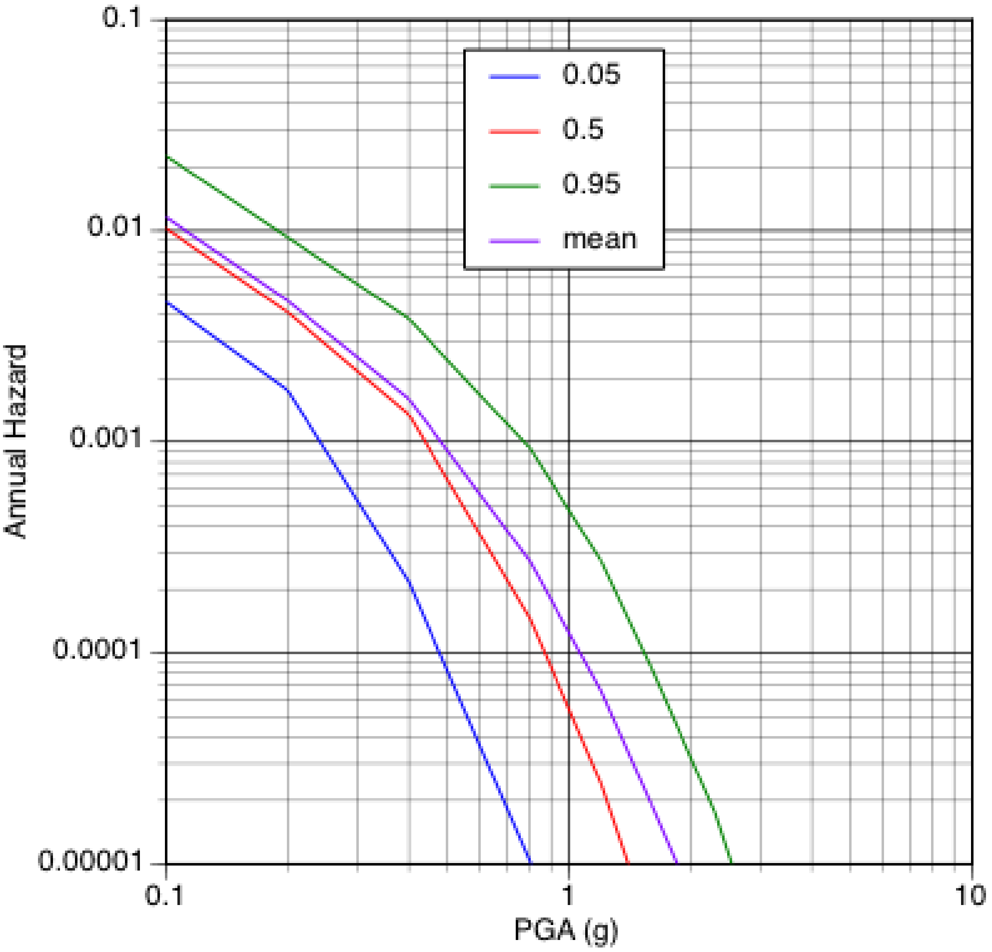

Figure 5. PGA hazard at the precarious rock sites.

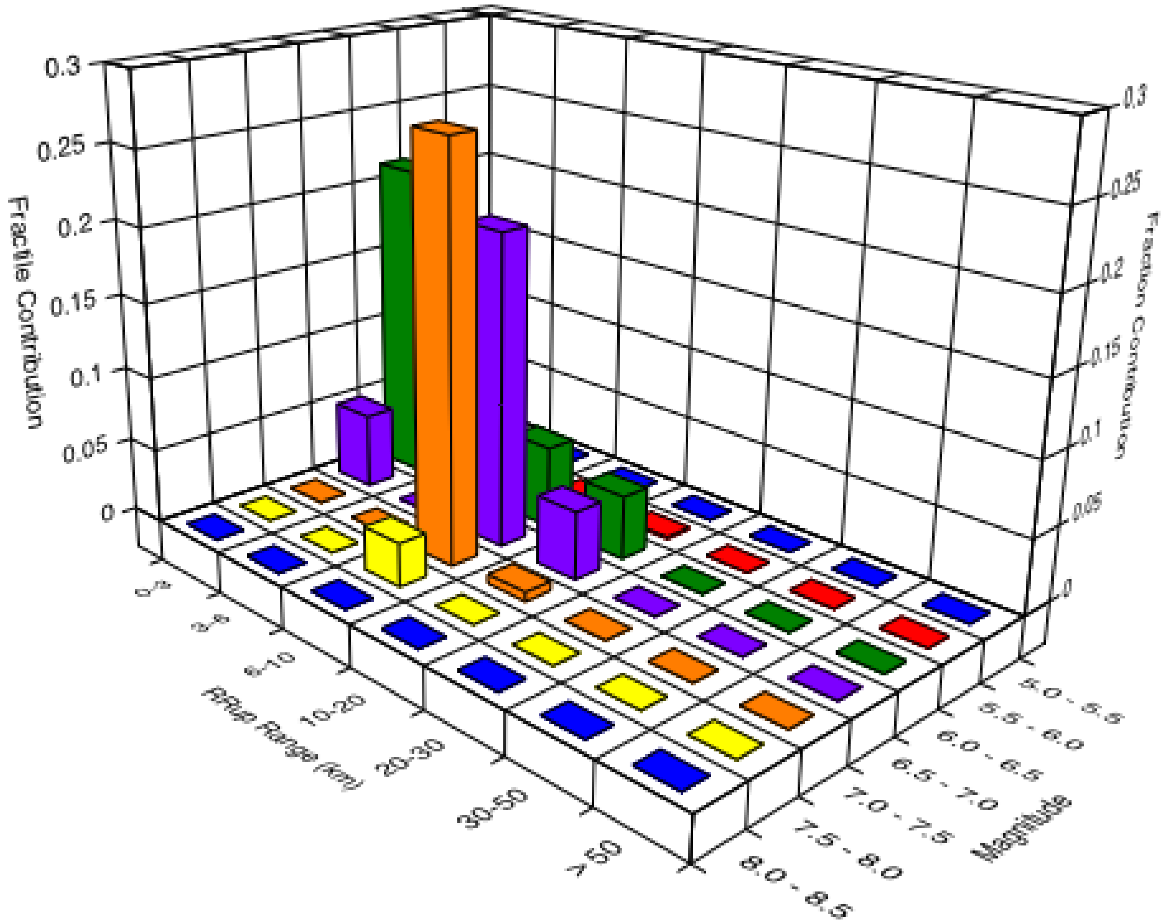

Figure 6. Deaggregation of PGA hazard for a hazard level of 5E-5.

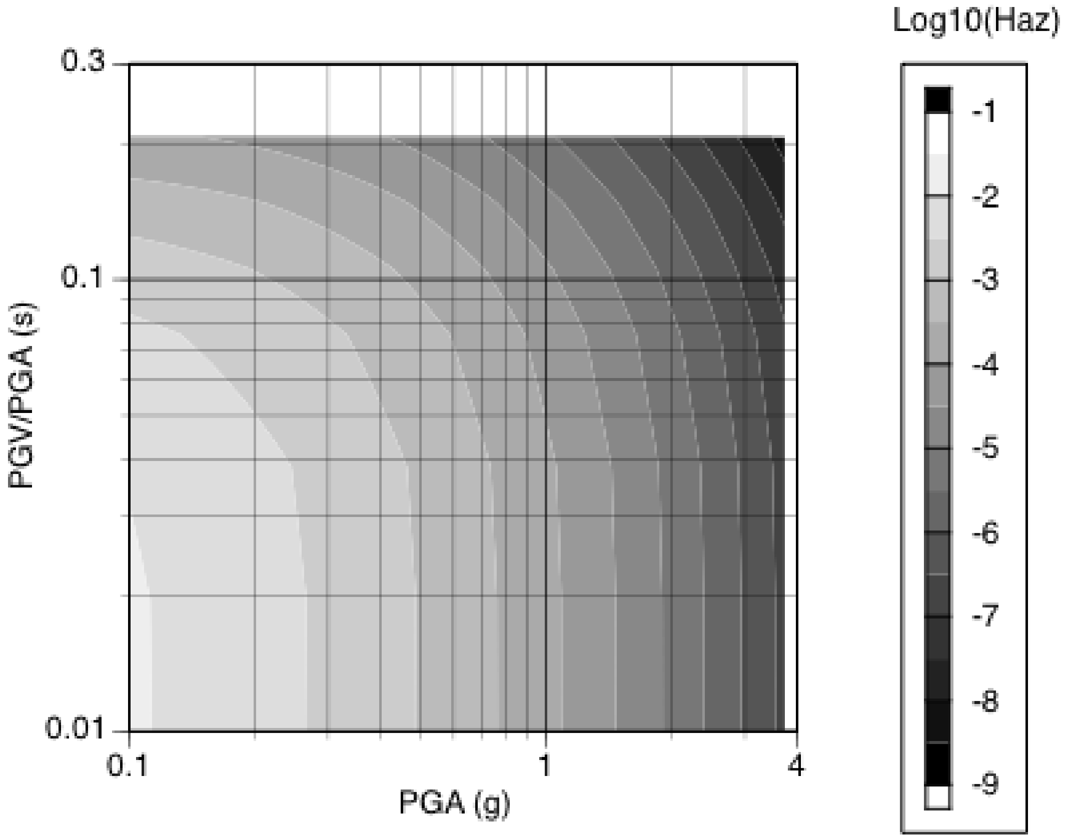

Figure 7. Vector hazard for PGA and PGV/PGA for the precarious rock sites.

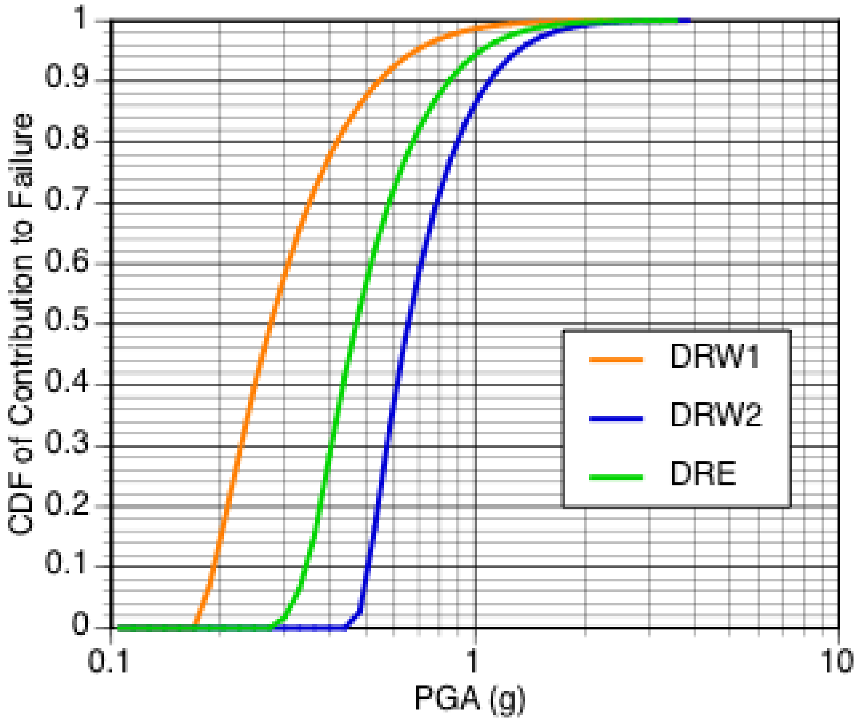

Figure 8. Cumulative distribution of the contribution to failure

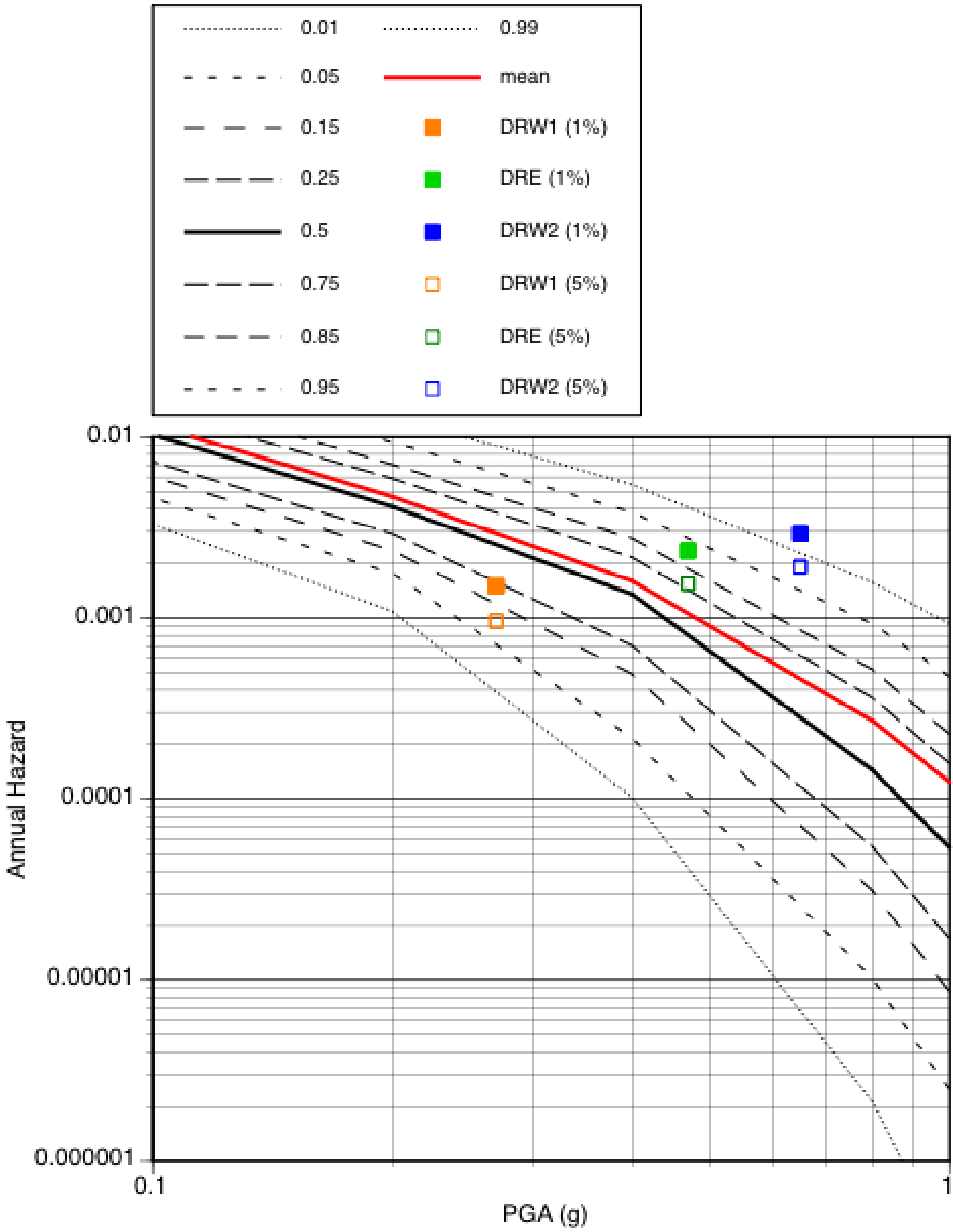

Figure 9. Comparison of constraints from the precarious rocks with the PGA hazard curves for the precarious rock sites.

Figure 10. Example of one of the nine additional precarious rocks identified in 2017. (From Stirling et al, 2017)

Peer Review of the D5-006/1 Document:

Testing hazard maps from precarious rocks analysis

By Paolo Bazzurro

SIGMA-2 Scientific Committee Member

June 5, 2018 Meeting, Paris

Background

On May 18, 2018 Dr. Durouchoux contacted me for the review of the following D5-006/1 document

1. Abrahamson, N., Kottke, A. and C. Madugo (2018). *Testing Site-Specific Hazard for the Diablo Canyon Power Plant Using Precarious Rocks*, May 16, 14pp.

This document was accompanied by the two additional documents listed below:

2. Baker, J.W., Abrahamson, N., Whitney, J.W., Board, M.P., and T. C. Hanks (2013). *Use of Fragile Geologic Structures as Indicators of Unexceeded Ground Motions and Direct Constraints on Probabilistic Seismic Hazard Analysis*, BSSA, Vol. 103, No. 3, pp. 1898-1911, June.
3. Caklais, A.H. (2017). *Earthquake hazard assessment of offshore coastal California: cosmogenic dating of precariously balanced rocks*, MSci Thesis, Imperial College of London, January

The approach followed in Document #1 was laid out in Document #2 with the support of data extracted from Document #3.

General comments.

Given the nature of the assignment, the review of D5-006/1 required a careful review of the 2013 paper listed at Document #2 (D#2) above and a review of selected parts of Document #3 (D#3). D#2 provides a methodology to constrain the results of Probabilistic Seismic Hazard Analysis (PSHA) based on the concept of Unexceeded Ground Motion (UGM) at the site where Fragile Geologic Structures (FGS) are located. Loosely speaking UGM is the level of ground motion that if observed during the lifetime of FGS would have most likely toppled it or destroyed it. The observation that the FGS is still intact at a given location is a "proof" that the UGM level has not been experienced by the FGS in the period, *T*, in which it is thought to have been fragile. If the PSHA results, however, predict that such UGM should have been observed with certainty during the period *T* then a clear inconsistency between observation and PSHA results exists. D#2 proposes a methodology to scale PSHA-based hazard curves in such a way that a pre-defined (and arbitrary) probability of survival in time *T* is ensured (e.g., 5%)

I found the procedure in D#2 clear and applicable also to regions outside California where FGS are identified. Document D#3 applies it very effectively to the region around the Diablo Canyon NPP in central California. This procedure can reveal inconsistencies between PSHA results for all branches of a logic tree or only for some. In any case, this approach can be used as a tool to modify the expert-based weights assigned to logic tree branches.

However, I have three main comments.

1. in areas such as France, where the seismicity is significantly lower than in California, it is unclear whether the UGM associated with existing FGS will provide a strong, useful constraint to the PSHA-based hazard curves for the ground motion intensity measures of interest. In the case of France I foresee that the methodology would be more likely to be useful if it were to be extended to include in a single test the survival of as many FGS as possible in the region of interest. Testing the consistency of the probability of joint survival of many FGS in a long period of time *T* with the results of PSHA would provide a much stronger test than the survival of any single FGS. For each earthquake considered in the PSHA, this modified methodology would require generating using a Monte Carlo (MC) Simulation approach several realizations of spatially correlated random fields of the ground motion Intensity Measures (IMs) used as input to the FGS fragility calculations (e.g., PGA and PGV). These random fields will be consistent with any selected branch of the PSHA study and if the simulation includes a sufficient number of random fields for any earthquake rupture, the hazard at any location computed using this MC simulation would be in complete agreement with the traditional PSHA results that are computed via numerical integration. However, the random fields would enable to compute the probability of survival of all the FGS without making untenable assumptions of independence between failures of different FGS in the same region caused by the same event.
2. The site characterization based on Vs30 is known to be deficient. It is very likely that including a site response analysis based on a geotechnical investigation into PSHA (e.g., using Bazzurro and Cornell (2004)[1]) may lead to more accurate hazard estimates. This methodology is an integral part of the procedure adopted by the U.S. Nuclear Regulatory Commission (USNRC) (e.g., see Section 6 and Appendix I in USNRC, 2001; and applications in USNRC, 2002) for developing hazard-consistent spectra on soil at nuclear facility sites:
    a) U.S. Nuclear Regulatory Commission (2001). "Technical basis for revision of regulatory guidance on design ground motions: hazard- and risk consistent ground motion spectra guidelines", Report NUREG/CR-6728.

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[1] Bazzurro, P., and C.A. Cornell (2004). ``Nonlinear Soil Site Effects in Probabilistic Seismic Hazard Analysis", *Bulletin of Seismological Society of America (B.S.S.A.)*, Vol. 94, No. 6, pp. 2110-2123, December.

    b) U.S. Nuclear Regulatory Commission (2002). “Technical basis for revision of regulatory guidance on design ground motions: development of hazard- and risk-consistent seismic spectra for two sites”, Report NUREG/CR-6769.

3. Finally, I question the applicability of GMPEs, that are derived mostly from accelerograms that are on flat, easily accessible locations for assessing hazard at sites where FGS are usually found. FGS tend to be at sites that are prone to topographic effects and such effects are only partially and implicitly included in the GMPEs used in PSHA studies. Being this outside of my area of expertise, I am not sure whether the existing topographic effects computation approaches are already mature enough to be included in the PSHA calculations. If they are, perhaps the project could consider including them in the PSHA calculations.

Conclusions and Recommendations

The methodology outlined in D#2 and applied in D#3 has potential to provide useful constraints to PSHA-based ground motion hazard estimates. However, the usefulness of this methodology when applied to areas of low and very low seismicity, such as France, remains to be seen. My recommendations are to consider:

1. including in the testing procedure the joint survival of multiple FGS rather than the survival of any single FGS
2. carrying out site characterizations beyond Vs30 and include them in the PSHA computations
3. studying whether the inclusion of topographic effects is warranted

Review of SIGMA2-2018-D5-006 “Testing Site-Specific Hazard for the Diablo Canyon Power Plant Using Precarious Rocks”

RMW Musson

INTRODUCTION

This document (Abrahamson et al. 2018) describes the initial stages of a project to apply hazard constraints from precarious rocks near the Diablo Canyon Power Plant (DCPP) using the Baker et al (2013) methodology. Three precarious rocks are identified so far near the DCPP site, of which one (DRW1) is estimated to have a survival chance of 50% if subjected to a PGA of 0.27 g, and the age of DRW1 is estimated at 17,000 years in its present state. Abrahamson et al. (2018) draws on the work of Caklais (2017) regarding the age and fragility of the three rocks.

Since I am not competent to comment on the age dating or mechanical analysis, I confine myself to some general issues.

TOPPLED ROCKS

Inevitably the question arises as to the existence of toppled precarious rocks, given that one cannot be completely deterministic about failure. Given a number of existing precarious rocks at some point in the past, one might expect a proportion to survive while others fail, and the observed rocks are therefore a small fraction of a larger population. According to Caklais (2017) this is ruled out by a study referenced as Brune and Brune (2007). This paper is not available to me, but another paper (Brune et al. 2006) is convincing in showing that this is not an issue.

GROUND MOTION COMPLEXITY

Abrahamson et al. (2018) states that “The spatial correlation lengths for the nonergodic source and path terms in the ground-motion models are about 15 km, so the rock site is close enough to DCPP to be useful for testing the source and path terms in the nonergodic GMPEs.” It would be useful to have a reference for this. I am inclined to be sceptical. One of the most under-rated aspects of ground motion is the effect of wave interference, which can produce large variations at very short distances. I have been trying unsuccessfully to trace a copy of a photo I saw some years ago taken after an earthquake in Turkey (it may have been the Bingol event in 2003) which showed a street of identical houses; every second house was demolished by the earthquake and the ones in between were undamaged. It seems that the spacing between nodes and antinodes was by chance equal to the distance between the houses. One can imagine the effect if a precarious rock was in the situation of an undamaged house; it would not tell you much about the ground motion a short distance away.

PROBABILITY OF FAILURE

I have a longstanding disagreement with some common practices in PSHA, exemplified by a statement in Caklais (2017): “it is customary to produce a family of hazard curves, in which there is a probability of n that the ‘true’ hazard curve lies below the nth curve”. But the values on a hazard curve are themselves probabilities. A probability of a probability makes no sense: it has to be collapsed. In my opinion, fractiles in a PSHA are simply internal workings of the hazard engine, used towards the calculation of the actual amplitude at the desired probability. Each end-member of a logic tree has no meaning on its own; it is not a possible value of the hazard, because that branch can never be "true". (For instance, there is no such thing as a "true" ground motion model.) The concept of a logic "tree" is misleading, and the preferable term "logic bush" has been suggested.

Given a model with its attendant uncertainties, "what is the probability of Y ground motion" has to have a unique answer, which is misleadingly referred to as the "mean". When hazard is modelled using simulations, the probability is a matter of observation similar to coin-tossing, and is not the mean of anything.

Therefore I would suggest that working from the mean hazard as in Table 1 of Abrahamson et al. (2018) is preferable to making comparisons to fractile curves as in Figure 9.

CONSTRAINTS ON PSHA

The cumulative weight of evidence concerning precarious rocks, and particularly papers like Brune et al. (2006) is getting to the state where, despite the cautions raised above, there can be little doubt that conventional PSHA, especially at very low probabilities (certainly below 10^{-4} per annum), is producing answers that are simply incompatible with field evidence. There can be little doubt, not just from the analysis of nearby rocks at DCPP but by analogy from experience elsewhere in California, that conventionally calculated hazard curves for sites in California tend to be inconsistent with the evidence from fragile geological structures. There is a danger, therefore, that the additional tasks listed in Abrahamson et al. (2018) will merely bang more nails into a coffin that is already nailed shut. There needs to be greater clarity about the ultimate aim of this project.

The Baker et al. (2013) methodology provides a way of providing constraints on PSHA to bring it in line with field evidence, but a crucial question is why these should ever be needed at all. This is all the more pressing because for many, or even most, parts of the world there are no handy precarious rocks or other from fragile geological structures to work with. Therefore there is a need to identify any basic problem, and fix it for general use. Brune et al. (2006) makes some suggestions, but I am doubtful that modelling background seismicity or smoothed seismicity could be responsible. My feeling is that the way aleatory variability of ground motion is treated in PSHA is the root of the problem, as in current attempts to change this (such as Atkinson 2006).

I have been exploring ways of testing PSHA results at least since 2001 (Musson et al. 2001, Musson 2004) and have found that computing hazard in terms of intensity generally produces results compatible with the observed history of felt effects, which suggests that the problem in PSHA only applies when the aleatory variability of ground motion is logarithmic (which is not the case for intensity) – but of course, comparisons with historical intensities can only be made for relatively short return periods.

The advantage of looking at precarious rocks is they provide a point of comparison for very long periods, and also they can be analysed in terms of physical ground measures, which is what is needed for engineering purposes. It would be interesting to see how the tests would work out using intensity rather than acceleration, but the fragility of a rock could not be modelled reliably in terms of any intensity scale.

Where I see particular potential in the further development of this project is in refinement of the alpha parameter representing the scaling of PSHA results needed to bring them down to a level consistent with the observed rock fragility. This could then be used to evaluate modifications to the PSHA model, or process to see if they bring about a reduction in line with the alpha value.

Abrahamson et al. (2018) suggest using the results to tune the weights on the logic tree, put possibly more drastic action is needed.

For instance, one could hypothesise (for the sake of argument) that lognormal variability is inappropriate for fault sources (but reasonable for background sources). One could suggest that, for a specific fault, a magnitude 7 earthquake will always result in a characteristic ground motion at a given distance, plus or minus a small amount (evidence from smaller events tends to support this). What is unknown, is what that characteristic ground motion actually is, but modelling this as an epistemic variable should be less onerous than allowing an unconstrained lognormal scatter. Also, it could be constrained from the precarious rock evidence. If one were to recalculate the hazard on this basis, and found that the natural reduction was in line with the alpha from the Baker et al. (2013) procedure, this would support the contention that the proposed modification brought the results into line with the geological data.

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SIGMA-2 Scientific Committee

2018, June 5th meeting

Document SIGMA-2 2019-D5-0006/1

Testing Site Specific Hazard for the Diablo Canyon Power Plant Using Precarious Rocks

Author: N. Abrahamson

Reviewer: P. Labbé

Rev. 0

Reviewed documents

Together with the here-above mentioned document, named A hereunder, the two following associated documents were considered for the review:

- B) Earthquake hazard assessment of offshore coastal California: cosmogenic dating of precariously balanced rocks, by Anna Hope Caklais, MSci Geology, Imperial College, London, Jan. 2017.
- C) Use of Fragile Geologic Structures as Indicators of Unexceeded Ground Motion and Direct Constraints on Probabilistic Seismic Hazard Analysis, by Jack W. Baker et al. BSSA, 103, pp 1898-1911, June 2013.

GENERAL

Purpose of the study

Document A is a short paper, the purpose of which is to describe the testing procedure of seismic hazard curves at Diablo Canyon Power Plant (DCPP) site against the fact that Precariously Balanced Rocks (PBR) are observed in the vicinity. The PBR site is located 5 km from DCPP, which is regarded as close enough compared to the 15 km correlation length of the hazard model. Three PBR are considered, aged between 17 000 and 62 000 years, described in details in Document B.

Methodology outlines

Key points in the proposed approach are a) PBR age estimate, b) PBR mechanical stability and c) evolution of stability in the past.

Geological consideration about age estimate, in particular regarding cosmogenic dating, are presented in B. They are far beyond the reviewer’s expertise.

According to the author, a feature of PBRs is that their stability is not controlled by acceleration only (PGA) but rather by a combination of PGA and PGA/PGV ratio. Questions on PBR toppling phenomenon are presented hereunder.

Regarding stability in the past, it is clear that a given PBR was more stable in the past than it is now because it is recognized that the current situation has been created by erosion. In this regard, Document B presents an assumption that the median value of the toppling PGV has evolved linearly with time (or by steps resulting in an average linear evolution with time). Likely this assumption may have a significant impact on the final conclusions. The reviewer suggests that this assumption is documented in the SIGMA-2 deliverable.

Main outputs

Using a method (Document C) that was developed for the Yucca Mountain site, a major result of Document A can be summarized as follows: Let's assume that "a hazard curve is regarded as consistent with a given PBR if the PBR surviving probability associated to this curve is at least 1%". With this criterion, an output of studies presented in A is that the majority of the branches of the PBR site logic tree for seismic hazard assessment are not consistent with one of the on-site existing PBRs. Quantified in other words, the mean hazard curve should be scaled by a factor 0.50 to be consistent with this PBR (the scaling factor becomes 0.32 with 5% in place of 1%).

A comment encountered about such approaches is that we observe only those PBR that have survived and ignore those that toppled in the past. Does the author propose a rationale to address such considerations?

FOCUS ON PBR TOPPLING PHENOMENON

Regarding the mechanical stability, the author of Document B introduces the slenderness as an indicator of PBR sensitivity to the level of input motion, expressed in acceleration (PGA or Sa(1Hz)). The reviewer is drawing the attention on the following well-known results: Regarding rigid block uplift, it is correct that the phenomenon is only controlled by slenderness and PGA. However, regarding rigid block toppling, it should be kept in mind that

- a) a well-established criterion was published by Ishiyama (1982), in terms of input motion velocity (PGV), validated against outputs of numerical simulations, with some exceptions;
- b) not only the slenderness plays a role in this criterion, but also the size of the block: Out of two blocks of the same slenderness, the larger one is the more stable. According to Ishiyama, for a given slenderness, the toppling PGV increases like the square root of the block height. For rectangular blocks, Ishiyama's formula reads (where v_0 is put for PGV and r is the half-diagonal of the block):

$$v_0 \simeq 0{\cdot}4 \sqrt{\left(\frac{8gr}{3}\cdot\frac{1-\cos\alpha}{\cos\alpha}\right)}$$

Comments about a):

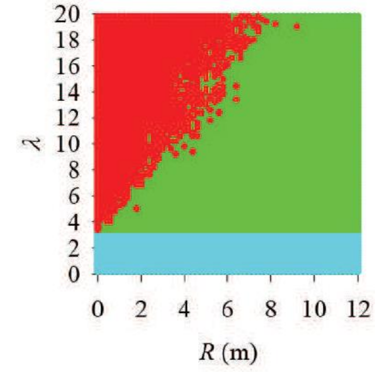
In Document C, PBR fragility curves are first presented in terms of PGV, which is consistent with the physics of the toppling phenomenon. Then it is mentioned that the toppling fragility is a function of both PGV and PGA (which implies that their joint probability should be known). This is an interesting point that could possibly bring some additional accuracy to the Ishiyama's formula. The reviewer would appreciate that the physics behind is made explicit in the SIGMA-2 deliverable.

In the Document A), as well as in B), the role played by the PGV appears incidentally, apparently as an output of the analysis of block responses to series of seismic input motion. The reviewer's opinion is that the rationale should be made more straightforward by enhancing the physics of toppling phenomena, and that consequently, the PGV should *a priori* be regarded as a pertaining parameter.

Comments about b)

The hereunder picture, one of the numerous presented by Roussis and Odysseos (2017), clearly illustrates that, for a given input motion, rigid block uplift is only controlled by slenderness, while toppling is controlled by slenderness and size. Therefore, it is surprising to the reviewer that the PBR size and its role is not mentioned in A or C, and only very incidentally in B[1]. Possibly it should be understood that a specific fragility surface is calculated for every PBR in the {PGA-PGV} domain, on the basis of refined 3D simulations of its seismic response to a series of input motions. In such case the size would be "hidden" in the fragility surface. However, it seems not to be the case according to Document B; it seems that only a 3D geometry simulation is carried out, in order to derive α and R.

The reviewer suggests that the role of the block size in toppling fragility is clearly addressed and discussed in the SIGMA-2 deliverable[2].



Response regime of rigid blocks in the λ-R (slenderness-size) domain under an input motion recorded at the occasion of the 1994 Northridge earthquake (Roussis & Odysseos, 2017)

Pierre Labbé

May 30th 2018

PS: Editorial comments are at the disposal of the author.

Y Ishiyama (1982); Motions of rigid bodies and criteria for overturning by earthquake excitations; *Earthquake Engineering & Structural Dynamics*, 10(5) :635–650.

P.C. Roussis and S. Odysseos (2017); Rocking Response of Seismically-Isolated Rigid Blocks Under Simple Acceleration Pulses and Earthquake Excitations[3]; *The Open Construction and Building Technology Journal*, *11*, 217-236; DOI: 10.2174/187483680171101

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[1] In a formula for the conversion of {PGV; PGA/PGV} pairs into {PGA; PGA/PGV} pairs, which incorporates a parameter "p" accounting for the moment of inertia of the block.

[2] Numerous tests were carried out on the CEA Azalée shaking table, which could possibly help.

[3] Although the title is on isolated blocks, non-isolated ones are also treated, as presented in the above picture.