REVIEW ROUND 1

Reviewer A:

Chen et al., develop a virtual shake robot to conduct physics engine shaking experiments to simulate the dynamics of precariously balanced rock (PBR) overturning and large displacement events. Such PBRs provide independent ground-motion constraints over the past thousands to tens of thousands of years, which can test seismic hazard estimates. Importantly, this present work develops the first tool to model both the ground motion intensity levels likely to result in PBR overturning and the associated trajectory of PBR after being overturned. Appropriate space is taken in the manuscript to describe the virtual shake robot system and validate the results against previous PBR toppling results using established methods. This manuscript will be used as an important independent verification of previous PBR fragility ideas and results, as well as a launch point of future directions in PBR research.

A lot is covered in this manuscript, which means that there was often not a clear separation between background, methods, results and what differed between a validation vs. experiment. In each section I felt that there was more to be investigated or considered beyond what was done in this manuscript, however, I appreciate that this manuscript was a first round of experiments in association with developing the virtual shake robot. Therefore, I take this as a sign of the future potential of applying the virtual shake robot to more detailed experiments now that the model set up has been documented here. I do, however, think that more clarification is required about the rational for selecting certain parameters as well as the extent to which the results in the manuscript are dependent on the parameters and set up of these first set of experiments.

I have read the manuscript and recommend minor revisions before publication. Please find my comments below.

Line 11: VSR is given as the acronym of virtual shake robot in the abstract, but this acronym is not used anywhere else in the manuscript. Whereas PBR is given as the acronym of precariously balanced rock in the abstract, and then this acronym is used throughout the manuscript. Please make consistent.

Line 39: The term boulder has a connotation of transport from its original location to its present one, i.e., Udden-Wentworth grain size classification of boulder. “blocks of rock” would be more appropriate, plus links the language to the blocks used in the experiments.

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Line 144 (+10): x is position in equation 3, correct? Please define. Also, please number the two equations separately to make it clear the updating to velocity and position, both here and elsewhere where two equations are provided for a single equation number.

Line 201: The thesis of Veeraraghavan 2015 should be referenced in the preceding section, as it provides a comparison between these methods.

Line 250: How simple a future work modification would it be to use a three-dimensional ground motion? As previous work (Veeraraghavan 2015) showed that 3-D PBR fragility results are more fragile than the 2-D fragility results for the same PBR. In the future, a virtual shake robot PBR fragility workflow that considers 3-D ground motions would be a huge advancement on the current 2-D fragility methods.

Line 286: What was the selection criteria for choosing DRE2 for this pilot study? Both in terms of the Double Rock site vs. a southern California PBR site (for example), and then also the selection of DRE2 from the seven PBRs studied there by Rood et al., 2020. For example, DRE1 is also included in the outcrop terrain model.

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Line 294: Please make it clear the DRE2 is not a granite PBR but is composed of chert. Please check that this is clear throughout.

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Line 304: What was the data source of the seismometer recording(s) used, and specifically what record(s) were used? These recordings should (ideally) be from magnitudes, fault mechanism, and distances appropriate for modeling the PBR rocking responses. It would be important to include the direction of ground motion expected from a Hosgri fault rupture to DRE2 and how this compares to the directions investigated. It's not clear to be yet how many seismometer recordings were investigated in this study, if multiple then also add a similar clarifying sentence that Figure 7 is applicable across a range of investigated PGA and PGV/PGA values.

Both figure 7a and 7b are for runs using the realistic terrain then? This should be clarified in the text and figure captions. Also, is it possible to make the red lines dashed, so that you can actually see that the blue line is underneath?

Line 310: Is the toppling/survival difference between the terrain/flat is it always observed over all input velocities?

Line 315: What was the rational for selecting W2 over the other blocks shown in Figure 4 of Purvance et al., 2008? For example, blocks W1 and W3 are the closest the 1.2 m steel beams in Figure 4 of Purvance et al., 2008.

The estimated dimensions of 5.5(H) x 1.1(W) x 1.1(D) cm give an alpha angle of 0.2 radians, however, Purvance et al., 2008 provide an alpha angle of 0.14 radians for block W2. Please provide the alpha and R of the virtual block used (to put the geometry in the context of PBR studies) and compare this to the Purvance et al., 2008 values, and discuss what this will mean for how the results are expected to differ.

Line 322: Relating to the point above, are the gray Purvance et al., 2008 lifted directly from that publication or calculated using the Puravnce et al., 2008 equations using the geometries estimated by the authors for W2. Please clarify.

Line 333: I would expect this threshold PGV/PGA value of 0.08 s to be specific to this geometry of block only – see Figure 6 in Purvance et al., 2008 where the different geometries have different shaped gray prediction intervals. I would be interested to know is this behavior of low vs. high PGV/PGA values being inconsistent vs. consistent with Purvance et al., 2008 is true across a range of block geometries, and what the distribution of threshold PGV/PGA values is.

Line 346: Typo, capitalized “we”.

Line 350: Please include the density of PETG and PLA, to compare to that of a granite.

Line 356: Please add a sentence here to describe to the reader what the results in Figure 9 are. The discussion later in the paper about the results is good, but the reader currently isn’t told what the results are, which is appropriate at this point.

Line 358: What is the reason for now making a different size and material 3-D printed model to do the fragility anisotropy validation? Please clarify why the same 12.8 cm 3-D model used in the first experiment could or would not be used in the second experiment.

I could see how it would be interesting to repeat the same experiment for a range of scales of 3-D printed models, to verify that the results are consistent regardless of the scale of PBR model used, but that’s not what was done here.

Line 360: See earlier comment to make sure these directions are related to the direction of ground motions of relevance to the Double Rock site.

Line 372: In sections 4.2 the block dimensions were presented with height as the first of the three values, which is not consistent with this section with here.

Line 387: Definitely “often” or “mostly” asymmetric – but not always.

Line 391: I think that it is worth making the point that in reality the orientation of the PBR is set, and what is effectively being modelled is the direction of the ground-motion coming from varying directions.

Line 417: I found that the large-displacement dynamics section came as a bit of an afterthought section after all the previous sections focused on the toppling dynamics of PBRs. This may well be because this is a less well-developed area of PBR research and so is less well presented.

I think that a clearer starting sentence connecting all the previous toppling sections to now the fall trajectories may help.

Line 430: I assume that when DRE2 gets caught up behind DRE1 in the white box in figure 14a that it lands in a stable orientation, i.e., that you wouldn't look at a DRE2 toppled to behind DRE1 and find DRE2 in a new fragile orientation. It would be interesting to get into the idea that ground motions can topple but also form PBRs and the virtual shake robot may be able to explore this. As well as allowing for some cascading event, where the falling DRE2 knocks over DRE1, and so observing DRE1 toppled would not be the result of a rocking and toppling failure.

Line 451: Make it clear that this value of 0.08 g is for one of the rectangular blocks studied by Purvance et al., 2008. Also, 0.08 g not 0.8 g, correct?

Line 495: Is Figure 16 surely not specific to the PBR geometry, surrounding outcrop geometry, and pedestal height of DRE2? The authors previously state that "PBR trajectories are affected by factors including PBR initial state, PBR physics properties, terrain morphology, and terrain physics properties." Please clarify this.

Please provide in the manuscript the height of DRE2 above the ground surface, as this will relate to its trajectory potential.

Recommendation: Revisions required.

Reviewer B:

This manuscript focuses on the use of Bullet physics engine and Gazebo toolkit to estimate the overturning response of PBRs to earthquake ground shaking. They also build a virtual robot that can simulate the response of objects under 1D ground shaking and replicate a similar set up using a mini-shake table. While the concept described here is interesting, the major concerns listed below regarding the accuracy of the algorithm need to be addressed before the manuscript can be published.

1. The authors claim that they can simulate large displacement rocking and sliding response of rocks with complex geometries using this Bullet physics engine. However, all the validation provided are from either cuboids or rocks that are nearly cuboidal (Fig.6) subjected to ground motion perpendicular to the edges of this cuboid/rock (yaw 0 and 270 deg). These are fairly simple scenarios with a well defined edge along which ground shaking occurs, essentially a 2D rocking problem. In lines 303-305, the authors have mentioned that there can be more complex overturning response such as twisting that is observed for complex shapes. The algorithm needs to be tested to see if it can model these complicated phenomena rather than rocking on a plane. For the 3D printed nearly cuboidal rock, ground shaking applied along the diagonal direction of these cuboids will initiate rocking on a corner. At least this type of 3D scenario needs to be considered for validation with a comparison of the 3D displacement vector of the rock at a point on the surface between the virtual robot and mini shaker experiment.

2. The contact surface plays a significant role in the overall reponse of the rock. Not much is mentioned about the resolution to which contact is characterized in this study. When using LIDAR or photogrammetry and when creating the PBR-pedestal model from these data, a lot of attention is given to capturing the rock-pedestal interface region. It is not clear if UAS can provide similar resolution near the contact interface. In lines 286-294, the authors briefly

describe how the PBR and terrain are modeled, but they say that they have added planes where they did not have data on the rock geometry and that this could add some uncertainity in the response. It is important to add more discussion on this aspect as the the fragility of the rock is very dependent on this contact interface as shown from the shake table tests conducted by Purvance et al. 2008.

3. The authors have presented analysis on the large-displacement dynamics of PBRs (i.e., rockfall trajectories). But they have not presented any validation of this aspect.

4. Why is the study restricted to ground shaking applied in one direction. In the 2-D studies presented by Purvance et al., they already identify a most fragile cross-section of the rock and apply ground motion along that direction. But given that a full 3D model is being constructed, the 3-component ground motion needs to be considered for more accurate results as the dominant ground motion only indicates the initial set of rocking points, after which the combination of different ground motion components will likely determine if the rock overturns and the direction in which the rock falls.

5. lines 125-126 - "Additional previous overturning simulations assumed flat pedestals". Both the works referred by the author have non-flat pedestals included in the simulation. Purvance et al. 2012 work contains multiple odd shaped rocks stack on top of each other resting on a pedestal that is created using a convex hull. The pedestal considered by Veeraraghavan et al. is created by fitting a surface to the point cloud obtained from the LIDAR data. In both studies, only the region within the initial contact area, which is the area on which the rock is resting on the pedestal at the start of the simulation, is assumed to be flat because (i) LIDAR or photogrammetry data cannot capture the region inside the initial contact area and (ii) only the outermost contact points determine when and where the rock will start rocking. While sliding may start at lower PGA if this enitre initial area is not in contact, this assumption leads a conservative estimate of ground motion required for sliding to start. Also, in most of these PBRs, rocking is the motion that is first initiated due to the rock being more slender, and while it is rocking on a single contact point or an edge, sliding could occur, which would be captured by the methods described in either of the previous works.

6. Section 2 - One of the issues with modeling the contacts as rigid (without using springs or other soft contact mechanics) is that there could be multiple solutions to the optimization problem that is described in lines 148-152. These multiple solutions can be triggered by simple things like changing the order of contact points. While all solutions satisfy the momentum conservation equations, they will result in completely different overall response of the rock. While this is usually okay for gaming type of applications, some more constraints maybe required to zero in on the correct solution from the infinite set of solutions. Part of this has been explored in Veeraraghavan et al. (ASCE JEM 2020). It is important for the authors to present if the optimization problem that is being solved by Bullet engine has a unique solution or whether the algorithm is picking the correct solution for this problem. Validation efforts for more complex rocking scenarios (as suggested in point 1) can likely provide more confidence on the accuracy of the algorithm on these aspects.

7. Line 152- What happens if the maximum number of iterations is met but the algorithm has not converged? Is that solution discarded and the optimization problem is solved using another set of initial guess?

8. In lines 317 - how were the values of friction and restitution chosen for this validation exercise? Do the results vary if these parameters are varied?

9. In section 4.3 - please add a image of the experimental setup.

Recommendation: Revisions required.

Response from authors:

Dear Professor Pablo Heresi,

On behalf of all the authors of the manuscript, I am writing in response to the review of our manuscript, titled "Virtual Shake Robot: Simulating Dynamics of Precariously Balanced Rocks for Overturning and Large-displacement Processes," which was submitted for consideration in Seismica. We would like to express our sincere gratitude to you and the reviewers for taking the time to evaluate our work and provide valuable feedback.

We greatly appreciate the thorough and constructive comments provided by the reviewers. Their insights have been instrumental in improving the quality of our manuscript. We have carefully considered each of their suggestions and have made the necessary revisions to address their concerns. In the following pages, we will provide a detailed response to the reviewers' comments and describe the changes we have made.

Once again, we would like to thank you and the reviewers for their time and effort in reviewing our manuscript. We believe that these revisions have significantly strengthened the manuscript and have addressed the concerns raised by the reviewers.

Sincerely,

Zhiang Chen

Reviewer A:

Review of '*Virtual Shake Robot: Simulating Dynamics of Precariously Balanced Rocks for Overturning and Large-displacement Processes'*

Chen et al., develop a virtual shake robot to conduct physics engine shaking experiments to simulate the dynamics of precariously balanced rock (PBR) overturning and large displacement events. Such PBRs provide independent ground-motion constraints over the past thousands to tens of thousands of years, which can test seismic hazard estimates. Importantly, this present work develops the first tool to model both the ground motion intensity levels likely to result in PBR overturning and the associated trajectory of PBR after being overturned. Appropriate space is taken in the manuscript to describe the virtual shake robot system and validate the results against previous PBR toppling results using established methods. This manuscript will be used as an important independent verification of previous PBR fragility ideas and results, as well as a launch point of future directions in PBR research.

A lot is covered in this manuscript, which means that there was often not a clear separation between background, methods, results and what differed between a validation vs. experiment. In each section I felt that there was more to be investigated or considered beyond what was done in this manuscript, however, I appreciate that this manuscript was a first round of experiments in association with developing the virtual shake robot. Therefore, I take this as a sign of the future potential of applying the virtual shake robot to more detailed experiments now that the model set up has been documented here. I do, however, think that more clarification is required about the rational for selecting certain parameters as well as the extent to which the results in the manuscript are dependent on the parameters and set up of these first set of experiments.

We are thankful for the reviewer's support of our initiative: This study introduced the first generation of technology that uses the Bullet physics engine and robotics to investigate PBR dynamics for ground motion analysis. We agree with the reviewer that more details and experiments need to be conducted in the future to fully assess the proposed technology. At the same time, we appreciate the reviewer's recognition of the potential of the virtual shake robot within this domain. Some suggestions by this reviewer and the other, while welcome, are beyond the scope of the first round of experiments presented here.

To enhance the clarity of the manuscript structure, we have implemented three key changes. First, we checked the topic sentences in each paragraph and refined some of them. Second, we improved the final paragraph in the introduction section. This paragraph describes an overview and organization of the remaining paper, aimed at improving the article structure clarity and building a clear separation between sections. Additionally, we conducted a thorough revision of the entire manuscript, eliminating redundant descriptions throughout the sections.

We have clarified the parameter selection in the manuscript. First, we have added more description about the differences between the physics engine parameters and DEM parameters in Section 2.2.

“The Bullet physics engine requires users to provide macro physics parameters, including restitution, Coulomb friction, and rolling friction coefficients (Chen, 2022)”. “Given the fact that the soft contact model in DEM is a hypothetical model, the user-defined parameters within this model lack direct connections to macro physics properties. These parameters can be calibrated through an iterative process of adjusting parameter values and matching experimental observations. In contrast, the parameters required in Bullet represent macrophysics properties and may be directly measured through experiments”.

Second, we explained that the parameter selections for the experiments in this study are based on materials and previous research. We have also added the corresponding references. E.g., “The two friction coefficients were selected based on dry rock friction (Byerlee, 1978), and the restitution coefficient of a wood block was measured from normal drop tests (Haron and Ismail, 2012)”. “These four cuboids had the same densities of 2,110 kg/m3 (chert density), 0.6 coefficient of Coulomb friction (dry rock friction), 0.6 coefficient of rolling friction (dry rock friction), and 0.38 coefficient of restitution (based on rockfall energy loss reported in Dorren, 2003)”

Third, we admit that parameter selection is challenging in any dynamics simulation, including both DEM and physics engines. However, as we have pointed out, the physics engine parameters have direct connections to macro physics properties. This is another advancement for utilizing the physics engine for the studies.

Fourth, Even though the parameters in the physics engines are more intuitive and correspond to macro physics properties, measuring accurate parameters still requires future work. Section 6.3: “Additionally, the values of physics parameters, such as friction and restitution coefficients, play a pivotal role in dynamics simulations within physics engines. Our experiments indicated that these parameters exhibit nonlinearity. For example, we found several thresholds for friction coefficients. Within these thresholds, the friction coefficient displays various nonlinear properties. Generally, a significantly high friction coefficient made PBRs more fragile compared to a very low coefficient. However, within certain threshold ranges, the influence of varying friction is less pronounced. To quantitatively measure this nonlinearity, we recognize the necessity for additional experiments in our future research endeavors.”

I have read the manuscript and recommend minor revisions before publication. Please find my comments below.

Line 11: VSR is given as the acronym of virtual shake robot in the abstract, but this acronym is not used anywhere else in the manuscript. Whereas PBR is given as the acronym of precariously balanced rock in the abstract, and then this acronym is used throughout the manuscript. Please make consistent.

Thank you for pointing this out. We have adapted VSR throughout the manuscript.

Line 39: The term boulder has a connotation of transport from its original location to its present one, i.e., Udden-Wentworth grain size classification of boulder. “blocks of rock” would be more appropriate, plus links the language to the blocks used in the experiments.

We agree that indeed these are blocks of rock; however we prefer to continue to write “boulder” to emphasize the application. The term "boulder" in geology typically refers to a relatively large rock or stone that is larger than a cobblestone and is generally considered to be greater than 10 inches (or 25.4 centimeters) in diameter according to the Udden-Wentworth grain size classification. While the term "boulder" itself does not inherently imply transport, in geological contexts, boulders can indeed be the result of transport processes. Boulders can be transported by various geological agents such as glaciers, rivers, or tectonic forces.

Line 44: For southern California, the PBRs studied by Rood et al., 2022 have ages of a few thousand to a few tens of thousands. This range covers the distribution of numerically dated PBRs globally.

Thank you for the comment. We have cited the work from Rood et al., 2022.

Line 51: I think it’s highly relevant to this study to make clear that the use of PBRs, particularly with the fragilities analyzed using the virtual shake robot, can be used not just to validated hazard curves (e.g., Rood et al., 2020) but also dynamic rupture models (e.g., Lozos et al., 2015) and other physics-based scenario simulations. As I could imagine, in the future, physics-based seismic estimates integrating physics-based PBR ground motions for toppling to validated the ground-motion results.

That's a great suggestion. In the introduction, we emphasized the application of PBR overturning and large displacement processes. While we agree with the review that VSR holds great potential in dynamic rupture models and other physics-based scenario simulations, including such information in the Introduction section might disrupt the flow for audiences. Therefore, we have incorporated this point in Section 6.3, Limitations and Future Work.

“Generally, physics engines hold promise in various physics-based scenario simulations, including dynamic rupture models (e.g., Lozos et al., 2015).”

Line 101: Please define h in equation 2.

We have updated the manuscript: “h is a function that maps an initial state to a trajectory”.

Line 127: A complex terrain, i.e., anything different from a flat pedestal, could in theory either make a PBR more or less fragile depending on the specific terrain surrounding a given PBR. It is true that the terrain surrounding DRE2 resulted in reducing its fragility, but this result should be made clear that it specifically relates to these experiments.

Good suggestion. We have added the following clarification. “Complex terrain—anything other than a flat pedestal—can either increase or decrease the fragility of a PBR, depending on the specific characteristics of the surrounding terrain and the contact.”

Line 144 (+10): x is position in equation 3, correct? Please define. Also, please number the two equations separately to make it clear the updating to velocity and position, both here and elsewhere where two equations are provided for a single equation number.

We have added the definition of x and separate equations throughout the manuscript wherever it is needed.

Line 201: The thesis of Veeraraghavan 2015 should be referenced in the preceding section, as it provides a comparison between these methods.

We agree that the rigid-body dynamics algorithm from Chapter 2 of Veeraraghavan's thesis (2015) is an important reference. This algorithm shares similarities with physics engines but also possesses nuanced differences. Categorizing this method as either a part of DEM or a physics engine would be inappropriate. Consequently, we provided a comprehensive introduction to this reference in the Introduction section, specifically when discussing the dynamics of PBR overturning. The relevant description is reproduced below:

“Veeraraghavan et al. (2017) presented an alternative method to analyze the 3D PBR overturning dynamics using a constraint-based model. The constraint-based model formatted a linear complementarity problem from contact constraints and solved contact impulses by an iterative numerical algorithm. From the contact impulses, contact forces were computed to update object velocity (Chapter 2 in Veeraraghavan, 2015). Their study \citep{veeraraghavan2017toppling} validated the constraint-based model in agreement with the physical shake table experiments from Purvance et al. (2008). The constraint-based model from Veeraraghavan et al. (2017) is similar to the collision response stage in physics engines. However, physics engines directly apply the contact impulse to change object velocity instead of computing intermediate contact forces (see Section 2.1).”

Line 250: How simple a future work modification would it be to use a three-dimensional ground motion? As previous work (Veeraraghavan 2015) showed that 3-D PBR fragility results are more fragile than the 2-D fragility results for the same PBR. In the future, a virtual shake robot PBR fragility workflow that considers 3-D ground motions would be a huge advancement on the current 2-D fragility methods.

It should be quite straightforward to extend the 1D motion of the VSR to 3D motion. We have included this idea in the future work section accordingly.

“The previous study by Veeraraghavan (2015) demonstrated that 3D PBR fragility results are more sensitive, indicating higher fragility, compared to their 2D counterparts. Looking ahead, the development of the VSR that incorporates 3D ground motions would represent a significant advancement beyond the existing 1D ground motion assessment methods.”

Line 286: What was the selection criteria for choosing DRE2 for this pilot study? Both in terms of the Double Rock site vs. a southern California PBR site (for example), and then also the selection of DRE2 from the seven PBRs studied there by Rood et al., 2020. For example, DRE1 is also included in the outcrop terrain model.

Thank you for raising this question. We selected the Double Rock site due to its proximity to PG&E's Diablo Canyon critical facility given the attention that site from other workers and the excellent access and interest of our coauthors. While we have not yet explored how our tool and scientific findings could be applied in hazard analysis, our study of Double Rock provides a foundation for future investigations in this area, which holds significant hazard implications. Additionally, Rood et al. (2020) have presented a detailed workflow for using PBRs at the Double Rock site in hazard analysis. It was a natural and straightforward decision for us to employ our VSR for the fragility analysis component there. In the future, we intend to follow their workflow to address the remaining aspects of hazard analysis. We understand that explicitly including such additional information in the manuscript could be helpful for readers. However, since the Double Rock site's proximity to a critical facility involves sensitive information with potential national security implications, we just provide the clarification in our response letter.

In our PBR selection process, we did not intend to specifically include or exclude any particular PBRs in this study. We have updated the clarification in the 'future work' section that we plan to investigate additional PBRs within the same study area.

Line 271: The mesh of PGA and PGV/PGA values is only investigated over for the cosine waves correct. But the seismometer recordings were not scaled to similarly consider a range of PGA and PGV/PGA? Or where multiple seismometer recording investigated that covered a PGA and PGV/PGA range? Please clarify.

For most of our experiments, we applied single-pulse cosine displacement ground motions. There are several reasons for this choice. First, such ground motions are easily synthesized, enabling us to comprehensively cover the parameter spaces of PGA and PGV/PGA. Second, while PGA and PGV/PGA are commonly used as representative ground motion descriptors in PBR studies, we have yet to fully understand whether they are the best descriptors. Recent concerns have emerged regarding their use in PBR studies. In cases where two seismometer data records share the same PGA and PGV/PGA values but differ in other properties, they may yield different PBR overturning responses. We wanted to avoid such ambiguity. We have added such clarification in the Discussion Section.

We conducted a few experiments using seismometer data. (1) We employed seismometer data to evaluate the performance of the PID controller. (2) We utilized the same seismometer data to assess DRE2, both with and without the surrounding terrains. The PBR was toppled on a flat surface, while it remained balanced with lateral support. The seismometer data had a PGA of 0.4 g and a PGV/PGA ratio of 1.2 s. Consequently, the overturning results align with the plots presented in Figure 12(b) and Figure 13(b). This point was also included in the manuscript in Section 6.1.

Line 294: Please make it clear the DRE2 is not a granite PBR but is composed of chert. Please check that this is clear throughout.

Thank you for correcting this. We have updated the manuscript.

Line 303: I assume that this close match between velocities shown in Figure 7 was seen at other PGA and PGV/PGA values, i.e., not only the quoted 0.2 g and 0.8 s? A final statement to this effect would strengthen this section.

Yes, we wanted to give examples to demonstrate the match between desired and actual velocities. The match is generally observed across other ground motions. We have added a final statement to avoid such ambiguity.

Line 304: What was the data source of the seismometer recording(s) used, and specifically what record(s) were used? These recording should (ideally) be from magnitudes, fault mechanism, and distances appropriate for modeling the PBR rocking responses. It would be important to include the direction of ground motion expected from a Hosgri fault rupture to DRE2 and how this compares to the directions investigated. It’s not clear to be yet how many seismometer recordings were investigated in this study, if multiple then also add a similar clarifying sentence that Figure 7 is applicable across a range of investigated PGA and PGV/PGA values.

Thank you for pointing this out. We have double checked our data source and found the realistic ground motion is from an accelerometer recording on a physical shake table. The physical shake table is a 7 ft x 7 ft platen. It has a stroke of +/- 5.5 inches in both horizontal directions. Capable of 0 - 30 Hz. The actuators are capable of up to 1 m/s velocity and up to 1 g acceleration. We have corrected this point in the manuscript.

Even though in this example we used a recording from an accelerometer, the VSR supports any realistic acceleration and velocity recordings.

Both figure 7a and 7b are for runs using the realistic terrain then? This should be clarified in the text and figure captions. Also, is it possible to make the red lines dashed, so that you can actually see that the blue line is underneath?

Figure 7a is from a single-pulse cosine displacement ground motion, and Figure 7b is from an accelerometer recording. We have updated the description of these two ground motions in the text (specifically in Section 4.1) and the figure caption accordingly. Using dashed lines is a good suggestion. Figure 7 is produced from a Robot Operating System tool RViz (http://wiki.ros.org/rviz), which enables real-time visualization of robot signals, including desired and actual velocities here. RViz does not provide the functionality to change line styles.

Line 310: Is the toppling/survival difference between the terrain/flat is it always observed over all input velocities?

We tested the DRE2 with and without the lateral support using the realistic ground motion that was generated from the accelerometer on a shake table. From this realistic ground motion, we found the PBR was toppled without the lateral support and still remained balanced with the lateral support.

We also examined the overturning responses with and without the lateral support using single-pulse cosine displacement ground motions. The results are shown in Figure 12 and Figure 13.

Line 315: What was the rational for selecting W2 over the other blocks shown in Figure 4 of Purvance et al., 2008? For example, blocks W1 and W3 are the closest the 1.2 m steel beams in Figure 4 of Purvance et al., 2008.

The direction dimensions (width, length, and height) of the blocks are not presented in Purvance et al. (2008). In the text of Purvance et al. (2008), they only described the metric dimensions, "*The blocks IB0, IB1, IB2, and IB4 consist of~1.2m tall steel I-beam sections with masses affixed to vary their geometries*". Table 1 in Purvance et al. (2008) only included the shape (alpha angles) but not the metric information of the blocks. Therefore, we were only able to estimate the metric dimension of their blocks using Figure 4, based on the description that the heights of IB0, IB1, IB2, and IB4 are 1.2 m. We clarified this in our manuscript,

"*Referencing the known height of a nearby steel I-beam section, we estimated the dimension of a wooden block (labeled W2) from Figure 4 in Purvance et al. (2008) as 5.5 × 1.1 × 1.1 cm*".

Specifically, what we did is to count the pixel numbers on IB4 and W2. Knowing that IB4 is 1.2 high, we use similarity to estimate the height of W2.

Blocks W1 and W3 are much smaller than 1.2 m, as shown in Figure 4 from Purvance et al. (2008). This figure is attached below. As IB0, IB1, IB2, and IB4 have a height of 1.2 m, W1 and W3 are much smaller in Figure 4, which indicates they are shorter than 1.2 m. We could also estimate the metric dimensions of W1 and W3 from Figure 4. However, because W1 and W3 are much smaller than W2 in Figure 4, estimating their metric dimensions is less accurate than the W2 dimension estimation.

Additionally, we want to use cuboids rather than I-beam. We have attached a photo of I-beam below, from which the reviewer can sense that I-beam is very different from a cuboid.

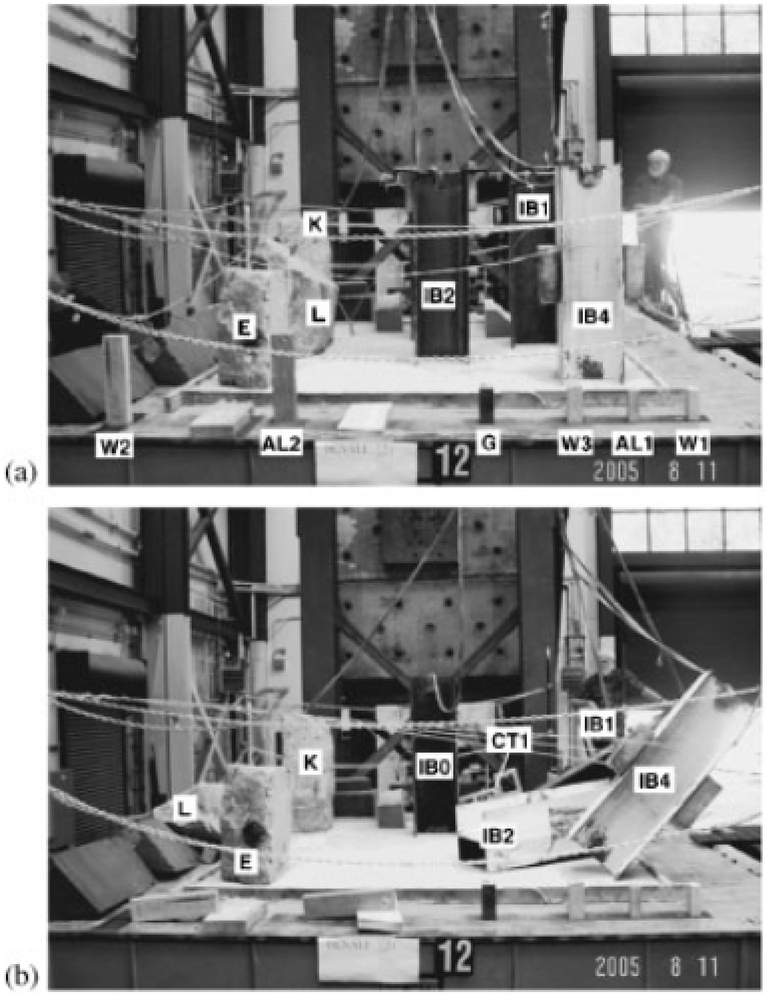


Figure 4. Typical shake table configuration (a) before and (b) after an experiment. A Kinemetrics K2 accelerometer has been installed on the surface of the shake table to record the achieved table motions.

Figure source: Purvance et al., 2008.

Figure: I-beam. Figure source: Google image

The estimated dimensions of 5.5(H) x 1.1(W) x 1.1(D) cm give an alpha angle of 0.2 radians, however, Purvance et al., 2008 provide an alpha angle of 0.14 radians for block W2. Please provide the alpha and R of the virtual block used (to put the geometry in the context of PBR studies) and compare this to the Purvance et al., 2008 values, and discuss what this will mean for how the results are expected to differ.

Thank you for bringing this up. We noticed the same issue before. When we counted the pixels on the height and width of W2 in Figure 4, we roughly estimated the height-width ratio of 5:1, which yields an alpha angle of 0.2 radians. This angle is different from the 0.14 value in Table 1 by Purvance et al. (2008). An alpha angle of 0.14 radians results in a height-width ratio of 7:1, which is different from what Figure 4 shows. We believe that the information from Figure 4 is more reliable and accurate than the text and table description.

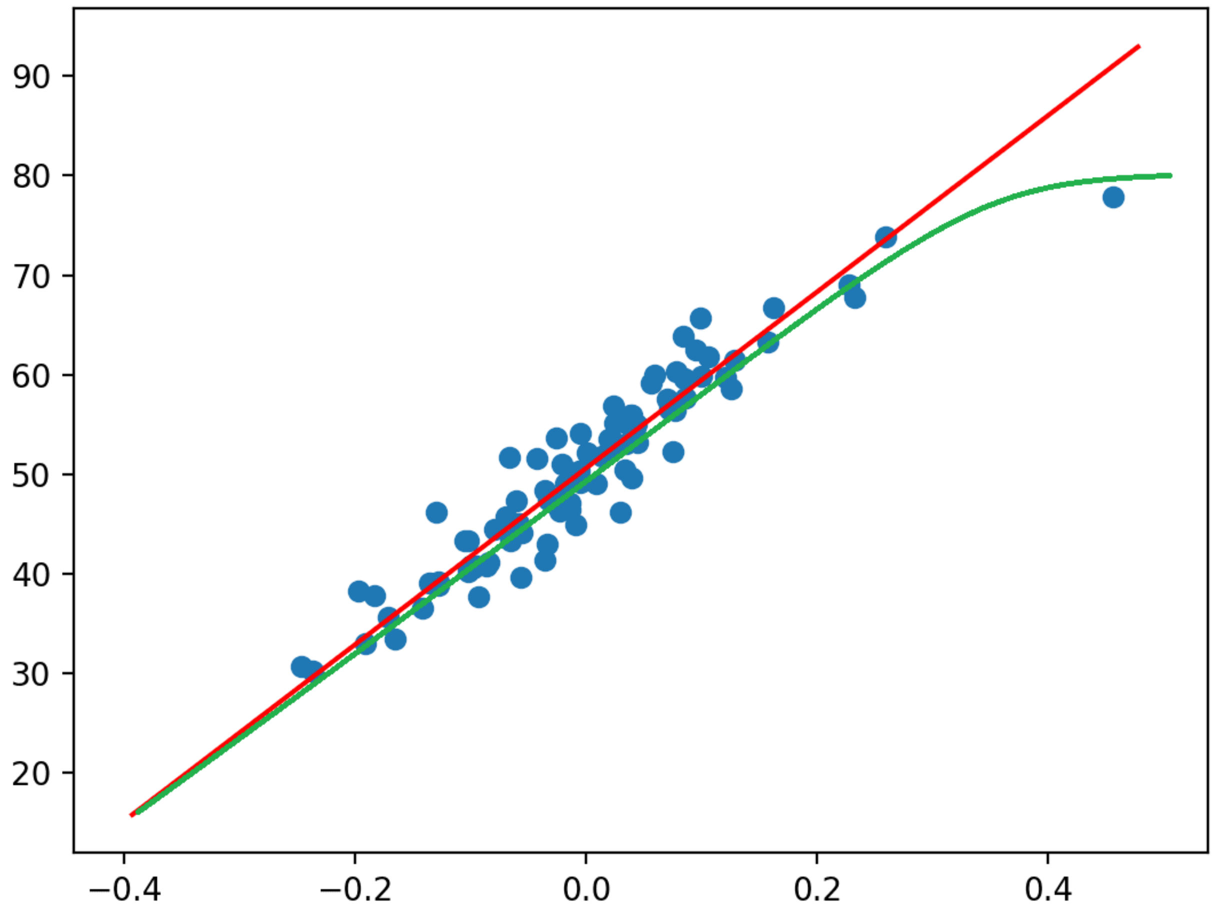
We agree with the review that discussing the details may help understand the difference between the VSR experiment and Purvance et al. (2008) experiments. However, because the dimensions in Figure 4 and Table 1 by Purvance et al. (2008) are inconsistent, highlighting such arguable detail may distract the readers. Again, we believe in the estimated dimensions from the figure. Even though the visual estimation might not be precise, the resulting uncertainties should be well-constrained. Additionally, our intention with this experiment was to demonstrate that the VSR experiment aligns with previous experiments within a certain range of ground motions. Measuring the specific thresholds that define this range requires careful calibration and comprehensive examination in the future, which is beyond the scope of this work.

Line 322: Relating to the point above, are the gray Purvance et al., 2008 lifted directly from that publication or calculated using the Purvance et al., 2008 equations using the geometries estimated by the authors for W2. Please clarify.

Yes for both. The gray-filled region and the squared dots are directly lifted from their publication. At the same time, the gray-filled region is calculated using Eq. (1) by Puravnce et al. (2008), where parameters are estimated from their experiments.

Line 333: I would expect this threshold PGV/PGA value of 0.08 s to be specific to this geometry of block only – see Figure 6 in Purvance et al., 2008 where the different geometries have different shaped gray prediction intervals. I would be interested to know is this behavior of low vs. high PGV/PGA values being inconsistent vs. consistent with Purvance et al., 2008 is true across a range of block geometries, and what the distribution of threshold PGV/PGA values is.

We agree with the comment. Objects with different geometry result in different gray-filled regions (95% prediction intervals), therefore the threshold should also be different. In the case of W2, we suspect that the gray-filled region for small PGV/PGA (e.g., the area smaller than 0.08 s) is underestimated because Purvance et al. (2008) included only one experiment data for small PGV/PGA, as shown in our Figure 8 and Purvance et al. 2008's Figure 6(b). In regression methods, it is quite common that the estimated objective functions (e.g., Eq. 1 in Purvance et al. 2008) take a data point as an outlier when there is only one data point in the near region. For example, as shown in the following figure, a regression method may mistake the single point at the top right as an outliner and estimate a straight line (red line) as the final objective function. However, a more accurate model (green line) should consider all data points. Because Purvance et al. (2008) included only one data point for small PGV/PGA, we are unsure if their model had the same issue. We are sure that our estimation does not have the same issue because our results are produced from a large number of experiments with dense ground motion settings, where experiments are so dense that an outlier does not exist.



Line 346: Typo, capitalized “we”.

We have corrected the typo.

Line 350: Please include the density of PETG and PLA, to compare to that of a granite.

We have added the densities of PETG (1240 kg/m^3) and PLA (1250 kg/m^3) in the manuscript.

Line 356: Please add a sentence here to describe to the reader what the results in Figure 9 are. The discussion later in the paper about the results is good, but the reader currently isn’t told what the results are, which is appropriate at this point.

Thank you for the suggestion. We have added the following sentence,

“Despite the observation that the real PETG PBR is more fragile, the boundary curves from the simulation and physical experiments were close”.

Line 358: What is the reason for now making a different size and material 3-D printed model to do the fragility anisotropy validation? Please clarify why the same 12.8 cm 3-D model used in the first experiment could or would not be used in the second experiment.

We printed a new PBR to avoid potential wear problems during the overturning experiments. We didn't intend to use different materials or design different dimensions. We had two 3D printers, one with PETG and the other with PLA. The dimensions were constrained by the 3D printer workspace and the available amount of printing materials.

I could see how it would be interesting to repeat the same experiment for a range of scales of 3-D printed models, to verify that the results are consistent regardless of the scale of PBR model used, but that's not what was done here.

That's a good idea. We have added this idea in the future work.

"To verify the consistency of the overturning results regardless of the PBR scale, future work should repeat the same experiment with 3D printed models at various scales".

Line 360: See earlier comment to make sure these directions are related to the direction of ground motions of relevance to the Double Rock site.

We tested the 3D-printed PBR using the single-pulse cosine displacement ground motions. We randomly picked two directions to demonstrate fragility anisotropy.

Line 372: In sections 4.2 the block dimensions were presented with height as the first of the three values, which is not consistent with this section with here.

We have clarified the purposes of the experiments in their topic sentences. In Section 4.2, the purpose is to "validate the overturning dynamics by comparing the shake experiments from the virtual shake robot and Purvance et al. (2008)". In Section 5.1, as stated in the topic sentence, "because rectangles were typically studied in the previous overturning studies (Milne and Omori, 1893; Kirkpatrick, 1927; Housner, 1963; Yim et al., 1980; Purvance et al., 200), we examined the overturning dynamics of cuboids on a flat pedestal using the VSR".

In summary, the validation experiments and the overturning experiments are designed for different purposes. That is, the overturning experiments in Section 5.1 were not conducted for validation. Therefore, their dimensions do have to be consistent with the dimensions in Section 4.2.

Line 387: Definitely "often" or "mostly" asymmetric – but not always.

We agree with this comment and have added "often".

Line 391: I think that it is worth making the point that in reality the orientation of the PBR is set, and what is effectively being modelled is the direction of the ground-motion coming from varying directions.

Thank you for pointing this out. We have added the following description.

"The orientation of PBR was defined in Fig. 12a. By placing the PBR with different orientations, we simulated the varying ground motion directions".

Line 417: I found that the large-displacement dynamics section came as a bit of an afterthought section after all the previous sections focused on the toppling dynamics of PBRs. This may well be because this is a less well-developed area of PBR research and so is less well presented.

I think that a clearer starting sentence connecting all the previous toppling sections to now the fall trajectories may help.

We believe that both the large displacement and overturning processes are equally important, as they were equally introduced in the Introduction section. However, we agree that the large displacement process is less well-developed and presents greater challenges for simulation validation. We were unable to conduct the same amount of work for the large displacement as we did for the overturning process. Consequently, the large displacement section may look like an afterthought section in the manuscript, but we want to emphasize its significance. We have also clarified this point throughout the manuscript:

“The overturning and large displacement processes of PBRs provide complementary methods of ground motion estimation. ”

“When the overturning dynamics provide upper-bound ground motion constraints by studying fragile PBRs, the large displacement dynamics provide lower-bound ground motion constraints by studying overturned PBRs.”

“Together, the overturning and large displacement dynamics form complementary methods to refine ground motion estimation. ”

Line 430: I assume that when DRE2 gets caught up behind DRE1 in the white box in figure 14a that it lands in a stable orientation, i.e., that you wouldn’t look at a DRE2 toppled to behind DRE1 and find DRE2 in a new fragile orientation. It would be interesting to get into the idea that ground motions can topple but also form PBRs and the virtual shake robot may be able to explore this. As well as allowing for some cascading event, where the falling DRE2 knocks over DRE1, and so observing DRE1 toppled would not be the result of a rocking and toppling failure.

That’s an interesting idea. This is another reason that we highlight the integration of VSR with robotic PBR mapping, which enables us to study PBR distributions instead of certain specific PBRs. The motivation for studying PBR distributions is that studying only certain PBRs may have a sampling bias issue. For example, in this case when DRE2 gets caught up in the white box and forms a new PBR, people may still assume the ground motion is small based on its new fragility status. However, the ground motion is large enough to topple the original PBR status. So looking at the PBR distributions is very important to remove such sampling bias. We have added one point in the manuscript,

“Using the VSR, we can also simulate a large number of PBRs with various shapes and dimensions to study the effects of ground motions on PBR distributions”. We try to keep our descriptions concise. First, we are mindful of the information we want to convey. At the same time, we don’t want to include too much information to distract the readers.

Line 451: Make it clear that this value of 0.08 g is for one of the rectangular blocks studied by Purvance et al., 2008. Also, 0.08 g not 0.8 g, correct?

Thank you for correcting this. We have checked and updated the manuscript accordingly.

Line 495: Is Figure 16 surely not specific to the PBR geometry, surrounding outcrop geometry, and pedestal height of DRE2? The authors previously state that “PBR trajectories are affected by factors including PBR initial state, PBR physics properties, terrain morphology, and terrain physics properties.” Please clarify this.

As explained in the Introduction section when introducing Eq. (2), “PBR trajectories are affected by factors including PBR initial state, PBR physics properties, terrain morphology, and terrain physics properties. Given the same configurations for all the other factors, a PBR trajectory is distinguished from its initial state”. In Figure 16, we have fixed all the factors, such as PBR physics properties (including its geometry), terrain morphology, and terrain physics properties, the resulting trajectories are only decided by the initial status of the PBR. In this case of seismic motivator, the initial status of PBR is determined by the ground motions.

Please provide in the manuscript the height of DRE2 above the ground surface, as this will relate to its trajectory potential.

Thank you for the suggestion. We have added the following sentence to the manuscript.

“The height of the PBR is approximately 12 m above the ground surface.”

Recommendation: Revisions Required

Reviewer B:

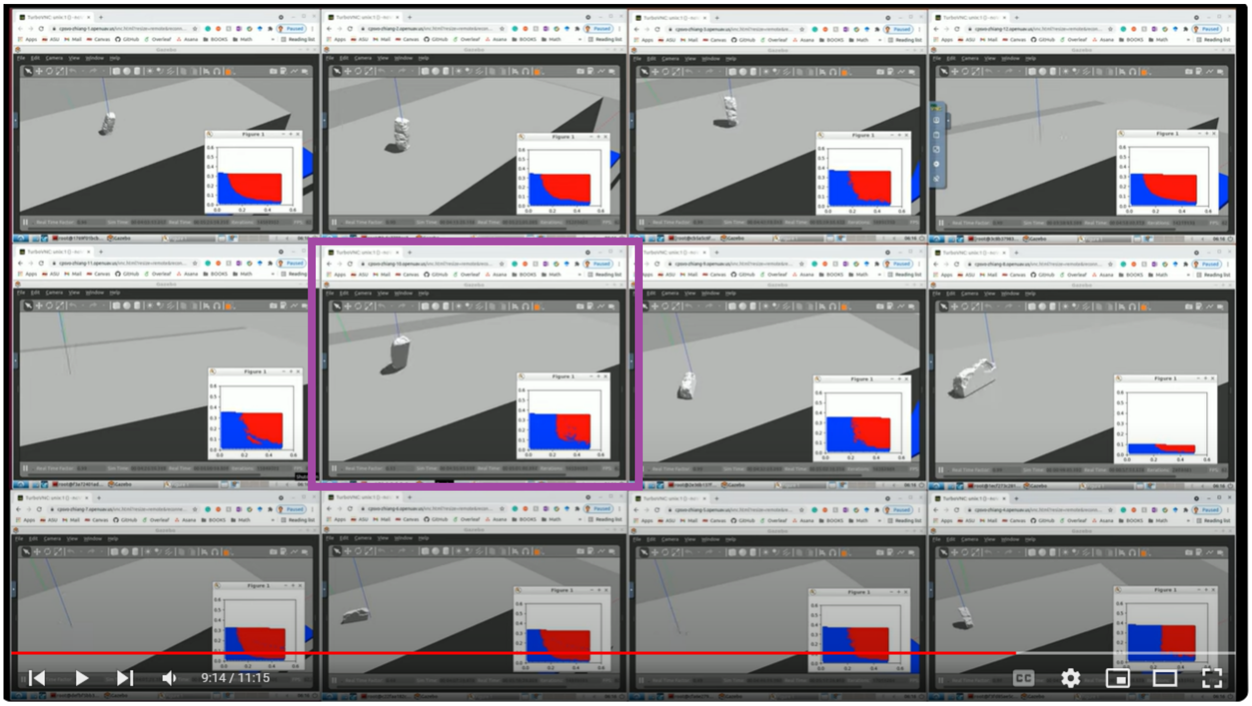
This manuscript focuses on the use of Bullet physics engine and Gazebo toolkit to estimate the overturning response of PBRs to earthquake ground shaking. They also build a virtual robot that can simulate the response of objects under 1D ground shaking and replicate a similar set up using a mini-shake table. While the concept described here is interesting, the major concerns listed below regarding the accuracy of the algorithm need to be addressed before the manuscript can be published.

1. The authors claim that they can simulate large displacement rocking and sliding response of rocks with complex geometries using this Bullet physics engine. However, all the validation provided are from either cuboids or rocks that are nearly cuboidal (Fig.6) subjected to ground motion perpendicular to the edges of this cuboid/rock (yaw 0 and 270 deg). These are fairly simple scenarios with a well defined edge along which ground shaking occurs, essentially a 2D

rocking problem. In lines 303-305, the authors have mentioned that there can be more complex overturning response such as twisting that is observed for complex shapes. The algorithm needs to be tested to see if it can model these complicated phenomena rather than rocking on a plane. For the 3D printed nearly cuboidal rock, ground shaking applied along the diagonal direction of these cuboids will initiate rocking on a corner. At least this type of 3D scenario needs to be considered for validation with a comparison of the 3D displacement vector of the rock at a point on the surface between the virtual robot and mini shaker experiment.

We appreciate the feedback from the reviewer. First, even though the edge of the Double Rock PBR seems well-defined and perpendicular to the ground motion direction (it seems the contact is simple, and only rocking behavior occurs), we did observe complex motions. This complexity arises because rock behavior is influenced not only by the contact conditions but also by factors such as the mass center, inertia matrix, and various other considerations. The contact geometry was not as simple as it may have seemed. The contact surface of the Double Rock PBR was actually quite asymmetric and did not have a rectangular basal geometry.

This is a link to the Double Rock PBR simulation recording: https://www.youtube.com/watch?v=xuSP21WI9ag&list=PLQFQ6M344AWcVceGyqwvHDmvLtTxphPdQ&index=13 . The PBR at yaw 270 deg corresponds to the one in the highlighted box in the following figure, and it showed complex motions in the video, such as twisting, point uplift (rocking on a corner), planar uplift (rocking on an edge), and rock-twisting (twisting while in an uplifted state). When testing the 3D-printed Double Rock PBR on the min shake robot, we also observed a similar complex behavior.



While the VSR can capture complex rock behaviors, we admit that comprehensively validating those behaviors, especially twisting and the combination of multiple types of complex behaviors, is challenging. The validation of complex rock behavior is less well developed compared with simple rock behavior such as rocking. We developed the VSR based on the Bullet physics engine and provided one possible solution. We recognize that much future work is necessary to further develop this direction for a comprehensive understanding of rock behavior.

With that said, we have made the following updates to the manuscript:

“Given that the edge of the Double Rock PBR appeared well-defined and perpendicular to the ground motion direction (yaw 270°), one might expect only rocking behaviors. However, we observed complex motions such as twisting, point uplift (rocking on a corner), planar uplift (rocking on an edge), and rock-twisting (twisting while in an uplifted state), in both the simulation and experimentation. This complexity arises because rock behavior is affected not only by the contact conditions but also by factors such as the mass center, inertia matrix, and geometry.”

PBR study YouTube playlist:
https://www.youtube.com/playlist?list=PLQFQ6M344AWcVceGyqwvHDmvLtTxphPdQ

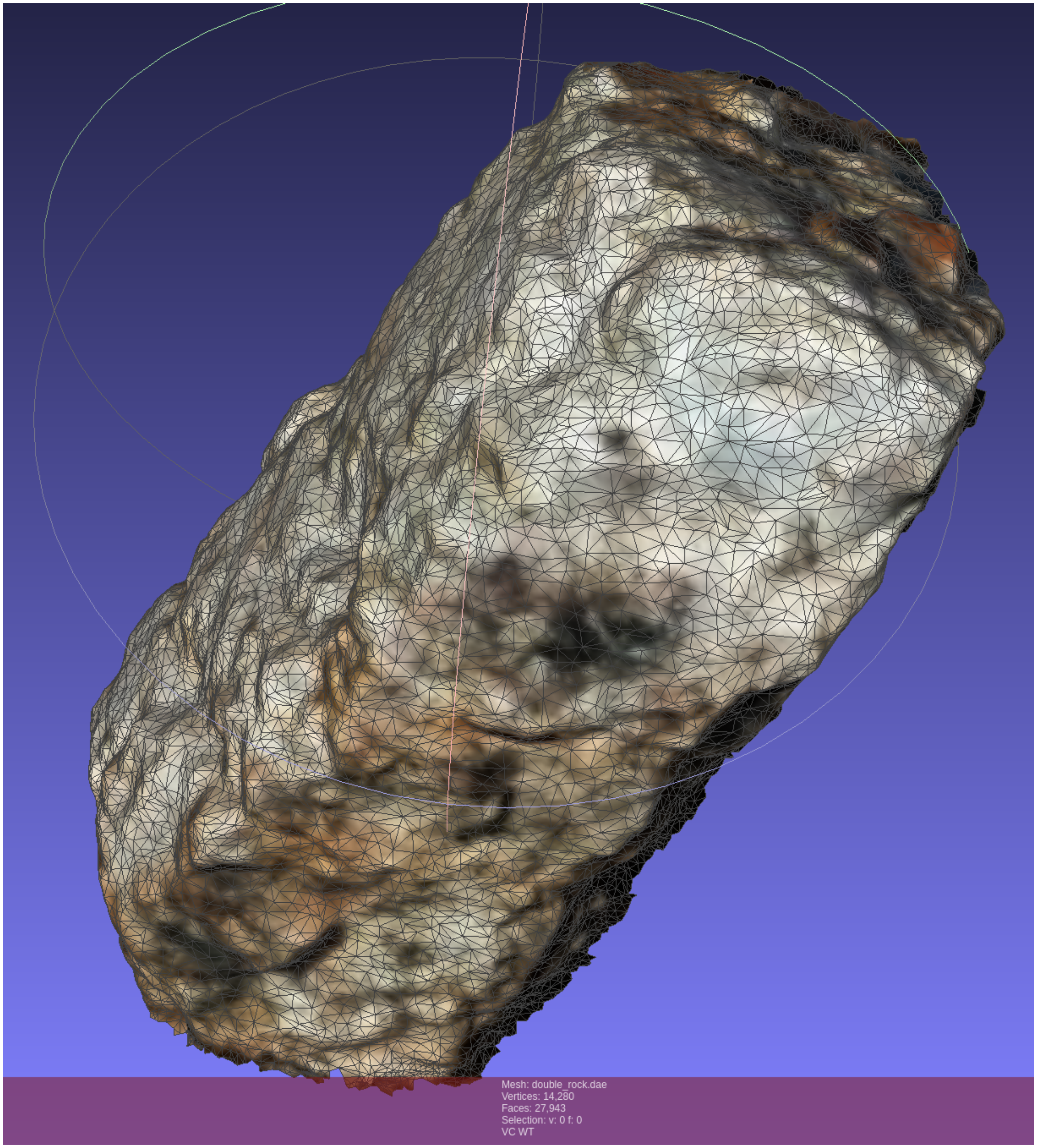
Double Rock PBR simulation video:
https://www.youtube.com/watch?v=xuSP21WI9ag&list=PLQFQ6M344AWcVceGyqwvHDmvLtTxphPdQ&index=13

We have included the youtube links to the Data and Code Availability. The experiment videos are also updated in the Zenodo repository.

2. The contact surface plays a significant role in the overall reponse of the rock. Not much is mentioned about the resolution to which contact is characterized in this study. When using LIDAR or photogrammetry and when creating the PBR-pedestal model from these data, a lot of attention is given to capturing the rock-pedestal interface region. It is not clear if UAS can provide similar resolution near the contact interface. In lines 286-294, the authors briefly describe how the PBR and terrain are modeled, but they say that they have added planes where they did not have data on the rock geometry and that this could add some uncertainity in the response. It is important to add more discussion on this aspect as the the fragility of the rock is very dependent on this contact interface as shown from the shake table tests conducted by Purvance et al. 2008.

We appreciate the comment highlighting the effects of surface properties on PBR overturning dynamics. First, we wanted to emphasize that this study focuses on the VSR and does not propose a new surveying technique. The contact can be made arbitrarily complex if necessary in the VSR, but that was not the goal of this paper. Our aim is to demonstrate the potential of the VSR, which relies on physics engines and robotic tools. Second, either lidar or SfM mapping methods may not accurately represent the actual contact geometry between a PBR and its pedestal. Finally, conventional geometric contact models may not fully capture the intricacies of real contact behavior.

In this study, we expect that the visible reconstruction of the Double Rock PBR using UAV-SfM should be better than hand-held lidar scanning (e.g., TLS). Given the significant height (~ 12 m) of the Double Rock PBR above the ground surface, we anticipate that using TLS from the ground would result in coarse point resolution and make capturing the basal contact challenging due to potential obstructions. Conversely, UAVs have the advantage of taking photos close to the PBR. In our SfM reconstruction, the top-down orthomap achieves a resolution of 7mm/pixel. The resulting PBR mesh model without inserted planes has 14,280 vertices and 27,943 faces, as shown in the following figure. Despite the advantages of UAV-SfM over TLS, we exclude this discussion (SfM vs. lidar PBR mapping) from our manuscript for two reasons. (1) We aimed to maintain a focused narrative for our readers without unnecessary distractions. The focus of this paper is the VSR, not a mapping method. Comparing UAV and lidar mapping methods is tangential. (2) On the other hand, we are currently in the process of developing a UAV-lidar mapping system for PBR mapping (different from hand-held TLS; as briefly described in the introduction section). Therefore, we plan to address this argument more comprehensively in future work.



Mesh: double_rock.dae
Vertices: 14,280
Faces: 27,943
Selection: v: 0 f: 0
VC WT

We acknowledge that introducing planes to the PBR could introduce uncertainties. It is impossible to obtain the actual surface without lifting the PBR, and lifting the PBR may ruin its application for future seismology research. Again, our primary focus in this study was to demonstrate the potential of this tool, particularly as a first-generation technology. We developed this tool and conducted experiments to reveal preliminary scientific findings. We appreciate your understanding of our approach in this context.

Based on the above response, we have updated the manuscript accordingly as follows.

“Geometric simplifications like this, particularly at the base or interface, introduce potentially significant uncertainties in overturning fragility. Complex basal conditions, as is the case for many PBRs, effectively introduce multiple points of rocking or potential uplift. The resulting increase in fragility was evident in the shake table tests of Purvance et al. (2008) and the analytical model of Wittich and Hutchinson (2018). More recent shake table testing by Saifullah et al. (2022) quantified that the overturning demand can vary up to ±50% because of small modifications in the basal geometry from surveying techniques. The basal contact can be made arbitrarily complex if necessary in the VSR, but that was not the goal of this paper. Although the geometric modeling approach taken herein does not fully capture the basal interface, this paper aims to provide a demonstration of a first-generation technology for modeling the dynamics of PBRs”.

“Because of the significant role of contact geometry in rock response, future work should thoroughly investigate the VSR's ability to model dynamic processes involving complex contact surfaces. Such modeling would include complex interface geometry, variable properties and rheology, and evolution of geometry and properties with continued loading”.

3. The authors have presented analysis on the large-displacement dynamics of PBRs (i.e., rockfall trajectories). But they have not presented any validation of this aspect.

We agree that we have not presented validation of the large displacement process. Even though large displacement has been studied in rockfall monitoring and prediction, the large displacement process is less well-developed for PBR studies. The dynamics are much more complex than those for overturning. Thus, there has not been a systematic way of studying PBR large displacement, including the large displacement validation. Second, validating the large displacement process in the field is very challenging, because it requires to topple a PBR and monitor its trajectory. Toppling a PBR would ruin its usefulness for future generations of seismologists. We have added this point in the “future work” section:

“Fourth, the validation of the large displacement process is not addressed in this study. Future research should focus on exploring this aspect.”

4. Why is the study restricted to ground shaking applied in one direction. In the 2-D studies presented by Purvance et al., they already identify a most fragile cross-section of the rock and apply ground motion along that direction. But given that a full 3D model is being constructed, the 3-component ground motion needs to be considered for more accurate results as the dominant ground motion only indicates the initial set of rocking points, after which the combination of different ground motion components will likely determine if the rock overturns and the direction in which the rock falls.

Thank you for bringing this up. We agree that incorporating 3D ground motion will significantly enhance the study of PBRs. Our tool development initially focused on 1D ground motion, and we have plans to expand it to include 3D ground motion in our future work. Validation initially focused on 1D ground motion to ensure proper treatment of the salient dynamic features of the PBR response, and to more easily correspond with the miniature shake robot. The VSR can be extended for 3D ground motion and is included in future work. Validation of this will require a more extensive shake table testing program that is outside the scope of this work. We have included this idea in the future work section:

“The previous study by Veeraraghavan (2015) demonstrated that 3D PBR fragility results are more sensitive, indicating higher fragility, compared to their 2D counterparts. Looking ahead, the development of the VSR that incorporates 3D ground motions would represent a significant advancement beyond the existing 1D ground motion assessment methods.”

5. lines 125-126 - "Additional previous overturning simulations assumed flat pedestals". Both the works referred by the author have non-flat pedestals included in the simulation. Purvance et al. 2012 work contains multiple odd shaped rocks stack on top of each other resting on a pedestal that is created using a convex hull. The pedestal considered by Veeraraghavan et al. is created by fitting a surface to the point cloud obtained from the LIDAR data. In both studies, only the region within the initial contact area, which is the area on which the rock is resting on the pedestal at the start of the simulation, is assumed to be flat because (i) LIDAR or photogrammetry data cannot capture the region inside the initial contact area and (ii) only the outermost contact points determine when and where the rock will start rocking. While sliding may start at lower PGA if this enitre initial area is not in contact, this assumption leads a conservative estimate of ground motion required for sliding to start. Also, in most of these PBRs, rocking is the motion that is first initiated due to the rock being more slender, and while it is rocking on a single contact point or an edge, sliding could occur, which would be captured by the methods described in either of the previous works.

We appreciate the reviewer’s correction. We have carefully examined the related references and removed the statement, “previous overturning simulations assumed flat pedestals”. We modified the corresponding text as follows.

“Additionally, complex terrain—anything other than a flat pedestal—can either increase or decrease the fragility of a PBR, depending on the specific characteristics of the surrounding terrain and the contact. Our VSR supports arbitrarily complex terrains, e.g., mesh models from UAS and SfM, to advance PBR dynamics studies”.

We also thank the reviewer for providing the details about the previous work. It is important to recognize the challenges associated with accurately modeling the dynamics of individual PBRs. In response to comment 6, we will explain our motivation for using a physics engine.

6. Section 2 - One of the issues with modeling the contacts as rigid (without using springs or other soft contact mechanics) is that there could be multiple solutions to the optimization problem that is described in lines 148-152. These multiple solutions can be triggered by simple things like changing the order of contact points. While all solutions satisfy the momentum conservation equations, they will result in completely different overall response of the rock. While this is usually okay for gaming type of applications, some more constraints maybe required to zero in on the correct solution from the infinite set of solutions. Part of this has been

explored in Veeraraghavan et al. (ASCE JEM 2020). It is important for the authors to present if the optimization problem that is being solved by Bullet engine has a unique solution or whether the algorithm is picking the correct solution for this problem. Validation efforts for more complex rocking scenarios (as suggested in point 1) can likely provide more confidence on the accuracy of the algorithm on these aspects.

Thank you for pointing this out. We want to clarify that our approach is not solely focused on achieving the utmost accuracy or providing the only solution. Rather, it involves a balance between efficiency and accuracy. As we have mentioned in response to a previous comment, we acknowledge that our approach is not the exclusive or definitive solution. In fact, we have openly acknowledged this in our manuscript, "Physics engines and DEM are numerical methods, neither of which is a true representation of reality, and both of which need calibration. Our goal here is to promote physics engine applications in PBR dynamics studies, which provides one more option with some advantages relative to DEM. More research is needed to compare the performance of physics engines and DEM on this topic". The validation and comparison will be done probabilistically in the future.

Second, the physics engine has the advantage of efficiency. "In our experiments, it took only a few seconds up to a minute to finish one overturning experiment in the VSR. In DEM, the computational time increases with the complexity of geometry, discretization, and contact stiffness. Finishing one overturning experiment in DEM usually takes a few minutes to hours".

The efficiency of the physics engine presents a range of promising opportunities. (1) In our future endeavors, we plan to employ Monte Carlo simulations to repeat overturning and large displacement experiments to build probabilistic models. This efficient approach is made possible by the fast implementation of physics engines, even when considering the uncertainties introduced by MLCP solutions and other variables. As such, for individual overturning experiments, the need for high accuracy in geometry models (including contact surfaces), MLCP solutions, and other factors may not be an absolute requirement. Secondly, the physics engine's efficiency offers the potential for integration with Unmanned Aerial Vehicles (UAVs) in large-scale on-site fragility assessments. These capabilities open doors to innovative and streamlined approaches in our research and applications. For example, "combined with our research of using robots and machine learning for rock detection and mapping, the VSR presents a paradigm of rock detection-mapping-analysis for automated geoscience. In the future, the VSR could be installed on a companion computer of a UAV that is also developed using ROS. Once the UAV detects and maps a PBR, the VSR can rapidly analyze the PBR fragility, facilitating field data collection. " The on-site assessment can offer a qualitative fragility analysis. This rapid analysis provides valuable insights for geologists when deciding which PBR candidates require detailed inspection.

Fourth, we acknowledge the importance of quantifying the uncertainty for individual rocks as a benchmark. Accordingly, we have cited Veeraraghavan et al. (ASCE JEM 2020) and updated the discussion section in our manuscript:

"Because iterative algorithms for solving MLCP may not always guarantee convergence, resulting in variations in rock responses (Veeraraghavan et al., 2020), future work should investigate solutions to mitigate such uncertainties. Following Purvance et al. (2008), we can use the Monte Carlo method to construct a probabilistic model and to quantify the uncertainties”.

7. Line 152- What happens if the maximum number of iterations is met but the algorithm has not converged? Is that solution discarded and the optimization problem is solved using another set of initial guess?

When the maximum number of iterations is reached without complete convergence, the Bullet physics engine like other physics engines doesn't discard the solution but proceeds with the best result available. Although this might yield solutions that aren't entirely accurate or stable, it aligns with the necessity for simulation efficiency, a critical advantage as we explained in the above response.

The Bullet physics engine refrains from initiating a new set of initial guesses as this could entail significant computational costs and noticeable delays. Despite potential non-convergence in a single frame, the approach offers opportunities for correction in subsequent frames, maintaining a delicate balance between performance and stability. Consequently, in Bullet and similar physics engines, the strategy is to keep the simulation running smoothly, even if occasional non-convergence entails trade-offs in precision or stability.

Thank you for raising these two valuable questions. They are important to understand the Bullet physics engine. At the same time, we also wish to strike a careful balance between providing technical insights and maintaining the focus on the scientific applications presented in this paper. We believe that an excessive infusion of technical details could potentially divert readers' attention from the core objectives of our research. As a result, we have chosen to omit these intricate technical details from the manuscript. Nevertheless, we have included relevant references in the manuscript for those readers who may wish to explore these aspects in greater depth. Your understanding of this decision is greatly appreciated.

Relevant references:

Bergen, G. v. d. Collision Detection in Interactive 3D Environments. CRC Press, 2014. doi: 10.1201/9781482297997.611

Coumans, E. and Bai, Y. PyBullet, a Python module for physics simulation for games. http://pybullet.org, 2016

Erleben, K., Sporring, J., Henriksen, K., & Dohlmann, H. (2005). Physics-based animation (Vol. 79). Hingham: Charles River Media.

Williams, J., Lu, Y., & Trinkle, J. C. (2014, August). A complementarity based contact model for geometrically accurate treatment of polytopes in simulation. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (Vol. 46391, p. V006T10A023). American Society of Mechanical Engineers.

8. In lines 317 - how were the values of friction and restitution chosen for this validation exercise? Do the results vary if these parameters are varied?

Thank you for pointing this out. We have clarified the parameter selection in the manuscript. First, we have added more description about the differences between the physics engine parameters and DEM parameters in Section 2.2.

“The Bullet physics engine requires users to provide macro physics parameters, including restitution, Coulomb friction, and rolling friction coefficients (Chen, 2022)”. “Given the fact that the soft contact model in DEM is a hypothetical model, the user-defined parameters within this model lack direct connections to macro physics properties. These parameters can be calibrated through an iterative process of adjusting parameter values and matching experimental observations. In contrast, the parameters required in Bullet represent macrophysics properties and can be directly measured through experiments”.

Second, we explained that the parameter selections for the experiments in this study are based on previous research. We have also added the corresponding references. E.g., “The two friction coefficients were selected based on dry rock friction (Byerlee, 1978), and the restitution coefficient of a wood block was measured from normal drop tests (Haron and Ismail, 2012)”. “These four cuboids had the same densities of 2,110 kg/m3 (chert density), 0.6 coefficient of Coulomb friction (dry rock friction), 0.6 coefficient of rolling friction (dry rock friction), and 0.38 coefficient of restitution (based on rockfall energy loss reported in Dorren, 2003)”

Third, we admit that parameter selection is challenging in any dynamics simulation, including both DEM and physics engines. However, as we have pointed out, the physics engine parameters have direct connections to macro physics properties. These parameters may be directly measured from material and experiments. This is another advancement for utilizing the physics engine for the studies.

Fourth, Even though the parameters in the physics engines are more intuitive and correspond to macro physics properties, measuring accurate parameters still requires future work. Section 6.3: “Additionally, the values of physics parameters, such as friction and restitution coefficients, play a pivotal role in dynamics simulations within physics engines. Our experiments in this study observed that these parameters exhibit nonlinearity. For example, we found several thresholds for friction coefficients. Within these thresholds, the friction coefficient displays various nonlinear properties. Generally, a significantly high friction coefficient made PBRs more fragile compared to a very low coefficient. However, within certain threshold ranges, the influence of varying friction is less pronounced. To quantitatively measure this nonlinearity, we recognize the necessity for additional experiments in our future research endeavors.”

9. In section 4.3 - please add a image of the experimental setup.

We have added an image of the experiment setup.

Recommendation: Revisions Required

REVIEW ROUND 2

Reviewer A:

Dear Professor Pablo Heresi,

I have reviewed the updates made to the manuscript of Chen et al., titled "Virtual Shake Robot: Simulating Dynamics of Precariously Balanced Rocks for Overturning and Large-displacement Processes", as well as the authors' response to reviewers' document.

I am satisfied that the authors have addressed the main points of my review, and I consider the updated text in the manuscript to be both clearer and strengthened. In addition, I believe that the authors have sufficiently addressed the valuable comments provided by the other reviewer.

I have no further comments and, therefore, recommend that this manuscript be accepted for submission in Seismica.

Recommendation: Accept Submission.

Reviewer B:

The authors have addressed most of my comments and made alterations to the manuscript where needed. I appreciate the author's efforts in addressing the comments.

After reading through the manuscript and the response to the reviewers, I believe some minor modifications are needed to address comments 6 and 7.

1. In response to comment 6, authors have made the following changes to the manuscript "Because iterative algorithms for solving MLCP may not always guarantee convergence, resulting in variations in rock responses (Veeraraghavan et al., 2020), future work should investigate solutions to mitigate such uncertainties. Following Purvance et al. (2008), we can use the Monte Carlo method to construct a probabilistic model and to quantify the uncertainties".

This comment discusses about non-unique converged solutions to the optimization problem, not just problems with convergence. So I suggest modifying the first statement to "Because iterative algorithms for solving MLCP may not always guarantee convergence or unique solutions, resulting in variations in rock responses (Veeraraghavan et al., 2020), future work should investigate solutions to mitigate such uncertainties."

2. In response to comment 7 on whether unconverged solutions are discarded, the authors have responded that these solutions are not discarded and are used in the developed of the overturning fragility. While the authors mention that they are not going into technical details on this aspect so as not deviate from the application presented in the manuscript, I believe it is important to present some level of technical details here, because they are significantly going to affect the accuracy of the solution, and therefore its use in the scientific application. The technical details can be just a statement or two referring to the percentage of simulations for which convergence is not reached. Because if 50% of the simulations do not converge, that could significantly affect the accuracy of the results, whereas if non-convergence is observed only in the fringe cases (~1-2%), then that would not significantly affect the accuracy of the overall

results. Given that the aim is to project the use the physics engine to provide quantitative estimates of the overturning probability of the PBR, some technical details on these aspects which focuses on the accuracy of the quantitative estimates could strengthen the manuscript.

Recommendation: Minor revisions required.

Response from authors:

Dear Prof. Pablo Heresi,

We would like to express our sincere gratitude to you and the reviewers for the constructive feedback on our manuscript. We are pleased to learn that Reviewer A is satisfied with our revisions and recommends publication. We also appreciate the insights provided by Reviewer B, which we believe have significantly improved the quality of our work. In response to Reviewer B's comments, we have made the following revisions:

Comment 1: We have modified the text to reflect the concern about non-unique converged solutions in the optimization problem. The revised sentence now reads: "Because iterative algorithms for solving MLCP may not always guarantee convergence or unique solutions, resulting in variations in rock responses (Veeraraghavan et al., 2020), future work should investigate solutions to mitigate such uncertainties."

Comment 2: We understand the importance of providing technical details about the convergence of our solutions, as this directly impacts the accuracy and credibility of our results. As we responded in the previous letter, when the maximum number of iterations is reached without complete convergence, the Bullet physics engine, like other physics engines, does not discard the solution but proceeds with the best result available. In our experiments, we haven't observed any toppling processes that are obviously unconverged. At the same time, quantifying convergence for every iteration is intricate. We have validated the PBR toppling processes, which we believe is more important information for the audience. Also, we have mentioned the convergence problem in the section on future work: "Because iterative algorithms for solving MLCP may not always guarantee convergence or unique solutions, resulting in variations in rock responses (Veeraraghavan et al., 2020), future work should investigate solutions to mitigate such uncertainties."

We believe these revisions adequately address the concerns raised by Reviewer B and strengthen the manuscript. Thank you for considering our work for publication.

Kind regards,

Zhiang Chen

REVIEW ROUND 3

Reviewer A:

[No revision.]

Reviewer B:

I appreciate the authors' efforts in revising the submission to address the comments. The article can be accepted in the current form.

Recommendation: Accept Submission.