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Interactive comment on "The effects of cushion's particle size and thickness on coefficient of restitution under the rockfall impacts" *by* Chun Zhu et al.

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Answer to referee 1 comments Reviewer 1 R 1: The English of this paper is not optimal, which prevents a clear understand of the experimental procedures and the physical signiïňĄcance behind observations. The format of the paper needs to be better arranged (e.g. sometimes the ïňĄgure and the caption are not on the same page). There are also many typo-errors. It is STRONGLY suggested that the authors try to improve the language of the paper through the corrections either from a native English speaker or scientific proof reading editing services.

AC: Thanks for the reviewer's suggestion. My manuscript has been edited for En-

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glish by using an English editing service, the embellishment proof is supplied as the attachment. The format of this paper has been adjusted to make readers easier to understand.

R 2: Section of ‘Introduction’: It is ideal to include more newly published researches to highlight the importance and uniqueness of the current study.

AC: Thanks for the reviewer’s suggestion. I have introduced some newly important references in the ‘Introduction’ section to highlight the importance and uniqueness of the current study, the newly references are listed as follows.

[1] Howald et al. (2017) evaluated the protective capacity of existing and newly proposed protection measures, and considered the possible reclassification of hazard as a function of the mitigation role played by the measure.

EP Howald, JM Abbruzzese, C Grisanti. An approach for evaluating the role of protection measures in rockfall hazard zoning based on the Swiss experience. Natural Hazards Earth System Sciences, 2017,17(7):1127-1144.

[2] Mignelli (2014), meanwhile, applied a rockfall risk management approach to the road infrastructure network of the Regione Autonoma Valle D’Aosta in order to calculate the level of risk and the potential for its reduction by rockfall protection devices. A comparative analysis of road accidents in the Aosta Valley was then undertaken to verify the methodology.

C Mignelli, D Peila, SL Russo, et al. Analysis of rockfall risk on mountainside roads: evaluation of the effect of protection devices. Natural Hazards, 2014,73(1):23-35.

[3] The effect of shape has been examined by performing tests with spherical and cubic blocks, finding that spherical blocks show higher and more consistent COR values than cubic blocks (Asteriou et al., 2016).

Pavlos Asteriou, George Tsiambaos. Empirical Model for Predicting Rockfall Trajectory Direction. Rock Mech Rock Eng, 2016,49:927-941.

[4] State-of-the-art simulation techniques incorporating nonsmooth contact dynamics and multibody dynamics have been applied to and adapted for the efficient simulation of rockfall trajectories, and the influence of rock geometry on rockfall dynamics has been studied through numerical simulation (Leineet al., 2014).

RI Leine, A Schweizer, M Christen, et al. Simulation of rockfall trajectories with consideration of rock shape. Multibody System Dynamics, 2014,32(2):241-271.

[5] Semi-rigid rockfall protection barriers have been installed along areas threatened by rockfall events, and numerical investigation of semi-rigid rockfall protection barriers has been carried out to obtain essential structural information such as the energy-absorption capacity of such barriers (Miranda et al., 2015)

SD Miranda, C Gentilini, G Gottardi, et al. Virtual testing of existing semi-rigid rockfall protection barriers. Engineering Structures, 2015, 85:83-94.

[6] Lambert et al. (2014) conducted real-scale impact experiments with impact energies ranging from 200 to 2200 kJ. They studied the response of rockfall protection embankments composed of a 4-m high cellular wall when exposed to a rock impact and compared this with previous real-scale experiments on other types of embankment. S Lambert, A Heymann, P Gotteland, et al. Real-scale investigation of the kinematic response of a rockfall protection embankment. Natural Hazards Earth System Sciences, 2014,14(5):1269-1281.

[7] Sun et al. (2016) used a tire cushion layer to absorb rockfall impact, utilizing the radial deformation of the tire. They built a reinforced concrete structure model with a tire cushion layer and carried out artificial rockfall tests.

J Sun, Z Chu, Y Liu, et al. Performance of Used Tire Cushion Layer under Rockfall Impact. Shock and Vibration, 2016, 2016 (10):1-10.

R 3: Section of 'CoefïňĄcient of restitution': It is better to use the absolute values of the velocities in Equations (1) and (2) since one notices that velocity has a direction.

Also it is not clear in e.g. Figures 7-9 that the CORs are calculated based on the velocities of normal direction or tangential direction, or they are calculated based on the kinetic energy? It is necessary to give a clear deïňĄnition of the normal and tangential directions for a rock-cushion impact. Also the expression 'the COR of cushion' does not seem to be correct since COR is not a physical property of cushion.

AC: Thanks for the reviewer's suggestion. I agree with the suggestion that using the absolute values of velocities in Equations (1) and (2) since velocity has a direction. I have supplemented in 'Experimental procedure' section that VCOR for the CORs measured in Figures 7-9 was calculated using the magnitudes of the incident and rebound velocities, and the calculation method of VCOR is shown in Equation (1). They are not calculated based on the velocities of normal, tangential direction or kinetic energy.

I agree with the point that the expression 'the COR of cushion' is not correct since COR is not a physical property of cushion, so I have adopted the expression of 'the COR of collision between rockfall and cushion' to substitute for 'the COR of cushion' throughout.

R 4: (1) Section of 'Experimental studies': It should be 'radius' in 'Spherical blocks with diameters of ...'. It is better to give more details about the experimental procedures. For example, how the rock velocities are calculated from the frames (any calibration or correction of the view distortion)? What is the relative position of the two cameras? If only the vertical velocity of rock is measured, does that mean the view axis of the camera is parallel to the cushion platform?

AC: Thanks for the reviewer's suggestion. I have detailed about the experimental procedures. Such as: the calculation of rock velocities, the relative position of the two cameras and the main uncertainties in the test results, the descriptions are as follows: The two cameras, which obtained the motion, velocity, and kinetic energy automatically, were placed symmetrically at a distance of approximately 0.9m from the impact surface (Figure 5). The distance between the two cameras was about 1.2m, making the cameras look down slightly at the targeted platform. The synchronized recordings from the two cameras captured a sequence of image stereopairs at time intervals of 1/200 s. By applying stereo-photogrammetric processing, the position of any point in both images can be computed in 3D space. In general, a digital image is a perspective projection of 3D space to the camera lenses. The image plane has a 2D coordinate system where position measurements can be made using pixel coordinates. The camera has a 3D reference coordinate system that is based on the image plane pointing in the viewing direction of the camera. The speed of the rocks can be obtained by measuring the distance they have moved between adjacent frames. Therefore, if only the vertical velocity of rock is measured, I think it doesn't mean that the view axis of the camera is parallel to the cushion platform.

R4(2) The paragraph below Figure 5 describes how to prepare the cushion platform. However, it is not easy to understand how the platform is established due to the poor English expression. It is suggested that the authors list clearly the experimental parameters in a table so that one sees clearly how the two groups of tests were performed.

Thanks for the reviewer's suggestion. My manuscript has been edited for English by using an English editing service and I have detailed about the experimental procedures, the preparation process of the cushion platform is described as follows: To simulate gravel cushions of different thicknesses, a large number of 40 cm length $\times$ 40 cm width $\times$ 2 cm height hollow gypsum boards were made. A 30cm length $\times$ 30cm width $\times$ 2cm height section was cut out of the center of each board. The hollow gypsum boards were stacked on top of each other to simulate gravel cushions of different thickness, and then the hollow parts of the boards were filled with gypsum particles. The hollow boards were fixed to a massive 40cm length $\times$ 40cm width $\times$ 6cm height gypsum base to ensure the preservation of momentum from the impact. As is shown in Tables 1 and 2 (See Supplement), because the space occupied by tables of two groups experimental parameters is so large, thus I think choose the table to express how the two groups of tests were performed is not relatively suitable in manuscript. Therefore, I have detailed the experiment procedure and Figures of experiment result, the experiment content has also been edited for English by using an English editing service to facilitate reader to understand.

R4(3) From Figure 5a it seems that rock has a tangential velocity when it impacts with the cushion platform. However, the authors used the release height (by changing the inclination of the release path?) as a reference parameter, which inïňĆuences both the normal and the tangential velocity of rock at impact. Thus it is not clear how the COR is affected by the distribution of kinematic energy between the normal and tangential directions (or the COR is calculated only based on the normal direction?).

Thanks for the reviewer's suggestion. I used the release height as a reference parameter, but I change the vertical height between the released position and the ground instead of changing the inclination of the release path. I think VCOR are more representative to reflect the motion situation of rockfall before and after colliding with the cushion compared with other forms of COR, thus the CORs measured in tests are VCOR calculated based on the velocity magnitude of the incident and rebound stage, the calculation method is shown in Equation (1).

R4(4) One wonders whether there still exists boundary effect in experiments, although the authors have tested spherical rocks and cushion platforms of different sizes (or thicknesses). It requires to clearly show that the current results are boundary-effect free.

Thanks for the reviewer's suggestion. I think there is a slight boundary effect in experiments, but which can basically be neglected. Due to the restriction of laboratory test, the coverage area of cushion is not so wide, but the proportion of the size of rockfall and the coverage area of cushion is relatively small in the experiment, and the impact range when rockfall collided with the cushion is far less than the coverage area of the cushion (See Figure 7 in Supplement). Therefore the current results are basically boundary-effect free.

R4(5) In Figures 8 and 9 the radius of rock and the diameters of particles do not have units. How many experiments are performed for each data points in these ïňĄgures?

Thanks for the reviewer's suggestion. I have added units in Figures 8 and 9. The main uncertainties in the test results arise in tests with large cushion particles, where the wider scatter of the values is attributed to the contact conïňĄguration between the large cushion particles and the blocks: large cushion particles have numerous different conïňĄgurations. This also affected the deviation in the trajectory caused by the impact, which had a drastically higher uncertainty than for small cushion particles. In order to counteract the effects of chance, a "three tests for the mean" method was adopted, and the average value was set as the final result for each data point in the figures and tables presented here. For cushion particle sizes of 1.8cm and 2.4cm, each test was repeated five times, and the middle three values were used to obtain the average value, while for cushion particle sizes of less than 1.8 cm, each test was conducted three times. If an obviously outlying result was obtained, the test was repeated to reduce the error. I have mentioned it in 'Experimental procedure' section.

R4(6) One needs to show the uncertainties. How the packing structure of the cushion particles will inïňĆuence the COR result? This is a topic which is worth discussing because one notices in Figure 4 that the geometry of particles is very regular. Do they form special interlocking structure in the platform? If so how does it affect the rock's impact-rebound behavior? How is the cushion prepared once again after one impact experiment so that the inïňĆuence of particle packing structure on the next experiment is minimized? It would be great if the author could show the photos of cushion before and after the rock impact experiments. In the discussion part the authors mentioned 'Because the small thickness cushion can be compressed in a very short time ...'. It needs to be clearly shown or demonstrated. The last paragraph of this section is very difïňĄcult to understand. It may be helpful if the important discussions are listed into bullet points so that one gets the ideas more quickly.

Thanks for the reviewer's suggestion. The main uncertainties in the test results arise in tests with large cushion particles, where the wider scatter of the values is attributed to the contact conïňĄguration between the large cushion particles and the blocks: large cushion particles have numerous different conïňĄgurations. This also affected the deviation in the trajectory caused by the impact, which had a drastically higher uncertainty than for small cushion particles. I think the packing structure of the cushion particles don't have the influence on the COR result. Because the proportion of the size of rockfall and the coverage area of cushion is relatively small in the experiment, and the impact range when rockfall collided with the cushion is less than the coverage area of the cushion (See Figure 7 in Supplement). In field engineering, when the rockfall collide with the cushion, the gravel particles cushion of other areas will also generate interlocking effect on the particles in the collision area, which is similar to the packing structure in the tests. Photographs of the cushion before and after a rock impact experiment are shown in Figure 7 (See supplement). The cushion was always repaired completely after each impact experiment to ensure that the next experiment was free from interference. If any particles had collided out from the platform, new particles were added to supplement the cushion, and the surface was blackened again before the next impact experiment in order for the cameras to obtain accurate measurements of block speed. Fig. 7 Photographs of a cushion (a) before and (b) after a rock impact experiment I have revised and reorganized the 'Discussion' part by using an English editing service. Such as, I have adopt 'Because a thin cushion can be more easily compressed in a very short time' to substitute for 'Because the small thickness cushion can be compressed in a very short time.

R 5: Section of 'Orthogonal test design': The deïňĄnition of 'damage depth' should be clearly given. The principle of 'orthogonal test' should be given for the reader who is not familiar with the concept. What is the purpose of doing this test? In Tables 2 and 3 not only the mean value but also the uncertainties should be given.

AC: Thanks for the reviewer's suggestion. I have introducted the clear definition of 'damage depth' and the principle of 'orthogonal test' in 'Orthogonal test design' section

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to facilitate readers to understand. The definition of ‘damage depth (L)’ is the depth to which the cushion is influenced after a rockfall has collided with it and can be used to represent the degree of damage to the cushion. The principle of ‘orthogonal test’ is described as follows: Orthogonal testing is a design method that allows testing of multiple factors and multiple levels. It is based on orthogonality and selects representative points from a comprehensive experiment for testing. The orthogonal test method has the advantages of being uniformly dispersed, neat and comparable, making each test highly representative so that fewer trials can fully reflect the impact of the variation of each factor on the index. The purpose of doing an orthogonal test is to explore the degree of influence of the four different factors on the COR and damage depth, L, and find the best combination to reach the optimal protective effect when a rockfall collides with a cushion. When these factors cannot be considered in full, the leading factor is considered to achieve the expected effects to a great extent. As there is a high degree of randomness inherent in the rockfall motion, each case was tested three times and the mean value was taken as the final result, so as to improve the accuracy of the experiments. The test results including the uncertainties are shown in Table 3 (See Supplement).

R 6: Section of ‘Conclusions’: It is interesting to see some comments from the authors on non-spherical rocks. In nature the shape of rock is always non-spherical or polyhedral. In addition, treating rocks as non-spherical bodies is nowadays already ‘standard’ for rockfall simulations such as in RAMMS::ROCKFALL (Leine et al., Simulation of rockfall trajectories with consideration of rock shape, Multibody System Dynamics, 2014). From the authors’ point of view, how will rock geometry inïňĆuence the conclusions obtained in this work?

AC: Thanks for the reviewer’s suggestion. Compared with the non-spherical bodies, spherical bodies with same quality are relatively difficult to be resisted by the same control methods through a large number of tests. such as in (Asteriou et al, Empirical Model for Predicting Rockfall Trajectory Direction, Rock Mech Rock Eng, 2016). The

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effect of shape was examined by performing tests with spherical and cubical blocks. Spherical blocks presented higher and more consistent COR values compared to cubical blocks. The difference in the scatter of the values is attributed to the contact coniňĄguration of the blocks; spheres impact in a repeatable manner while cubes have numerous different coniňĄgurations. A phenomenon is also reported in (Leine et al., Simulation of rockfall trajectories with consideration of rock shape, Multibody System Dynamics, 2014; Giani, G. Rock Slope Stability Analysis. Balkema, Rotterdam,1992) and it is suggested that tabular shaped rocks gradually become rounded and wheel-like due to sharp corners breaking off during the descent. Because the kinetic energy of rocks with non-spherical or polyhedral shape can be reduced more sharply during the process of rolling. If the designed cushion can resist the spherical rocks, and it also can resist effectively the non-spherical rocks. When designing the protective cushion, we should consider the serious conditions of spherical rocks to ensure fully the safety of worker, thus I think it is significant to perform cushion test using spherical rock, and rock geometry will have a slight influence on this conclusions.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2018-16/nhess-2018-16-AC1-supplement.pdf

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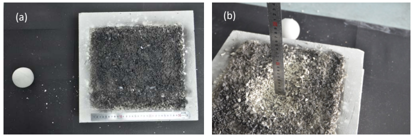

Fig. 7 Photographs of a cushion (a) before and (b) after a rock impact experiment

Fig. 1.

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