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Discussions

Interactive comment on "Effects of the impact angle on the coefficient of restitution based on a medium-scale laboratory test" *by* Yanhai Wang et al.

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I, on behalf of other co-authors, would like to express our gratitude for the reviewer's attitude towards the reviewing.

General comments: Most of the results given in the paper, in particular the variation of the coefficients of restitution as a function of the impact angle, were already reported in previous studies. It is not clear what this paper brings new to the research on energy losses during impacts. Please state clearly in the introduction what are the main questions that are posed at the end of the previous studies and needed additional experiments and answer to these specific questions in the conclusions. It is not clear

what people doing computer simulations of rockfalls should retain from this work and how they could use the presented results. I think that one important parameter that could allow us to better understand why kinetic energy losses are larger at high impact angles is the energy lost in rotational modes of the impactor. The more energy is dissipated in rotation after the impact, the less energy is restituted to the block as kinetic energy for rebound (cf Farin et al. (2015) Characterization of rockfalls from seismic signal: Insights from laboratory experiments, JGR:Earth Surface, Figure C1b). The authors could take advantage of the fact that their experimental setup has 8 cameras around the impact to measure precisely the rotation of the impactors before and after the impact and evaluate the rotational energy. This energy could be defined as 1/2* I * omega_rËĘ2, where I is the moment of inertia of the block (that could be approximated to a full sphere) and omega_r is its rotation speed. A figure showing the kinetic coefficient of restitution, Re, as a function of the rotational energy after impact could be interesting to show to bring additional contribution with respect to the previous work on the subject. Also, it is important to precise in the paper that the 'energy coefficient of restitution' is the 'kinetic energy coefficient of restitution', which does not represent the whole energy lost by the block but only the kinetic energy Ek lost. If a lot of energy is transmitted in rotation energy Er maybe the total energy of the block Ek + Er does not decreases at large impact angles (?). The authors suspect at several times in the paper that the impact speed has an influence on the coefficients of restitution. Thus, they should produce a Figure showing the coefficients of restitutions (and the rebound angle) as a function of the impact speed (event if only 3 different impacts speeds are investigated here, they could also use the data from previous work). Such a figure could support their discussion. I find that the discussion section is a bit difficult to follow. Maybe it could be reworked with subsections, discussing for example 'Interpretation of normal coefficient of restitution larger than 1', 'Relation between kinetic energy losses and normal coefficient of restitution': : :

Reply: Thanks you very much for your suggestion! The initial purpose of this study is to investigate whether the existing conclusions is valid when the test scale changes. To date, restrained by the measure devices, the existing laboratory test are mainly small scale tests. For the model test on coefficients of restitution, the similarity theory is still absent because the influence factors are much more than the material properties and sizes. It is questionable whether the test scale influence the laws regarding the effect of the impact angle on the coefficients of restitution. So, bigger samples and a new measure technique are adopted to perform a medium-scale test, and the above question is expected to be answered by the result comparisons between our test and the existing small scale tests. Considering comments by all reviewers, the rotation is involved in the calculation of the energy coefficient of restitution RE, and the role of rotation in the effect of the impact angle on the coefficients of restitution is investigated. Because the magnitudes of the total kinetic energy before impact varies, the percentage of the total kinetic energy converted to rotational energy is used as a reference. Results show that the percentage increases as the impact angle decreases, and large samples are more likely to have a stead and small percentage than small samples. A higher percentage always induces a higher Rn and a lower Rt. While, no clear correlations occurs between the percentage and the other two coefficients, Rv and RE. In the revised manuscript, this has been listed as another contribution of this study. Thank you again for your suggestion! In this study, the small scale tests performed by Chau (2002), Cagnoli and Manga (2003), Asteriou (2012) are selected in the comparison. It is our pleasure that Cagnoli has also posted his comments. The magnitude difference in the coefficients of restitution between the tests compared attracted our attention, and we considered the impact velocity difference as the main reason. Actually, this deduction is arbitrary, considering that those tests differ from each other in multiple test conditions listed in Table 2. Cagnoli suggested that "The small Rn values in Cagnoli and Manga (2003) are due to the weak strength of pumice whose damage upon impact dissipates energy" in the comment. In Asteriou's latest paper (Asteriou, P. and Tsiambaos, G.: Effect of impact velocity, block mass and hardness on the coefficients of restitution for rockfall analysis, Int J Rock Mech Min Sci, 106, 41-50, 2018), a free fall test is performed using spherical balls vertically impacting the surface, and

results show that Rn reduces when increasing the impact velocity, and increases as the material become harder. Because multiple factors can affect the magnitude, it is unreasonable to appraise the effect of one specific factor on the magnitude of the coefficient of restitution using data from the tests under various conditions together. The mean value of Rn versus the impact velocity in this study are drawn with different slope angles in the new manuscript as Fig. 7, and no determined trend is observable. We cannot make a definitive conclusion which factor is the main reason for the magnitude difference in the coefficients of restitution between the tests compared. I am very sorry for the poor structure in the previous manuscript. Considering all comments, the structure of the paper and all figures are rearranged. I hope the new manuscript has an easy access to be scanned.

The main changes in manuscript: Considering all comments, the structure of this paper is rearranged. All figures are modified and rearranged. The purpose of this study is described as: (1) to verify whether the test scale influence the laws regarding the effect of the impact angle on the coefficients of restitution, (2) to determine the role of rotation in the effect of the impact angle on the coefficients of restitution. Rotation is involved in this study. As a consequence, the kinetic energy coefficient of restitution RE is recalculated, and results of the kinematic coefficient of restitution Rv is added in this study. The fitting curve are replaced by mean value lines of data points, and the fitting formula is removed. In the original manuscript, we considered the impact velocity difference as the main reason for the magnitude difference in the coefficients of restitution between the tests compared. In the revision, we withdraw this deduction. The role of rotation in the effect of the impact angle on the coefficients of restitution is investigated. As the percentage of the total kinetic energy converted to rotational energy increases, Rn increases but Rt decreases. The percentage increases as the impact angle decreases, and large samples are more likely to have a stead and small percentage than small samples.

To special comments Abstract: - l14: the impact angle 'with respect to the slope' page2, L2: define the coefficient of restitution Reply: Thank you very much! In the revised abstract, the related sentence has been rephrase as your suggestion. Section 1 and 2 in the original manuscript are merged together and restructured as the introduction section in the new manuscript. The definition of the coefficient of restitution are given first, and then the previous study are illustrated.

Introduction: - l 26: 'the similitude requirements: : : cannot be easily matched': I do not understand this sentence. Please rewrite. Reply: When conducting a model test, the similarity ratio is usually important. While, a matured similarity theory is absent for those laboratory tests on the coefficients of restitution. The main reason is that the various factors are involved, such as the material properties, the shape of the rocks, the roughness, and the kinematic parameter. Thus, it is questionable whether the existing conclusions that the impact angle affects the coefficients of restitution based on small scale tests are valid when the test scale changes. In the new manuscript, the related sentence is rewritten. "Therefore, the existing results are restrained by the small scale of the laboratory tests. Influence factors are much more than the material properties and sizes, which induces the absence of the matured similarity theory for the model test on the coefficient of restitution (Heidenreich, 2004)."

page 2 L32: define the energy coefficient of restitution. 'The kinetic coefficient of restitution' is more appropriate. Reply: Thank you a lot! We have inspected the related literatures. Sometimes RE is called as the kinetic energy coefficient of restitution, and in some papers it is directly called as the energy coefficient of restitution. Of course, the first is more appropriate and it has been revised in the new manuscript.

page 2 l.34: Please do not give the same results as that given in the abstract. Please raise the general questions that require you to conduct additional experiments and that you answer in this paper, and answer these specific questions in the conclusion section. Sections 1.2 and section 2 should be merged with 1.Introduction and this whole section should lead to the problematic of the paper: what new contribution are you bringing to this research subject? To what questions are you answering? Reply:

Thank you for your suggestion! Section 1 and 2 in the original manuscript are merged together and restructured as the introduction section in the new manuscript. And the purpose of this study include: (1) to verify whether the test scale influence the laws that the impact angle affects the coefficients of restitution, (2) to determine the role of rotation in the effect of the impact angle on the coefficients of restitution. In the revised manuscript, the purpose has been stated in the ending of the introduction section.

- Page 3, L.15: ncor and tcor are never used in the following of the paper thus they should not be introduced. Reply: Thank you for your reminding! We have noticed the issue, and in the revised manuscript they are removed.

- Page 3, L.20: it could be also interesting to present the results for Rv as a function of the impact angle and the kinetic energy lost because lots of people are using this definition. Is it varying differently than Rn with the impact angle? Reply: In the original manuscript Rv wasn't presented because it is the square root of RE when the rotational energy isn't involved in RE. In the revised manuscript, the effect of the impact angle on Rv is also investigated, and the trend of Rv versus the impact angle is plotted as Fig. 5c.

- Page 4, l.2: ratio of kinetic energies Reply: Thank you for your reminding! In the revised manuscript it is revised.

- Page 4, l.26: 'the impact angle can influence the rebound angle': be more precise. Does the rebound angle increase or decrease when impact angle increases? Reply: Thank you a lot! In their paper, Cagnoli and Manga (2003) stated "The rebound angles are relatively larger at small and large impact angles with smaller values in between." In the original manuscript, we try to give a concise restatement while the meaning maybe unclear. In the new manuscript it has been revised as your suggestion.

Page 4, l.29: 'the kinematic coefficient of restitution Rv was more appropriate than the normal COR for use in correlations with the impact angles'. The relation between Rv and the impact angle should be also represented in this paper to check whether this statement is also true with the present experiments. Reply: Thank you for your suggestion! In the revised manuscript, the effect of the impact angle on Rv is also investigated, and the trend of Rv versus the impact angle is plotted as Fig. 5c. In this study this statement is not valid. Various functions have considered to match data points, but no function can provide a correlation coefficient R2 more than 0.40 in terms of Rv for all options considered. Power function provides the best R2 in matching data points of Rn, which reaches 0.80.

- Page 5, l.3-4: These are poor sentences to sum up the previous results and motivate your work. Please clearly state at the end of the introduction what is missing from the previous work and requires you to do additional experiments. Reply: You are right! This is caused by the poor structure of the original manuscript. In the new manuscript, Section 1 and 2 in the original manuscript are merged together and restructured as the introduction section. And our motivation are illustrated.

- Page 5, l.14: what is the 'rebound hardness value'? Does not it have units? I think it could be more useful to give the Poisson's ratios and Young's moduli of the materials composing the impactors and the slabs. For example, people may want to use your data to compute impact forces (for example using Hertz's impact model) and compare the impact forces to the coefficients of restitution and impact angles and such computations require the Poisson's ratios and Young's moduli. Reply: Thank you for your suggestion! In the first place, the 'rebound hardness value' represent the hardness value measured by Schmidt hammer method, and it has no units. Some scholars considered the hardness as the key factor in the determination of the coefficient of restitution. In the revised manuscript, we provided the Poisson's ratios and Young's moduli for the material, and replaced "rebound hardness value" by "Schmidt Hardness R", which is a more formal name.

- Fig 6: The coefficient of restitution does not seem to depend on diameter, except 2 data points of higher value for D=10cm at low impact angle. In fact, the theory says that the coefficient of restitution should not depend on impactor size for impacts on a

thick block (when the thickness of the impacted slab is large compared to the size of the impactor) and that the COR decreases as the impactor size increases when the impact is on a substrate whose thickness is small compared to the impactor size (cf Farin et al. (2015) Characterization of rockfalls from seismic signal: Insights from laboratory experiments, JGR:Earth Surface). The slab you are using could be considered as thin compared to the impactor size but because the slabs seem to be a bit buried in ground, they may be considered as thick substrates, thus the coefficient of restitution does not depend on the impactor size. A comment on this could be interesting to explain the fact that the measured COR is independent of the impactor size in your experiments. Reply: Thank you for your suggestion! The law that the impact angle influence the coefficients of restitution appears independent of the sample sizes in this study. Your excellent study supports our results and we have list it as a reference. It is very interesting that in this study the sample size can affect the percentage of the total kinetic energy converted to rotational energy, but cannot affect the effect of the impact angle on the coefficients of restitution. We have checked the related literature till now, and we can't find similar works. Because more detailed information, such as the erosion caused by each impact and the impact orientation during collision, is not recorded when performing the test, the further research is absent. It is a pity and we would like to investigate this problem in the future.

- All Figures in general: Please use a larger and sans-serif font to improve figures readability. Reply: Thank you for your suggestion! In the new manuscript the figures are redrawn as your suggestion.

- Figures 6, 7 and 8: I would use the same kind of scaling law (power law) for the 3 coefficients of restitution to compare them. A 2nd order polynomial law for figure 8 makes no sense because (1) you could fit everything why it and (2) you change your mind after that and use a linear law in figure 5c because it compares better with the previous results. Reply: You are right! Considering comments by all reviewers, the best-fit curve is replaced by the mean value line for data points in the related figures in the new manuscript. Considering the discreteness in data points, a general trend is more appropriate than a fitting cure to illustrate the effect of the impact angle on the coefficients of restitution. Although Wu (1985) suggested the linear correlation between the impact angle and Rn, Rt, a few literatures adopted the linear function to fit data points. In most literatures, data are not matched. In this study, test performed by by Chau et al. (2002), Cagnoli and Manga (2003), Asteriou et al. (2012) are selected to make a comparison. Cagnoli and Manga adopted a second-order polynomial to fit Rn, and adopted the linear function to fit Rt and RE. Asteriou adopted the power function to fit Rn and Rv. As your comment, we should pay more attention on the sence of the function adopted in fitting rather than their imitative effect. In the new manuscript, our efforts in matching data points are briefly described, and the related formula is removed. A conclusion which type of function should be recommended is not given, because the previous study and this study haven't provide sufficient evidence.

Please merge some of the figures together (e.g Fig. 2,3,4; Fig. 6,7,8; Fig. 12,13: : :) Reply: In the new manuscript the figures are merged as your suggestion and other comments.

Page 9, L.14: the sentence 'The values of Rt : : :' is unnecessary, one can read the values on the figure. Reply: In the new manuscript the sentence has been removed.

Page 10, L.5: the sentence 'The values of Re : : :' is unnecessary, one can read the values on the figure. Reply: In the new manuscript the sentence has been removed.

Page 10, L.16: Have you measured the depth of erosion created by the impacts? Maybe the largest impactor have caused more erosion of the slabs and thus lose more energy in deformation of the slab than the smallest impactors. A figure showing the energy lost as a function of the depth of erosion due to the impact could be interesting if you can do it. Reply: I am very sorry that more detailed information, such as the erosion caused by each impact and the impact orientation during collision, is not recorded when performing the test. We would like to investigate this problem in the subsequent

studies.

Page 12, L.3: 'The data points are stably located above the 45_ line until the impact angle reaches 36_' may be a clearer sentence. Reply: Thank you for your suggestion! In the new manuscript the sentence has been revised as your suggestion.

The '45_ line' is misleading because the compared variables are angles. The 'equality line' or 'y = x line' are other possibilities. Reply: Thank you for your reminding! In the new manuscript it is replaces by the "α=β line".

Page 12, l.5: 'the kinetic energy loss constituted 50-75% of the total kinetic energy' This is false: total energy also includes the rotation energy. Reply: You are right! Now the rotational energy is involved in the calculation of the kinetic energy coefficient of restitution. Therefore, the percentage is reduced. In the new manuscript, this mistake has been revised.

Page 12, l.6: 'the energy loss level cannot be assessed by comparing the rebound and impact angle': not clear Reply: Thank you for your suggestion! Results of our test shows that for a given impact angle, larger rebound angle doesn't means more kinetic energy dissipation than smaller rebound angle. The original sentence is not very clear. In the new manuscript, it has been revised as "Therefore, the ratio between the rebound angle and the impact angle cannot be directly used as a reference in estimating whether the energy loss level is high or low."

Page 12, l.18: Maybe you should directly compare your results with that of previous studies before drawing conclusions because your conclusions seem to change a bit after the comparison with the other studies (for example you say later than Rt does not depend on the impact angle and you change the scaling law for Re), thus sections 4.1, 4.2 and 5 are redundant and confusing. Reply: Thank you very much for your suggestion! Considering the purpose of this study, the paper is restructured. In the new manuscript, the results comparison between this study and the existing small scale tests follows the test results of this study, and they compose Section 3. The conclusion is given after the comparison. "Various experimental conditions induce different results for Rn, Rt, Rv and RE, although there are certain trends that occur regardless of the test conditions. The normal coefficient of restitution Rn, kinematic coefficient of restitution Rv and kinetic energy coefficient of restitution RE all decrease with increasing in the impact angle, while the tangential coefficient of restitution Rt increases as the impact angle increases in most cases."

Page 12, L.23 to Page 13 L.2: This should be in the introduction. Reply: Thank you for your reminding! In the introduction, tests conducted by Chau et al. (2002), Cagnoli and Manga (2003), Asteriou et al. (2012) had been briefly introduced. Here, the detailed test conditions of those studies are provided in Table 2.

Page 13, L.9: what is the 'ideal state'? If you observe rebound angles larger than 1.2 times the impact angle, there is a chance that we can also observe this in nature. You should not exclude data points just because they do not compare well to the previous work. On contrary, you should keep these points and interpret why you observe such situation in your experiments and why it is not observed in the previous work. Reply: Thank you very much for your reminding! In the revised manuscript, all data points are reserved.

Table 2 and Fig. 11: please replace 'Wang 2018' by 'this study' to avoid confusion. Reply: The words in the figure have been revised as your suggestion.

Page 15, L.3: 'The minimum Rn occurred: : : erosion and particle breakage'. This explanation that stronger kinetic energy dissipation due to erosion may explain the lower Rn value for Cagnoli's experiment does not work because (1) you also observe erosion by the impacts and the Rn in your experiments are larger and (2) you state later that the normal coefficient of restitution does not correlate with kinetic energy loss: : : Reply: You are right! This study verifies that the test scales don't alter the general law regarding the effect of the impact angle on the coefficients of restitution. The reason that causes the magnitude difference is still questionable. Cagnoli suggested that "The

small Rn values in Cagnoli and Manga (2003) are due to the weak strength of pumice whose damage upon impact dissipates energy" in the comment. The existing studies and this study cannot provide sufficient evidence to determine the reason, because the test conditions are different in multiple aspects. Asteriou indicated that Rn reduces when increasing the impact velocity, and increases as the material become harder in the latest paper (Asteriou, P. and Tsiambaos, G.: Effect of impact velocity, block mass and hardness on the coefficients of restitution for rockfall analysis, Int J Rock Mech Min Sci, 106, 41-50, 2018). This problem is proposed in the ending of Section 3.

Page 15, L.9-12: the exact scaling law that describe best the data is not very important given the large scattering in the data. What matters more is if you can explain the general trend. Also, if you give a scaling law for you data, you should also try to fit the data of the previous work with the same kind of scaling law. If the scaling law works for your data and not with the other work, its usefulness is very limited: : Reply: Thank you very much for your reminding! Considering comments by all reviewers, the best-fit curve is replaced by the mean value line for data points of this study in the related figures in the new manuscript. In section 3.2, the trend line for the existing small scale tests are drawn as the original literature. The lines with data markers are the mean value lines, while those lines without data markers are fitting lines.

Page 15, L.15: The variation of the kinetic energy COR with impact angle may be better understood if you also show the rotation energy (more energy dissipated in rotation means less energy restituted in kinetic energy for the rebound). You should not remove data points just because they do not compare well with previous work. Explain the difference otherwise the same conclusions could have been drawn by just comparing the previous work together and this present work contribution is limited. Reply: Thank you very much for your suggestion! It is unreasonable to exclude those "non-ideal data points" for a better fitting curve. When the rotational energy is involved in this study, some interesting phenomenon is observed. When the impact angle is small, two sample sizes appear a clear distinction in the percentage of the total kinetic energy converted to rotational energy. Small samples always induce bigger percentage than large samples. Considering that a higher percentage will results in a larger Rn and a lower Rt, the magnitude difference in the coefficients of restitution within the first impact angle interval is reasonable between two sample sizes.

Page 10, l.16: 'The impact velocity is an important: : : resulting coefficients of restitution': please show a figure of the CORs as a function of the impact speed (even including the previous work data) to support your conclusion. Reply: The magnitude difference in the coefficients of restitution between the tests compared was attributed to the difference in their impact velocity in the original manuscript. But, this deduction is arbitrary, considering the various test conditions. The mean value of Rn versus the impact velocity are drawn with different slope angles in the new manuscript as Fig. 7, and no determined trend is observable. The previous work data is not involved. In our opinion, to determine the effect of one specific factor on the magnitude of the coefficient of restitution using data from the tests under various test conditions together may be unreasonable. We cannot make a definitive conclusion which factor is the main reason for the magnitude difference in the coefficients of restitution between the tests compared.

Discussion section. Different things are discussed here, please add subsections to make the discussion clearer. Reply: Thank you very much for your suggestion! In the new manuscript, Discussion section is composed by three subsections.

Page 16, L. 24: I do not understand what you mean by 'with a parallel motion' Reply: I am sorry for the poor sentence. In the original paper, "with a parallel motion" means that only translational motion is involved. But we considers that this expression is also confusing. So, in the new manuscript, the related sentences are rewritten. "When the impact angle is sufficiently large to generate a rebound angle as the solid arrow, the border imposes no constraints on the rebound motion, and the sample can leave with the default rebound angle. But, when the impact angle is small and generate a default rebound angle as the dashed arrow, rotation motion must be involved to overcome the

constraint."

Page 16, L. 27: 'Therefore,ÂËŸa: : :' I do not understand the logical link with the previous sentence. If rotation speed has an important effect on rebound angle and coefficient of restitution, you should show it on Figures. Reply: Thank you very much for your suggestion! In the new manuscript, the direction transitions of translational velocities and the rotation are regarded as two consequence of the impact in Section 4. And the effect of the rotation on the coefficient of restitution is investigated. In the original paper, the logical link is not clear.

Page 17: I understand that basal roughness can lead to higher angles of rebound, but in this case, the impactors on intact slabs should have in average lower angles of rebound than impactors on eroded slabs. Can you draw a figure or give the average rebound angles on intact vs eroded slabs to support your discussion? If you measured the depth of erosion on the slabs, maybe the rebound angle could be correlated to with erosion depth (?). Reply: I am very sorry for the information isn't recorded. When one slab are too eroded, it is replaced by another one. For one specific slope angle, the data points from intact slabs and eroded slabs are mixed together, and we can't distinguish them now. And the depth of erosion is not measured for each impact. It is a pity. We would like to verify this phenomenon in the subsequent studies.

Page 20, l. 5: This conclusion does not bring anything new to the research. I believe you could draw much more results from you experimental data. Reply: Thank you very much for your encouragement! In the new manuscript, the contribution of this study is concluded as two points: (1) verified that several general laws occur when accounting for the effect of the impact angle, regardless of the test scales and conditions, (2) indicated that the rotation plays an important role in the effect of the impact angle on the coefficient of restitution. A higher percentage of kinetic energy converted to rotational energy always induces a higher normal coefficient of restitution Rn and a lower tangential coefficient of restitution Rt.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2018-108/nhess-2018-108-AC1-supplement.pdf

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