Answer to RC2

We earnestly appreciate your time in reviewing the manuscript as well as your valuable comments. Please find our corrections and responses to your comments and suggestions. The corrections are listed in this response and shown in the revised manuscript.

Comments (Scientific questions):

- **My main concern is that the basic mechanism that you consider is the simplest case when studying the stability of the subsequent blocks close to the cliffs fronts …**

Answer:

Thank you very much for your comments. In this answer, we try to further summarize the innovation and limitation of our model to clarify its basic mechanism. If it is not clear or not adequate, we will be very glad to hear your comments in the future.

This study supplements the basic LEM method with the consideration of eccentric effect. Meanwhile, in order to generalize the basic mechanism of rock blocks with cavity, the model in this study was proposed based on some simplifications.

Firstly, the traditional LEM method only calculates the global stability of rock blocks with natural cavities, which results in overestimation of the stability. Considering the non-uniform stress distribution due to eccentric effect, we introduce partial damage (compressive and tensile damage) of soft underlying layer into LEM.

Besides, since we use a 3D coordinate system and bending theory, it is difficult to consider diverse shapes of rock blocks and complicated fracture water in vertical discontinuities. Therefore, the rock block was simplified as a prismatic column with uniform water height in a fracture. Meanwhile, in the boundary discontinuities of sandstone, rock bridges probably exist to keep stable of rock block. However, the rock bridge is insidious and difficult to be ascertained. So, in this study, we discuss the most adverse state of rock blocks by assuming that the sub-vertical discontinuities has complete connectivity. In the future study, we will improve the basic mechanism of the model by considering complicated rock shape and fracture water state.

- **The next issue is not a limitation only of your method but is a general drawback of the LEM: it does not consider the deformations...**

Answer:

Thank you very much for your comments. This study was putted forward based on the basic assumptions of traditional LEM. Therefore, we don't consider rock deformation.

Besides, in the geological model of this study, there are two kinds of lithology. The sandstone doesn't present distinct deformation before failure because of its high stiffness. Slight deformations can be observed in mudstone before it fails, which usually manifest as rock structure damage, for example micro-fractures and cleavages. The influence of mudstone damage to rock block stability mainly lies in the accelerated weathering, retreat of basal cavity and stress redistribution, rather than the deformation of itself. Therefore, we think it is reasonable to follow the basic assumptions of LEM in this study.

In the text, the statement about rock deformation was not clear and concise. We have modified in the new version as follows.

"Mudstone is mainly loaded by compressive stress and tensile stress. When the compressive stress of mudstone exceeds its strength in the outer side, the initial damage appears partially. The effective contact surface between mudstone and sandstone is reduced, which aggravate the non-uniform distribution of stress. Therefore, the ability of mudstone providing resistance to the sliding and toppling of overlying sandstone will be reduced.

In the field, compression deformation of mudstone can be observed, which usually manifest as micro-fractures and cleavages. The deformation is very slight and slow in the short term. Besides, the LEM is essentially a Force/Stress approach that do not take into account the deformation. Therefore, in this study, it is assumed that mudstone is not subjected to deformations."

- **Thus, we have to be prudent when examining the results and when deriving conclusions. For instance, in lines 341-342 the authors are discussing some results with four decimal places…**

Answer:

In section 5.4, We have revised this problem.

"Fig. 14 shows that along with the increase of retreat ratio, the susceptibility level of rock blocks changes from low to moderate susceptibility. Corresponding to the critical state of $\min\{\mathrm{Fos}_{\mathrm{co}}, \mathrm{Fos}_{\mathrm{te}}\} = 1$ of all blocks, the minimum retreat ratio is 0.26, and the maximum retreat ratio is 0.41, which are marked by vertical gray dotted line in the Fig. 14. According to the statistics analysis of critical retreat ratios, both the mean and median are 0.33. Therefore, the critical retreat rate of the rock blocks in this study area can be determined as 0.33, which is marked by vertical red dotted line in the Fig. 14."

- **Another point arises here: Let's consider a 4m wide block with a cavity of 1 m, i.e. retreat ratio of 0.25, stable situation. What will happen if we find a new (or previously hidden) vertical discontinuity in the middle of the block? The retreat ratio changes suddenly to 0.5 and the block becomes unstable. This reasoning highlights the difficulty when trying to use the critical retreat ratio to new sites after the field reconnaissance.**

Answer:

Thank you for this insightful question. Micro-fractures or discontinuities likely form in natural rock blocks. The fully persistent discontinuities may disassemble the former rock block to multiple small ones and change the original stability. We think after field reconnaissance, in each specific site the block stability should be judged based on both critical retreat ratio and elaborative field investigation. The field investigation is supposed to ascertain the boundary condition of rock block at the present time. The random variation of boundary condition isn't easy to be involved in mechanical model.

Besides, inspired by this comment, we added an assumption in this model, "the sandstone block is assumed to be a complete body without persistent discontinuity, and it will not disintegrate before it falls."

- **The Conclusions section must be re-elaborated, now is too short.**

Answer:

The Conclusions section has been rewritten as follows.

"Due to differential weathering in sub-horizontal layers, multi-layer biased rockfall are developed on the slopes. In mountainous ranges, cut slopes, and coastal cliffs, the rockfall may cause significant facilities damage and casualties in residential areas and transport corridors. The aim of this study was to present a new three-dimensional analytical method for the stability of rock block with basal cavity. A non-uniform distributed force due to eccentric effect was applied at the contact surface, instead of a point force.

Taken the northeast edge of Sichuan basin in Southwest China as study area, the proposed method was used to calculate *Fos* of the biased unstable rock blocks. The results show that in natural scenario, the underlying mudstone of some rock blocks has been partially damaged, compression failure of the mudstone have been observed in the field. Some rock blocks will fail as a whole in rainfall or earthquake scenarios. The statistical analysis indicates that retreat ratio is the crucial factor influencing the *Fos* of biased rockfall. On the basis of different critical *Fos*, rockfall susceptibility was classified into three levels. As the retreat rate increases, the rock blocks undergo an evolution process from stability to partial instability and then overall instability. Based on the current mechanical parameters of eastern Sichuan basin, the critical retreat ratio from low to moderate rockfall susceptibility is 0.33.

The proposed method improves the three-dimensional mechanical model of rock block with basal cavity, by considering non-uniform distributed force at the contact surface, which could promote the accuracy of rockfall stability analysis. Due to the assumptions adopted because of the complexity of mechanical failure mechanism of biased rockfall, there are some limitations in this method, mainly including the simplification of boundary conditions and rock deformation. These limitations will be the important considerations in the future study."

- **We have added a section "Limitations" in Discussion.**

Answer:

5.5 Limitations

This study proposed an analytical model for three-dimensional stability of biased rockfall, combining the basic LEM method and the consideration of eccentric effect. Due to the complexity of rock structure and force analysis, it is necessary to highlight the limitations of this model.

First, we use a three-dimensional coordinate system and bending theory, it is difficult to consider diverse shapes of rock blocks and complicated fracture water in vertical discontinuities, the rock block was simplified as a prismatic column. The assumption of fully persistent discontinuities may underestimate the stability of rock blocks, it ignores the stress transmission in joints or rock bridges. Then, follow the basic framework of general LEM method, this study assumed that the rock is not subjected to deformations. The complete stress-strain behaviour such as the damage in mudstone layer was not considered in this study. Furthermore, the block stability is strongly influenced by the uncertainty of mechanical parameters. However, because of the difficulties in sampling strong weathered mudstone, it is difficult to obtain adequate parameter values for uncertainty statistics. These limitations will be the important considerations in the future study.

(Technical corrections)

- **Suggestion: Put all the appearances of *Fos* in italics.**

Answer:

We have corrected the appearances of *Fos* in full text. Thank you very much for all the comments about technical corrections.

- **Line 92: "absence of inventory data" … too sharp to say "absence". Even in your paper, you have some inventory data… I suggest saying "lack of complete inventory data".**

Answer:

"However, its application to rockfall hazards is limited due to the absence of inventory data (Budetta and Nappi, 2013; Malamud et al., 2004)."

->

"However, its application to rockfall hazards is limited due to **lack of complete inventory data** (Budetta and Nappi, 2013; Malamud et al., 2004)."

- **Line 100: I guess is "Fig.2c" instead of 2b.**

Answer:

"Frayssines and Hantz (2009) proposed the limit equilibrium method (LEM) to predict block stability considering sliding and toppling in steep limestone cliffs (Fig. 2b)."

->

"Frayssines and Hantz (2009) proposed the limit equilibrium method (LEM) to predict block stability considering sliding and toppling in steep limestone cliffs (**Fig. 2c**)."

- **Figure 2a, inset in the graph, "Sagaseta" instead of "Saganseta".**

Answer:

"*Saganseta(1986)*" **->** "***Sagaseta****(1986)*"

- **L.110: "to applied" -> "to be applied"**

Answer:

"The supporting force at the contact surface is assumed to applied at a point in the current LEM methods (i.e., N in Fig. 2 b and c)."

->

"The supporting force at the contact surface is assumed **to be applied** at a point in the current LEM methods (i.e., N in Fig. 2 b and c)."

- **Fig 3 caption: wording "tectonic sketch profile of A-A' "**

Answer:

"tectonic sketch profile of A-A" **->** "**tectonic profile of A-A', whose location is showed in Fig. 3b**".

- **Fig.3 caption: "serial numbers": I think it is not correct. Same in Table 1 columns header.**

Answer:
"serial numbers" -> "**numbers**"

- ***L. 144: "which" Do you refer to the slopes or to the blocks? "which are consists" wording.**

Answer:
"which" refers to the slopes. The statement was modified to "The slopes in the study area are consist of sub-horizontally interbedding of sandstone and mudstone layers. Therefore, there are multi-layer unstable rock blocks in the slopes."

- **L.80: As is the first appearance of "Eccentric effect", you must define/explain it.**

Answer:
We have added definition of eccentric effect in Introduction.
"Along with the retreat of basal cavity in mudstone layer, the gravity center of the overlying sandstone block moves outward in relation to the mudstone. In this case, the stress distribution in the contact surface of sandstone and mudstone is non-uniform. The mudstone in the outer side bears higher compressive stress than it in the inner side. This phenomenon can be defined as eccentric effect, which will lead to the damage of mudstone and failure of the overlying sandstone by toppling or sliding."

- **L.156, consider using triggering instead of predisposing.**

Answer:
We modify the sentence to "According to the rockfall events in this area, precipitation is the main triggering effect on rock instabilities"

- **Fig.5: lower or upper hemisphere? Which is the location of the data? E1 to E5 show quite different BP dip/dip direction…**

Answer:
The lower hemisphere is marked in new Fig.5. The location of the data is added in the caption of Fig.5 "The data was collected in the rockfall-prone area shown in Fig. 3d." E1 to E5 are all located in sub-horizontal layers. Their BP dips are relatively small. So, their BP dip directions are likely quite different.

- **L.170 "forces" -> "stresses"**

Answer:
"The underlying mudstone plays the role of a rectangular base, which provides non-uniform distributed forces at different locations."
->
"The underlying mudstone plays the role of a rectangular base, which provides non-uniform distributed **stresses** at different locations."

- **L183: consider deleting “The predisposing factor’s s of”. And start the statement: “Rainfall and earthquake …**

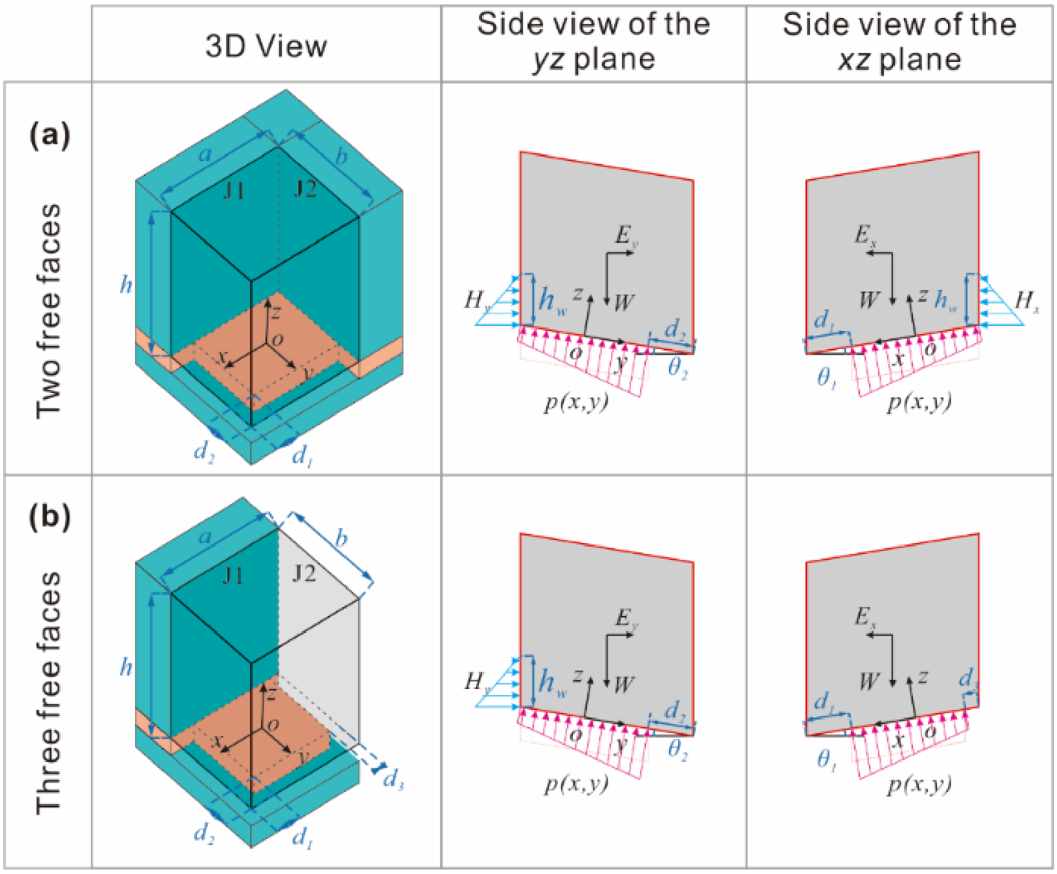
Answer:

We have changed the wording “Rainfall and earthquake decrease Fos by generating hydrostatic pressure H in the vertical crack and horizontal seismic force E on the block.”

- ***Fig 8: “x direction” must swap with “y direction”. “along” is a little ambiguous. Attention: the “z” axis can fall outside the drawings.**

Thank you for this comment. The statement is ambiguous in Fig. 8. In the new version, the two side views are labeled as *yz* plane and *xz* plane, respectively, and Fig. 8 has been corrected. Besides, in Section 3.1, we added a description of coordinate system in Fig.8.

“A Cartesian coordinate system is established in three-dimensional space for the force analysis. The origin O is located at the center of contact surface of sandstone and mudstone. For the case with two free surfaces, the orientation of the free surfaces is set to be the positive direction of x-axis and y-axis, respectively; For the case with three free surfaces, the negative direction of x-axis will also be a free surface. The joint J2 is perpendicular to x-axis, and joint J1 is perpendicular to y-axis.”



- **Fig 8 caption: “three free surfaces” -> “three free vertical surfaces”**

Answer:

“(a) and (b) represent the case of unstable rock blocks with two or three free surfaces, respectively.”

->

"(a) and (b) represent the case of unstable rock blocks with two or **three free vertical surfaces**, respectively."

- **L189: "Distributed force" … You mean "Stress distribution at the block base"?**

Answer:

"3.2.1 Distributed force"

->

"**3.2.1 Stress distribution at the block base**"

- ***L194: Are you sure of writing "bending moments"? This is not a beam, better saying "non symmetric stress distribution"**

Answer:

bending moments -> non symmetric stress distribution

- *** Eq. 8 &9: define the factors K1 to k3.**

Answer:

We further explain the role of the three coefficients. For different scenarios, the three Boolean coefficients enable the formulas to be expressed in a unified form.

k_1, k_2 and k_3 are the coefficients set to make Eq. (8) and Eq. (9) compatible with different calculation scenarios. So that Eq. (8), Eq. (9) and the following formulas can be expressed in a unified form. At natural scenario, k_1 and k_2 are both equal to 0. At rainfall scenario, $k_1 = 1$. At earthquake scenario, $k_2 = 1$. For the case of two free faces, $k_3 = 1$; for the case of three free surfaces, $k_3 = 0$.

- **L229: "underlying" sandstone? Rewrite all the line, please**

Answer:

"$p_p(x, y)$ provides support normal force for the underlying sandstone, and $p_n(x, y)$ provides tension force."

->

"$p_p(x, y)$ provides support normal force for the **overlying** sandstone, and $p_n(x, y)$ provides tension force."

- ***L236: "is not exists"? wording**

Answer:

Added description "For the case of anaclinal slope, the sliding direction is opposite to the free surface. Therefore, the rock block will not slide and Fos_{sl} is not considered in the model."

- **L 258: "aggregate" -> "consider simultaneously"**

Answer:

"It is necessary to aggregate four Fos to judge the stability of unstable rock mass."

->

"It is necessary to **consider simultaneously** four Fos to judge the stability of unstable rock mass."

- **L.264: "…blocks is" -> "blocks was"**

Answer:

"The size of the blocks is determined by on-site measurement with tape and laser rangefinder."

->

"The size of the blocks **was** determined by on-site measurement with tape and laser rangefinder."

- **L266: are ->were**

Answer:

"the morphological characteristics of mudstone foundation are mainly described with the average erosion depth of the cavity."

->

"the morphological characteristics of mudstone foundation were mainly described with the average erosion depth of the cavity."

- **L268: Consider rewriting "are abundantly recorded in the investigation reports and published literatures in this area."**

Answer:

The mechanical parameters of rock blocks were determined referring to the published literature and investigation reports in this area.

- **Table 2: Wording "obtained from the analytical method in section 3"**

Answer:

The title of Table 2 was changed to "Geometric parameters of rock blocks in study area and Fos results"

- **Table 2: consider drawing vertical lines between columns 12 and 13, 17 and 18, and 21 and 22, in order to group the *Fos* by scenarios….**

Answer:

We have added vertical lines between columns 12 and 13, 17 and 18, and 21 and 22 in Table2.

- **L280: Can you improve the section title?**

Answer:

We modified the title of Section 5.1 to "Characteristics of rock block stability".

- **L297: the statement "The shade of the points does not change significantly in the x-axis direction, which indicates that the dip of contact surface has little correlation with rockfall stability in this area" seems to me too audacious.**

Answer:

Thank you for your comment. We revised the statement to "The shade of the points does not change significantly in the x-axis direction as Fig. 11a shows. Therefore, compared with the maximum retreat ratio (r_{max}), the dip of contact surface has fewer influence on rockfall stability in the study area."

- **L300: the statement: "*Fos*$_{min}$ of the points in the upper part are all lower than the critical state (*Fos* =1)" is false.**

Answer:

Thank you for your comment. It isn't rigorous to divide these points by a straight line. In the new version, we delete this line in Fig. 11b and change the statement as follows.

"In Fig. 11b, as the retreat ratios increase in the positive direction of the x-axis and y-axis, the rock blocks show an obvious tendency to be unstable."

- **Fig. 11 caption: wording**

Answer:

We have modified the caption to "The correlation between Fos and the dip of contact surface and retreat ratio. α is the dip angle of the contact surface between rock block and underlying mudstone. r_x and r_y are the retreat ratio in x direction and y direction, respectively, equal to d_1/a and d_2/b. r_{max} is the larger one of r_x and r_y."

- **L312: What does it mean "near"? (the vertical axis is Log). L313: Wording: "…well agrees with the field insight, that is most rock blocks…"**

Answer:

We modified this paragraph in the new version.

"Instability of the blocks starts from the failure (or damage) of the foundation. Fos_{te} and Fos_{co} reach critical state much earlier than Fos_{sl} and Fos_{to}. This result is consistent with Fig. 10, in which 63.7% of the purple and green points (Fos_{te} and Fos_{co}) are located between $Fos = 0.7$ and $Fos = 2.0$. This result can be validated by the field phenomena. In the study area, the rock damage (e.g. micro-fractures and cleavages) can be observed in the underlying mudstone. However, most overlying rock blocks are stable at the present time. It means even if Fos_{sl} or Fos_{to} is higher than 1, in fact its foundation has begun to be damaged. In the case of heavy rain or earthquake, Fos_{sl} and Fos_{to} may be reduced to less than 1, and the rockfall will occur."

- **L351: Conclusions. Conclusions section: as stated in the general comments, more stuff must be derived from the study.**

Answer:

We have substantially revised the conclusion section and answered this question above.