Answer to RC1

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:

- **English language presents some mistakes throughout the paper and needs to be improved.**

Answer:

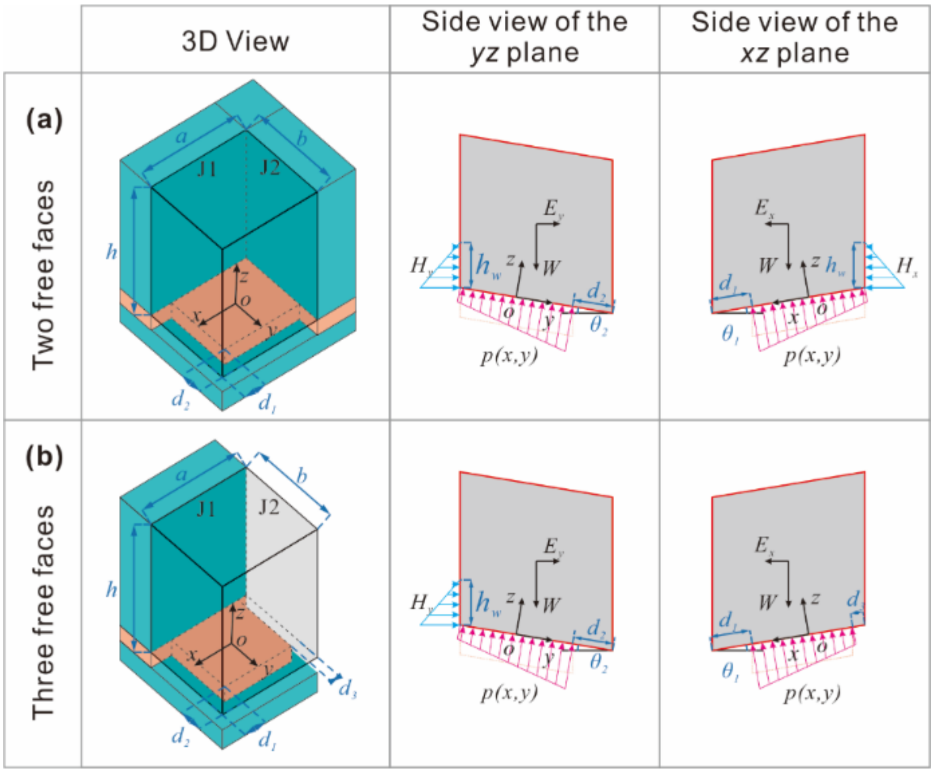
Thank you for your corrections. We have checked grammar mistakes and improved the wording in the manuscript. Then we further improved the full text according to the comments of reviewer #2.

If the language is still below the journal standard, we will be very glad to hear your comments and suggestions in the future.

- **Figure 8: it is unclear why for case b (three free faces) there is the scheme corresponding to the side view along the x direction (lower and right portion of the figure), since the corresponding face should not exist. Moreover, the upper captions (side view along the x and y directions) should be exchanged, according to this reviewer.**

Answer:

Thank you for your comments. There was ambiguity about the formulation of side view direction in the previous manuscript. The two side views are labeled as *yz* plane and *xz* plane respectively in the new version, and the figure has been corrected.



- **Line 156: the sentence "rainfall is the main predisposing factor of rockfall" is strongly questionable from a theorical point of view. Rainfall is universally known to be not a predisposing factor.**

Answer:

Thank you for your comments. In the universal theorical point of view, rainfall isn't a main predisposing factor of rockfall. However, in the study area, most of the historical rockfall events were recorded after heavy rainfall, because of the hysteretic draining of fissure water due to the obstruction of basal mudstone. The hydrostatic pressure caused by the transient steady flow during heavy rainfall triggers the detachment of rock blocks.

Therefore, in the new version we changed the wording as "According to the historical rockfall events in this area, precipitation is considered as a triggering effect of rock instability."

If it is still ambiguous, we will be very glad to hear your comment in the future. Thank you.

- **The coefficients k in all the equations at pages 11-13 are not introduced at all. Please, check that all the parameters mentioned are clearly defined in the text.**

Answer:

For different scenarios, the three Boolean coefficients enable the formulas to be expressed in a unified form. We explain the role of the three coefficients in the new version as follows. 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, $k_3 = 0$.

Besides, we have checked all the parameters in the manuscript to make sure they are clearly defined in the text.

- **The Authors state that, according to the results of in situ surveys, mudstone is not subjected to deformations (line 171). If so, why the need to introduce Fos corresponding to compressive strength (Fos_{co}) and tensile strength (Fos_{te}). What happens if these strength are reached? What is the effect of stresses exceeding strength in the mudstone? Please, clarify this point, since it represents a central innovative concept proposed in the manuscript, although it is not sufficiently described in detail.**

Answer:

Thank you very much for your professional comments. The expression in initial manuscript about the deformation of mudstone is ambiguous.

According to site survey, compression deformation can be observed in mudstone, which usually manifest as micro-fractures and cleavages. The deformation is very slight and slow in the short term. Therefore, when we analyse the rock block stability in the current state, the deformation of mudstone can be neglected. Besides, Fos_{sl} and Fos_{to} of rock blocks were calculated based on the the limit equilibrium method (LEM). If the deformation of underlying mudstone is considered, the model complexity will be greatly increased. So, in order to reasonably simplify the calculation model, the assumption is proposed that “mudstone is not subjected to deformations”.

Mudstone is loaded by compressive stress and tensile stress. When the stress exceeds the ultimate strength of mudstone, the strength of mudstone is reduced to residual value and the initial deformation appears. As previously mentioned, the deformation is slight, but the micro-fractures and cleavages will accelerate weathering and cause the retreat of cavity. Then, the consequent eccentric effect further increase the compressive stress and tensile stress loading on the mudstone. Therefore, stress exceeding strength in the mudstone will continually accelerate the retreat of mudstone cavity. Mudstone’s ability to provide resistance to the sliding and toppling of sandstone blocks will be reduced. Fos_{sl} and Fos_{to} will subsequently decline.

So we introduce Fos_{co} (in the form of the ratio of ultimate compressive strength to maximum compressive stress) to represent the current damage degree of mudstone due to compressive stress. According to the stress distribution pattern of rectangular shape foundation, the stress are redistributed in mudstone. When $Fos_{co} < 1$, it means that the compressive stress of some areas in mudstone exceeds the compressive strength. The partial areas, whose strength have not been exceeded, could provide support to overlying sandstone.

Theoretically, the upper resultant load is placed outside the core of mudstone, tension stress should appear at least in one corner of the mudstone (Fig. 7 Partially unstable state). Therefore, in the same way, we introduced Fos_{te} to represent the damage degree of mudstone due to tension stress. When $Fos_{te} < 1$, it means that the tension stress of some areas exceeds the ultimate tension strength. The smaller the value of Fos_{co} and Fos_{te}, the greater the damage to the underlying mudstone. The effective contact area between sandstone and mudstone becomes smaller as the development of compressive and tension damage, which significantly affects the stability of the overlying sandstone block.

If the above explanations are not clear or not adequate, we will be very glad to hear your comments in the future. Thank you very much.

We have modified the text in section 3.1 related to this comment 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.”

- **Related to the previous point, while the text portion corresponding to the 3D sliding and toppling stability analysis is not new and well-known in the literature, what should be the effect of a Fos_{co} lower than 1.0 from a physical point of view? Is actually important for the block stability? And what about the effect of a Fos_{te} lower than 1.0? The phenomenological and physical interpretation of these**

concepts seem to be not sufficiently investigated by the Authors.

Answer:

Thank you for your comment. The effect of Fos_{co} and Fos_{te} lower than 1.0 has been expound in the previous comment. The statement about the phenomenological and physical interpretation of Fos_{co} and Fos_{te} has been added in the new version.

"Fos_{co} and Fos_{te} represent the current damage degree of mudstone due to compressive stress and tensile stress. When the stress exceeds ultimate strength, the strength of mudstone is reduced to residual value, and the initial deformation appears. The ability of mudstone to provide resistance to the sliding and toppling of sandstone blocks will be reduced. Fos_{sl} and Fos_{to} will subsequently decline. The smaller the value of Fos_{co} and Fos_{te}, the greater the damage to the underlying mudstone. The effective contact area between sandstone and mudstone becomes smaller as the development of compressive and tension damage, which significantly affects the stability of the overlying sandstone block."

- **It seems that in eq. 31 and 32 the terms should be exchanged: σ_{tmax} tmax should refer to Fos_{te}, while σ_{cmax} refers to Fos_{co}. Again, terms σ_{tmax} and σ_{cmax} have not been defined in the text.**

Answer:

Two formulas were corrected in the new version. The two terms have been defined in the list of symbols, representing the ultimate tensile strength and ultimate compressive strength of mudstone, respectively.

- **Lines 289-290: if there is uncertainty related to the choice of the mechanical parameters, has been such uncertainty quantified? Why not providing a range of the parameter values to account for such uncertainty, along with the corresponding results in terms of Fos?**

Answer:

Thank you very much for your comment. Uncertainty quantification is important for the stability analysis of rockfall. In this manuscript, we mainly focus on the study of stability analysis model based on the traditional limit equilibrium method. Besides, mudstone is difficult to be sampled for laboratory test because of its strong weathering. Field test is an alternative solution, but it is also difficult to obtain adequate parameter values for uncertainty statistics. Therefore, we currently use the results of plate load tests in adjacent area (Zheng et al., 2021). Parameter uncertainty will be an important consideration for us in the future study.

- **Figure 10: if a large amount of cases provides Fos_{te} lower than 1.0, why have the authors not observed tensile failure in the field?**

Answer:

For the same reason as the previous comment, mudstone is difficult to be sampled for laboratory tensile test. So, in this study we valued the tensile strength based on its compression strength with a reduction coefficient of 0.11. According to the calculation results, tensile failure occurs only at a partial area inside the mudstone. Therefore, it is hard to directly observe the internal tensile failures in the field. In addition, partial tensile

failure of mudstone isn't equal to the failure of overlying sandstone. It only means the partial damage of mudstone, which will reduce its resistance to the sliding and toppling of sandstone blocks, and subsequently reduce Fos_{sl} and Fos_{to}. Then, for some cases with particularly small Fos_{te} (e.g. W06 Fos_{te} =0.15, W10 Fos_{te} =0.30), the blocks are still stable in the field, we agree with reviewer 2#'s comment "probably because the presence of rock bridges". This is a limitation of our method, which has been added in section 5.5 "Limitations" in the new manuscript.
If the above explanations are not clear or not adequate, we will be very glad to hear your comments in the future. Thank you very much.

We have modified the text in section 5.1 related to this comment as follows,
"The compression failure of the exposed mudstone can be investigated in the field survey (Fig. 4d). However, it is difficult to observe the phenomenon of tensile failure inside the mudstone base. In the case of weak tensile strength, the mudstone base will suffer from tensile failure, and the compression failure usually occurs before the tension failure."
We added a section in the new version to highlight the limitations of the model proposed in this study.
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.

- **Figure 11b does not show rmax, so line 299 is uncorrect. In general, Figure 11b is not adequately explained. Lines 300-301 are uncorrect, since Fos_{min} is not always lower than 1 for the points lying above the red dashed line (see points with 1.53, 2.95, 1.06).**

Answer:
The statement in this part is not rigorous, we have revised in the new version as follows,
"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. There is a significant positive correlation between the retreat ratio (r_{max}) and Fos_{min}. 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."

- **The relationship in Figure 11b (red line) cannot be considered to be generalized for block stability analysis, since the block stability is highly affected by the value of mechanical parameters chosen and the driving factors acting on the block (water level height within the joints, seismic actions), which have been assumed as fixed in the analysis presented. If these input data should vary, the corresponding Fos will change.**

Answer:

Thank you very much for your suggestion. The results in Figure 11b cannot be generalized for block stability analysis. So, we have modified this part concerned with the changing trends of relevant parameters.

"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."

- **Lines 308-315: this part of the text is highly important because it provides a global interpretation of the conceptual model proposed by the Authors, However, it is excessively synthetic, while it should be enlarged and enriched with a clearer description. The Authors should highlight in a clear way that compressive and tensile states within the block foundation do not provide global instability, as sliding and toppling, but could be only considered as preliminary signs of a possible future failure.**

Answer:

Thank you very much for your professional suggestion. we have revised in the new version as follows,

"Fig.12 shows the variations of Fos of two specific blocks during the evolution process of mudstone cavity. In the initial stage, the cavity is small, and the overlying block is stable, all Fos are greater than 1.0. The cavity expands over time as the mudstone weathers, then the contact area decreases and the non-uniform stress distribution occurs. When the stress exceeds the ultimate strength of mudstone in partial area, Fos_{co} and Fos_{te} decrease significantly as Fig.12 shown. Fos_{co} and Fos_{te} reach critical state much earlier than Fos_{sl} and Fos_{to}. To these two specific blocks, when the $\mathrm{r_{max}}$ increases to 0.4, Fos_{sl} and Fos_{to} are still higher than 1.0. It means that the rock blocks can still remain global stable in this condition.

These results further elucidate the stability analysis model proposed in this study. Fos_{co} and Fos_{te} introduced in this model present the damage state of basal mudstone caused by compressive and tensile stress, which do not provide global instability of overlying block as sliding and toppling. However, Fos_{co} and Fos_{te} are important preliminary signs of subsequent global failure of rock block. The damage in the basal mudstone could significantly accelerate weathering and prompt expanding of cavity, which will lead to the global failure. The lower the Fos_{co} and $\mathrm{Fos_{te}}$, the lesser safety margin the blocks have.

Therefore, the four Fos used in this study could provide a more comprehensive quantification of rockfall stability."

- **Figure 14: this reviewer again strongly suggest to avoid emphasizing excessively the generalization of the results in terms of threshold value for stability, for the same reason described above.**

Answer:

Thank you for the comments about result generalization. In section 5.4, in order to expand the practical significance of this conceptual model, we want to present an analysis method for the critical retreat ratio of potential unstable rock blocks with the same geological structure. Using the samples in the study area, the analysis process was demonstrated. The critical retreat ratio was calculated based on the results at natural scenario (as Figure 14 shows), which can be used for the preliminary identification of potential unstable rock blocks in routine field survey. These identified rock blocks would also be the primary focus when the study area encounters heavy rainfall and earthquake.

Besides, in order to confine the result generalization to specific scenario, we restrict the analysis conclusions to the current study area and further emphasize the influence of mechanical parameters on rockfall stability.

If the above explanations are not clear or not adequate, we will be very glad to hear your comments in the future. Thank you very much.

The results analysis of section 5.4 has been changed as follows,

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 $\min\{\mathrm{Fos_{co}}, \mathrm{Fos_{te}}\} = 1$ 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.

The critical retreat ratio calculated by this method can be used for the preliminary identification of potential unstable rock blocks in a specific area, which could help concentrating limited risk treatment resources on these priorities. It must be emphasized that the mechanical parameters and analysis scenarios significantly affect the critical value. Therefore, the elaborative risk control of a given rockfall should be arranged based on its specific parameters and analysis scenarios.

- **The Conclusions section**

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."