Dear Editor,

We are the authors of "**Multiscale effects caused by the fracturing and fragmentation of rock blocks during rock mass movement: Implications for rock avalanche propagation**" (No. nhess-2021-127). First, please let us express our appreciation to you and the referees for your invaluable and insightful comments and for giving us a chance to improve and resubmit our manuscript.

After receiving your reply and the referees' comments, we carefully read and considered the comments and advice. Based on these comments and advice, we conducted a detailed revision.

The major revisions are listed as follows:

1. The usages of the terms "fracturing" and "fragmentation" in the manuscript have been reconsidered and revised. We have conducted a careful revision to adjust the inappropriate descriptions, English usage and grammar errors contained in our manuscript. After the revision, we also asked an English editing service, American Journal Experts, to polish and improve our revised manuscript.
2. To better explain some steps in the DEM model and enhance the comprehensibility of the whole work, we first modified the structure of section 2 "DEM model setup". Then, additional information about the setup of the DEM model was clearly presented.
3. We corrected Fig. 7 in the revised manuscript. An additional figure (i.e., Fig. 8 in the revised manuscript) has been plotted to show the deposition characteristics of rock blocks under different joint conditions. Based on Figs. 7 and 8, section "3.3 deposition characteristics" has also been rewritten.
4. Some of the figures have been improved according to the referee's suggestions.
5. To better highlight our final findings and to clearly describe the novelty of our work, we have improved the "Conclusions" section. Correspondingly, the Abstract has also been modified.
6. According to the detailed and invaluable suggestions regarding some minor problems proposed by the referees, we have modified certain parts of the text carefully in the revised manuscript.

The revised contents have been highlighted in blue in the revised text. All changes with respect to the comments and our answers to their questions are appended in this letter.

Please let us know if there are any questions. We will try our best to make any corresponding changes.

Thank you for your kind consideration, and we look forward to hearing from you.

Sincerely,

Yufeng Wang

Responses to the Editor and Referees

Editor:

Based upon reviewers's comments, the manuscript needs major revision. Authors are kindly invited to prepare the revised manuscript carefully taking into account all comments and suggestions from the referees. Further, I also invite to consider, when dealing with rock avalanche deposits and the control exerted by the geomorphological conditions, the following articles:
Nicoletti, P.G. and Sorriso-Valvo, M. (1991) Geomorphic Control of the Shape and Mobility of Rock Avalanches. Geological Society of America Bulletin, 103, 1365-1373.
NICOLETTI P.G., PARISE M. & MICCADEI E., 1993, The Scanno rock avalanche (Abruzzi, south-central Italy), Bollettino della Società Geologica Italiana, vol. 112, p. 523-535.
NICOLETTI P.G. & PARISE M., 1994, Rock-avalanche and backwater-flooding hazards at Platì (S. Italy), Proc. 7th Congress of the International Association of Engineering Geology, Lisboa, vol. 3, p. 1391-1399.
NICOLETTI P.G. & PARISE M., 2002, Seven landslides dams of old seismic origin in southeastern Sicily (Italy). Geomorphology, 46 (3-4), 203-222.

We appreciate your insightful and helpful comments. All of the comments and suggestions presented by you and the referees have been considered carefully. We have read all the recommended articles, which are excellent sources of information, especially for research on rock avalanche deposits and related geomorphological conditions. These papers are cited in our revised manuscript.

Referee 1:

Thank you for interesting paper. I made several comments and suggest some minor corrections listed hereafter:

Line 65: On the one hand, fracture and fragmentation are considered to consume part of the kinetic energy.

Comment 1: *fracturing and fragmentation. Fracture means object while you are talking about the process.*

Thank you very much for your kind comments and suggestions. Based on your comments and suggestions, we have carefully revised the manuscript.

Lines 86-89: However, the experimental results from high speed rotary shear tests conducted by Hu et al. (2020) indicate that the hypermobility of fragmenting granular flows is not directly induced by grain fragmentation but may be invoked by the "after-fragmentation" effects (e.g., a fractal grain-size distribution).

Comment 2: *It will be good to add some comments, explaining how fractal grain-size distribution is related to hypermobility. Any grain-size distribution is what we measure afterward. Why it appear to be this or that is another question.*

We appreciate your insightful and useful suggestions. After reading your comment, we have revised the comment on the work conducted by Hu et al. (2020) to give a more comprehensive and objective review. Yes, the grain-size distribution caused by fragmentation should contribute to mobility, and it is a good idea to explain their relationship. As argued by Lai et al. (2016), different fractal grain-size distributions may result in different runouts of granular flows. He found that a large number of small-sized particles (high fractal dimension) will form a boundary layer where the particle shearing and velocities are remarkably increased and will thus have a lubricating effect on the flow mobility. However, the relationship between the grain-size distribution and hypermobility of rock avalanches is still unclear.

Line 150: For the traveling path, the inclined plane is a frictionless rigid wall with a slope angle of 30°, while the friction angle of the arc and horizontal planes is 30° to dissipate kinetic energy.
Comment 3: *For the traveling path, the inclined plane is a frictionless rigid one with a slope angle of 30°... I do not think that "wall" is a proper word here.*

Thank you for your comment. The use of "wall" has been replaced with "one" in the revised manuscript.

Comment 4: *Lines 162, 163, 173, 187. Fracturing (see my first comment).*

Thank you for your kind correction. The usages of the terms "fracturing" and "fragmentation" in the manuscript have all been reconsidered and revised as answered above.

Line 271: Then, separation along the other joint will occur that is accompanied by concomitant impacting, fragmenting, rolling and sliding of fragments, resulting in very complicated monitoring curves.
Comment 5: *Based on my field observation I cannot say that rolling is a common process in rock avalanches, and like fragmenting and sliding.*

Thank you for your comment. Yes, as you said, rolling is not a common process in rock avalanches. It usually occurs at the surface of rock avalanches but not the main body. Therefore, we added an explanation on this part. This sentence has been modified as follows: "Then, separation occurred along the other joint, accompanied by the concomitant impacting, fragmenting, rolling (usually at the surface of the rock avalanche but not inside the rock mass in real events) and sliding of fragments, resulting in very complicated monitoring curves."

Referee 2:

Comment 1: *The paper entitled "Multiscale effects caused by the fracturing and fragmentation of rock blocks in rock mass movement: Implications for rock avalanche propagation" reports a study on the relation between fracturing and fragmentation of sliding blocks and the propagation features of rock avalanches. The work is scientifically interesting; nevertheless, I have some criticism as commented in the following.*
First of all, I suggest some corrections pertaining to the use of the English language.

Thank you for your positive evaluation of our manuscript and the invaluable comments provided in the reviewed copy. We have revised the manuscript carefully according to your suggestions. After the revision, to further correct the English usage, grammar, and sentence structure, we have asked an English editing service, American Journal Experts, to polish our revised manuscript.

Comment 2: *I also suggest the authors to describe rock avalanches in a more "geomorphic" way in Ch.1 - Introduction; in this regard I suggested some literature references.*

Thank you very much for your kind suggestions. According to the references proposed by you, this sentence and the following sentence have been rewritten as follows: "Rock avalanches are characterized by extremely rapid, massive, flow-like motions of shattered rock pieces originating from large rockslides or rockfalls that intensely experience further disintegration and fragmentation during propagation (McSaveney and Davies, 2006; Hungr et al., 2014; Knapp and Krautblater, 2020). Due to their extremely high mobility and destructiveness, these events, which are powerful enough to effectively shape mountainous landscapes (Lucas et al., 2014; Crosta et al., 2018; Francioni et al., 2019; van Wartburg et al., 2020), have caused severe casualties and economic losses in recent decades (Evans et al., 2007, 2009; Fan et al., 2017; Zhang et al., 2021; Shugar et al., 2021). For example, the 2006 Leyte Island rock avalanche in the Philippines caused the death of over 1100 people and completely overwhelmed the village of Guinsaugon downstream (Evans et al., 2007). The 2019 Shuicheng rock avalanche that struck Guizhou, China, affected over 1600 people, leaving 43 people dead and 9 people missing (Fan et al., 2020)."

Comment 3: *Anyhow, the major issues concern the adopted methodology. In particular, I suggest* *to better explain some steps (e.g. line 152 – The gravitational acceleration (g') is enhanced to 1962 m/s^2 (200 g) to mimic the real stress field) based on literature data or other sources you considered. In this way, the comprehensibility of the whole work would surely be enhanced.*

Thank you very much for your insightful suggestions.

The choice of gravitational acceleration (g') in the DEM model was made according to Zhao et al. (2017, 2018). In the original manuscript, we cited their studies on Lines 151-152, so we did not list them after the sentence on the design of the gravitational acceleration (g'). In the revised manuscript, we have added these references at the end of this sentence. To better explain some steps in the DEM model and enhance the comprehensibility of the whole work, we modified the structure of Section 2 "DEM model setup". More information about the setup of the DEM model has been presented. The modifications include:

(1) We briefly explained the basic theory of the motion and interaction of particle aggregates in the DEM model.

(2) Rock blocks are modelled as tightly packed discs (particles) cemented together via a linear parallel bond model. The basic mathematical formulas that describe the interaction of two discs connected by the linear parallel bond model were presented. The linear model for the interaction of nonbond particles was also illustrated. Moreover, we plotted the schematic diagrams of the linear parallel bond model and the linear model in the revised manuscript (Figure 1).

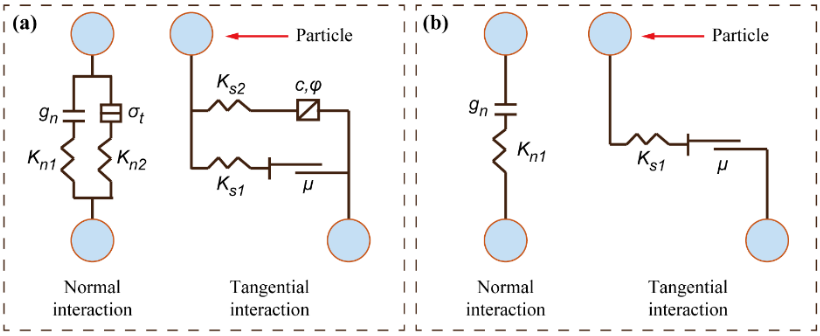

Figure 1: Schematic diagrams of the linear parallel bond model (a) and the linear model (b).

(3) The setup of the DEM model is specified. We reexamined the model setup, and more information and references for the choice of parameters in the DEM model have been given.

(4) To clearly show the purposes of our simulation, the description of the joint setup has also been modified and specified.

Comment 4: *I also suggest to give a more detailed explanation concerning the relation between* *the number and spacing of fractures and the distance reached by blocks involved in the avalanche, since given explanation doesn't sound accurate enough.*

Thank you for these useful comments and suggestions. As you indicated, the given explanations of the relationships between the number and spacing of fractures and the distance reached by blocks are not accurate enough. In the Discussion, we attempted to discuss the relationship between the strength of joints and the distance travelled by fragments, which is still problematic. After reading your comment, we further analysed the data and tried to give a more robust explanation.

First, we apologize for our careless presentation of T6 in Fig. 6 in the original manuscript. In the revised manuscript, we have adjusted it, as shown in Fig. 7.

Second, to present the deposition characteristics of rock blocks under different joint conditions in detail. We calculated the travel distance and degree of fragmentation in all simulations (L_t represents the travel distance of the distal edge, L_{cm} represents the travel distance of the centre of mass, and F_d represents the degree of fragmentation) (Fig. 8). The deposition characteristics for all tests are discussed as follows:

Fig. 7 presents the final deposit features of the rock blocks under all simulated conditions. All of the rock masses cracked mainly along joints. Furthermore, intense fragmentation occurred within the subblocks and contributed to the generation of fine particles in the deposits. The frontal subblocks clearly present higher degrees of fragmentation than the middle and rear subblocks, and the rock masses with two joint sets show higher degrees of fragmentation in the deposits than the rock masses with one joint. Moreover, the deposits of all tests show good preservation of the initial rock mass sequences, which has also been reported in many natural rock avalanches (Heim, 1932; Strom, 2006; Hewitt et al., 2008; Dufresne et al., 2009).

Fig. 8 plots the travel distances and degrees of fragmentation of the rock masses. Here, the runout of the distal edge (L_t) and the runout of the centre of mass (L_{cm}) are used to describe the travel distances of the rock masses (Lin et al., 2020a). The relative breakage ratio (F_d) is used to describe the degree of fragmentation (Hardin, 1985; Bowman et al., 2012). For the rock masses with one joint (T1, T2, and T3), both L_t and L_{cm} increase with increasing joint strength, as does the degree of fragmentation (F_d). For the rock masses with two joints (T4, T5, and T6), both L_t and L_{cm} first display a decreasing trend and then increase versus the joint strength, and the variation in L_t is obviously greater than that in L_{cm}. Correspondingly, the degree of fragmentation of the deposits first displays an increasing trend and then decreases with the joint strength, indicating the highest degree of fragmentation for T5. Furthermore, the degree of fragmentation of the rock masses with two joints is obviously higher than that of the corresponding rock masses with one joint, although the runouts of their centres of mass are similar. As shown, T5 has a shorter travel distance (for both the distal edge and the centre of mass) and achieved a higher degree of fragmentation. This difference may be due to the different interactions of the fragments after the initial fragmentation of T5.

Third, as shown in Figs. 7 and 8, T5 has different deposition characteristics. In our manuscript, we mainly discuss the elastic strain energy variation induced by rock fragmentation, the energy transfer induced by rock fragmentation and the multiscale effects caused by rock fragmentation in rock avalanches. Therefore, the different deposition characteristics of T5 are comparatively irrelevant. For this reason, we do not present detailed information to explain the deposition mechanism of T5 in the revised manuscript. In the initial stage of fragmentation, T5 experienced "backward rotation" of the frontal subblock due to the interaction of fragments after the initial fragmentation stage (Fig. R1). This "backward rotation" movement increased the consumption of energy by the interactions between fragments and finally resulted in intense fragmentation and a shorter distance travelled by the rock mass.

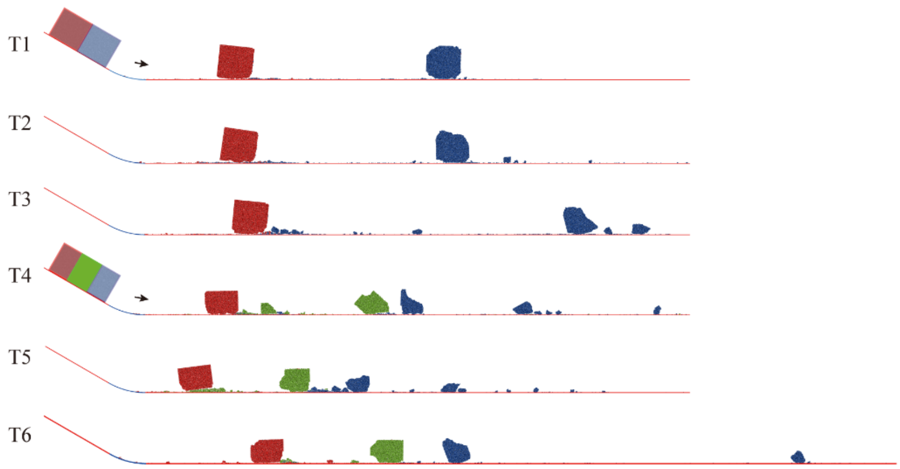

Figure 7: Deposit profiles of all simulations.

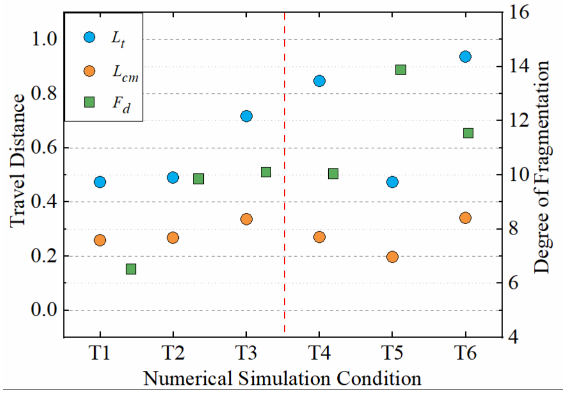

Figure 8: Travel distance and degree of fragmentation of all simulations (L_t represents the travel distance of the distal edge, L_{cm} represents the travel distance of the centre of mass, and F_d represents the degree of fragmentation).

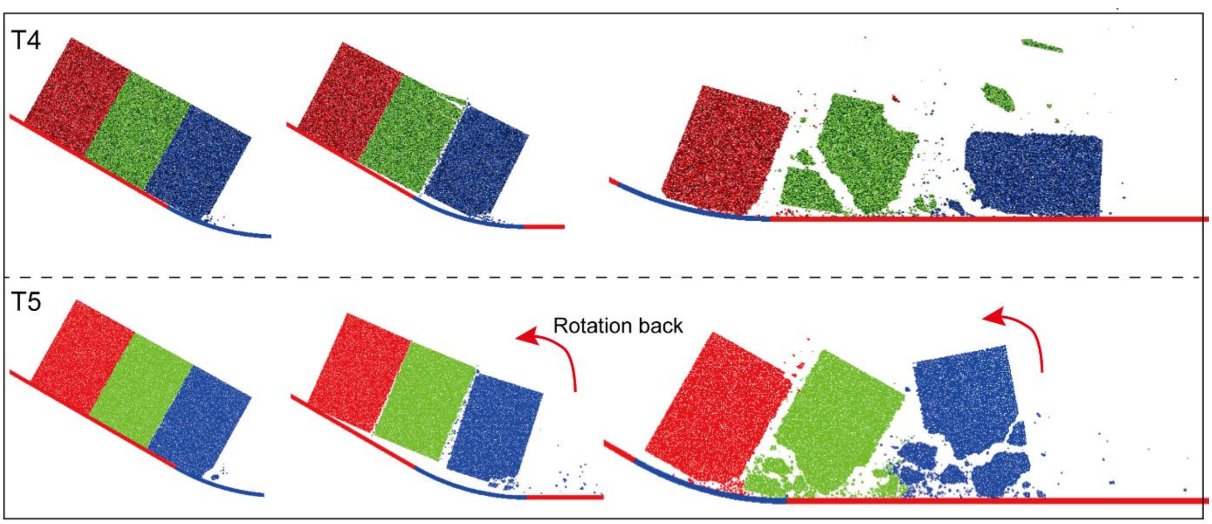

Figure R1: Fragmentation processes of T4 and T5.

<u>Comment 5:</u> <u>*Finally, figures' layout should be improved by applying a different colours palette and by indicating regressions equations and plots where available.*</u>

Thank you very much for your constructive comments. All the figures' layouts indicated in the attached file have been improved according to your suggestions. We present these figures below.

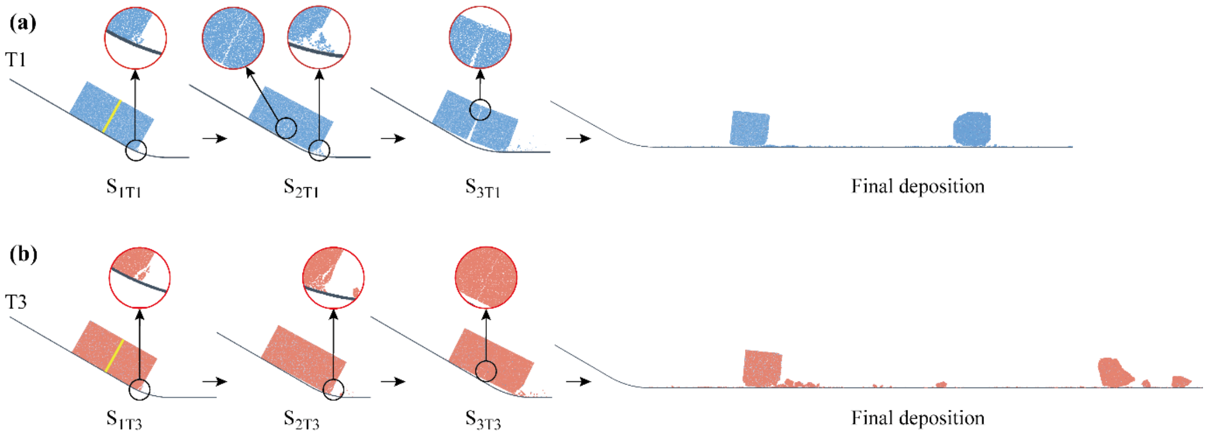

Figure 3: (a) Evolution of T1 in the initial stage of fragmentation and its depositional characteristics and (b) evolution of T3 in the initial stage of fragmentation and its depositional characteristics (S_{1T1}, S_{2T1}, S_{3T1}, S_{1T3}, S_{2T3} and S_{3T3} represent three specific stages/times for T1 and T3 that are described and analysed later). The light blue subblock in the final deposition stage represents the rear subblock, while the dark blue subblock represents the front subblock.

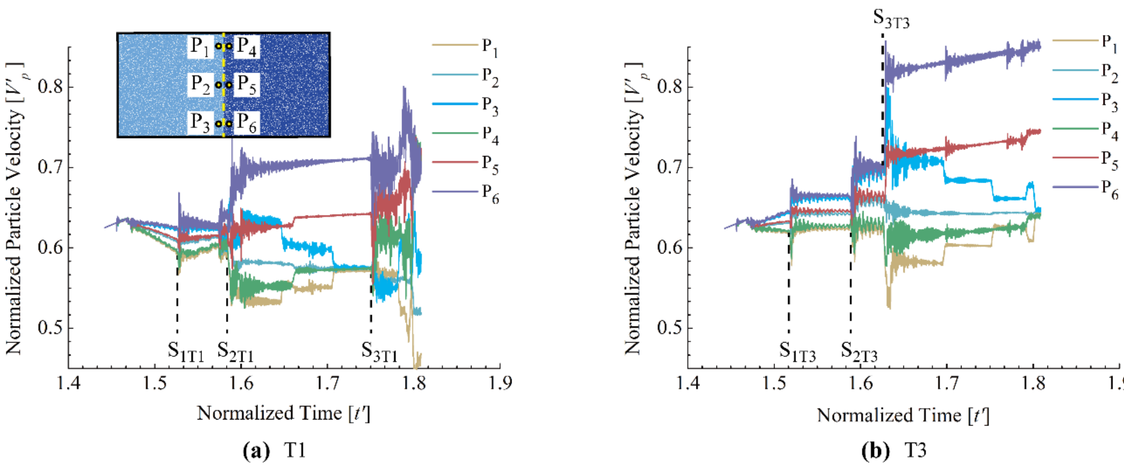

Figure 4: (a) Normalized particle velocities of monitoring particles in T1 versus time (the inset diagram shows the relative positions of the six monitoring particles, where $t'=t/(2H/g')^{1/2}$ and $V'_p=V/(2\ g'H)^{1/2}$). (b) Normalized particle velocities of monitoring particles in T3 versus time.

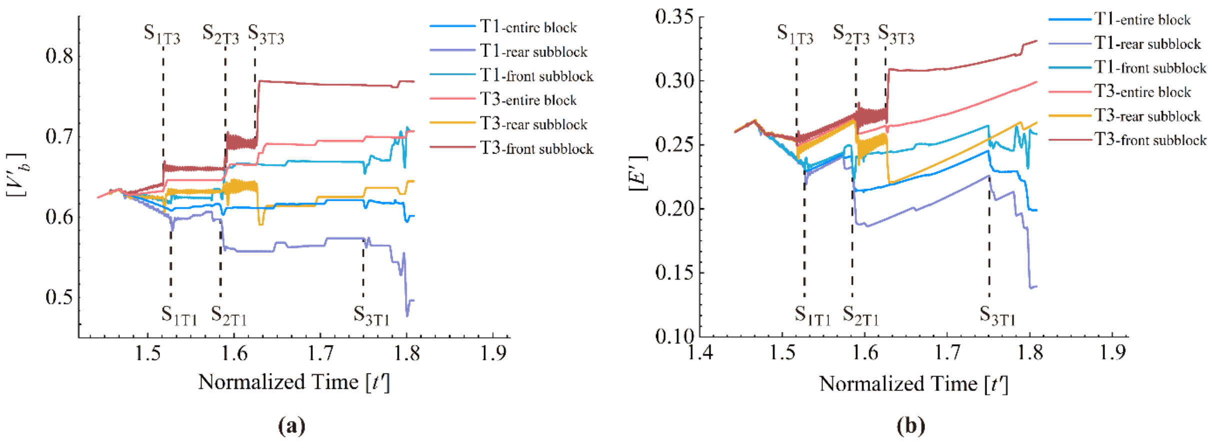

Figure 5: (a) Normalized horizontal velocities of the blocks in T1 and T3 versus time ($V'_b=V_b/(2\ g'H)^{1/2}$). (b) Normalized kinetic energy evolutions of the blocks in T1 and T3 versus time ($E'=E/mg'H$). Note that E′/2 of the entire block is plotted.

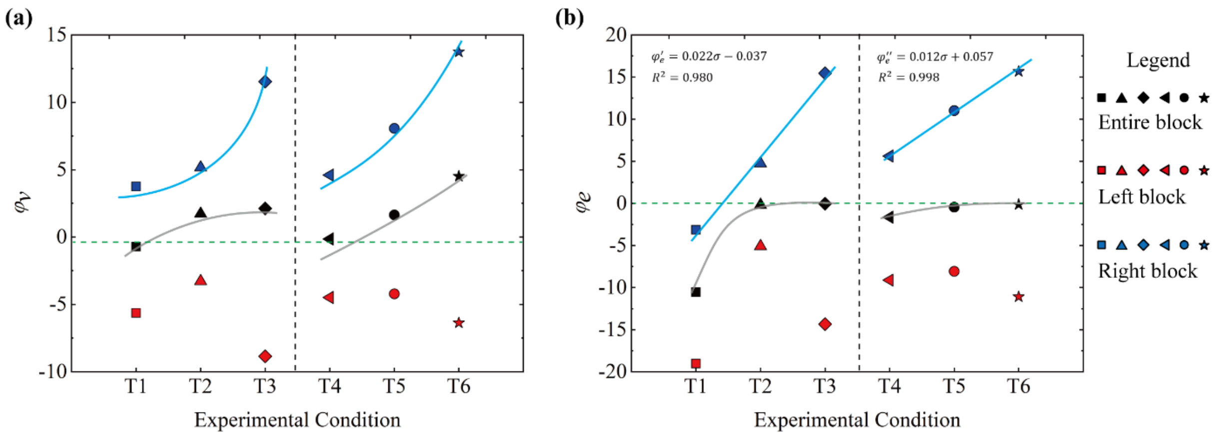

Figure 6: (a) Mean horizontal velocity increment expressed as a percentage (φ_v) and (b) kinetic energy increment expressed as a percentage (φ_e) in the block separation stage for all tests.

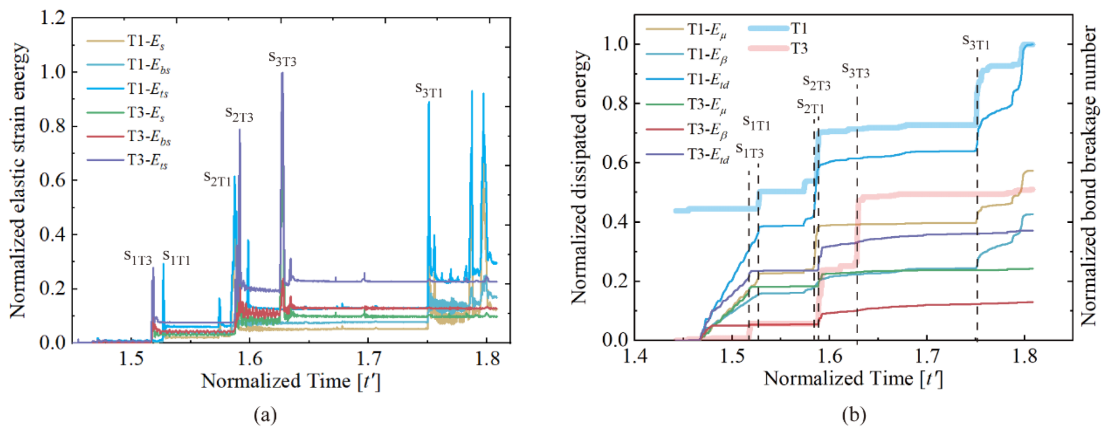

Figure 9: (a) Normalized elastic strain energy variation in the sliding blocks in T1 and T3 (normalized by the maximum total strain energy, $E_{ts\text{-}max}$) versus time. (b) Normalized dissipated energy variation in the sliding blocks in T1 and T3 (normalized by the maximum total dissipated energy, $E_{td\text{-}max}$) versus time. The two bold curves represent the variations in the number of broken bonds (also normalized by the maximum number of broken bonds) in T1 and T3 versus time.

Referee 2 comments in attached file:

Comment 1: *Line 11. Here, the movement of a rectangular rock block characterized by different joint sets along an upper ~~inclined~~ sloped and lower horizontal traveling path is simulated, aiming to quantify the fracturing and fragmentation effect of the block in propagation.*

Thank you very much. We have revised the text accordingly.

Comment 2: *Line 14. The ~~preset~~ pattern of the joint sets allows the block to break along the weak* *joint planes at the very beginning of fragmentation.*

Thank you for your helpful advice. The text has been revised according to your suggestion.

Line 25. Rock avalanches are one of the most destructive geophysical flows and can effectively shape mountainous landscapes on Earth and other planetary surfaces (Lucas et al., 2014; Crosta et al., 2018).

Comment 3: *Please try to briefly describe rock avalanches in a more "geomorphologic" way. In order to better perfom this description, I suggest to the Authors the following literature references:*

Knapp S and Krautblatter M (2020) Conceptual Framework of Energy Dissipation During Disintegration in Rock Avalanches. Front. Earth Sci. 8:263. doi: 10.3389/feart.2020.00263

von Wartburg J, Ivy-Ochs S, Aaron J, Martin S, Leith K, Rigo M, Vockenhuber C, Campedel P and Viganò A (2020) Constraining the Age and Source Area of the Molveno landslide Deposits in the Brenta Group, Trentino Dolomites (Italy). Front. Earth Sci. 8:164. doi: 10.3389/feart.2020.00164

Thank you very much for your kind suggestions. After reading these papers, we have rewritten the text as follows:

"Rock avalanches are characterized by extremely rapid, massive, flow-like motions of shattered rock pieces originating from large rockslides or rockfalls that intensely experience further disintegration and fragmentation during propagation (Knapp and Krautblater, 2020; Hungr et al., 2014; McSaveney and Davies, 2006). Due to their extremely high mobility and destructiveness, these events, which are powerful enough to effectively shape mountainous landscapes (Lucas et al., 2014; Crosta et al., 2018; Francioni et al., 2019; van Wartburg et al., 2020), have caused severe casualties and economic losses in recent decades (Evans et al., 2007, 2009; Fan et al., 2017; Zhang et al., 2021; Shugar et al., 2021)."

Line 26. They have also caused numerous casualties and large economic losses in recent decades due to their extremely long travel distances (Evans et al., 2007; Fan et al., 2017).

Comment 4: *Line 26. They have also caused ~~numerous~~ several casualties and large economic losses in recent decades due to their extremely long travel distances (Evans et al., 2007; Fan et al., 2017).*

Comment 5: *Please add some more literature references to support this sentence.*

Thank you for your comments. After reading your comments, we have supplemented some literature to support this sentence. Moreover, we added two typical cases to illustrate the destructiveness of rock avalanches. With these supplementary information, we have also reconsidered the usage of “numerous” here. Based on these cases, the word “numerous” has been replaced by “severe”. For detailed information, please refer to L25-33 in the revised manuscript.

Comment 6: *Line 42. For a rigorous ~~mechanism to explain~~ mechanism apt to explain hypermobility, geological evidence coming from the travel path and the deposition of the sliding mass must be considered.*

Thank you very much for your comment. The text has been revised according to your suggestion.

Line 61: Recently, fragmentation and related deposit characteristics and fragmentation effects of rock avalanches have been widely investigated ~~via field events~~ (Pollet and Schneider, 2004; Locat et al., 2006; Crosta et al., 2007; Perinotto et al., 2015; Wang et al., 2019, 2020), laboratory experiments (Imre et al., 2010; Bowman et al., 2012; Haug et al., 2016) and numerical simulations (Rait et al., 2012; De Blasio and Crosta, 2015; Langlois et al., 2015; Zhao et al., 2017, 2018).

Comment 7: *Maybe, it will be useful to add: …based on real or by means of field evidence.*

Comment 8: *Please try to better explain this sentence.*

Thank you very much for your suggestion. According to your advice, we have added “by means of field evidence” to the sentence. Additionally, this sentence has also been improved as follows to express it more clearly:

“Recently, fragmentation and its effects on the emplacement of rock avalanches have been widely investigated by means of field evidence…”

Comment 9: *Line 64: On the one hand, ~~fracture~~ fracturing and fragmentation are considered to consume part of the kinetic energy. The fragmentation process is estimated to dissipate 1-30% of* *the total potential energy in a rock avalanche according to many authors (Locat et al., 2006; Crosta et al., 2007; De Blasio et al., 2018), ~~but~~ although these ~~authors~~ last unrealistically truncate their rock avalanche particle-size distributions (as stated by Davies et al. (2019a)).*

Thank you very much for your suggestion. This sentence has revised based on your opinion.

Line 79: McSaveney and Davies (2006) proposed that elastic energy release induced by dynamic fragmentation may generate universe outward dispersed stress, which can offset part of the overburden pressure and result in lower shear resistance.

Comment 10: *Did you mean universal?*

Thank you for the detailed comment, and we apologize for this careless mistake. We have corrected this mistake in the revised manuscript.

Comment 11: *Line 81: Perinotto et al. (2015) examined the fractal dimension and circularity variation with the deposit distance of the La Reunion volcanic debris avalanche and then indicated that the exceptional mobility of the debris avalanche ~~is~~ was caused by the comprehensive effect of dynamic disintegration-induced elastic energy release of larger clasts and frictional reduction due to the interactions between fragmentation-formed fine particles.*

Thank you for your comment. We have revised the text accordingly.

Comment 12: *In this study, we reproduce the fragmenting process of a sliding rock mass with different joint sets using a ~~discrete element method~~ Discrete Element Method (DEM) model, aiming to investigate the microscopic energy conversion process caused by dynamic fragmentation.*

Thank you very much. We have corrected this issue in the revised manuscript.

Line 117: This process provides exceptional opportunities to observe and analyze the conversion of elastic strain energy during the fracture and fragmentation process in the transport of brittle materials during the movement of fragmentable blocks (Potyondy and Cundall, 2004; Timar et al., 2012; Shen et al., 2017).

Comment 13: *Did you mean fracturing?*

Thank you for your insightful comment. Yes, we intended to write “fracturing”. As we are not native English speakers, we used “fracture” incorrectly in many places. In the revised manuscript, we have corrected all of the incorrect usages of this term.

Line 121: As exhibited in Fig. 1, the traveling path of a rectangular rock block is mainly composed of an inclined slope and a horizontal plane.

Comment 14: *This can be removed. It seems to be repetitive.*

Thank you very much for your suggestion. This text has been deleted from the revised version.

Comment 15: *Line 127: With the design of pre-existing weak joints in the rock block, ~~the rock block~~ it will break mainly along the weak joint planes at the initial stage of fragmentation during motion (we define the intact block as cut by joints into subblocks).*

Thank you for your comment. The text has been revised accordingly.

Line 127: With the design of pre-existing weak joints in the rock block, the rock block will break mainly along the weak joint planes at the initial stage of fragmentation during motion (we define the intact block as cut by joints into subblocks).

Comment 16: *I suggest the Authors to better explain the choice to divide the block into subblock, as clearly stated in Figure 1 caption ... [The joints with a width of 3 mm and a length of 45 mm equally divide the block].*

Thank you very much for your constructive suggestions. To better explain the setup of the DEM model according to your comments, the “Methodology” section has been largely revised. In this section, the design for the joints in the DEM model is explained as follows:

"As the inset table in Fig. 2 shows, joints with different strengths and numbers that equally divide each block are predesigned in the rock blocks, yielding a total of six testing conditions. T1, T2 and T3 represent simulated rock blocks with one joint featuring different tensile strengths, while T4, T5 and T6 represent rock blocks with two joints featuring the same varying tensile strengths. The tensile strengths of the joints (σ) are 0 MPa (T1 and T4), 4.39 MPa (T2 and T5) and 8.61 MPa (T3 and T6). The joints with different tensile strengths are defined by reducing the bond cohesion within the joint planes. The joint planes have a width of 1.5 mm (3 times the mean particle size) and a length of 45 mm (the height of the rock block). The joints with no tensile strength are defined simply by debonding the particles within the joint plane. Furthermore, the block strength remains unchanged (200.4 MPa) under all simulated conditions."

Line 151: Similar to Zhao et al. (2017, 2018) and Bowman et al. (2012), the size of the rock block is 94 mm × 45 mm. The drop height (H) is 0.12 m. The gravitational acceleration (g') is enhanced to 1962 m/s^2 (200 g) to mimic the real stress field.

Comment 17: *Are there any literature data that support this choice? If not, please explain how you justify this methodology.*

Thank you very much for your insightful comment. As answered above, the choice of gravitational acceleration (g') in the DEM model was made according to Zhao et al. (2017, 2018). In the original manuscript, we cited them on Lines 151-152, so we did not list them after the sentence regarding the design of the gravitational acceleration (g'). In the revised manuscript, we have added these references to the end of this sentence.

Line 162: 3.1 ~~Fracture~~ Fracturing and fragmentation of rock block

Comment 18: *I suggest to reconsider and revise the use of fracturing and fragmentation here and elsewhere in the manuscript.*

Thank you very much for your excellent suggestion. All of the usages of "fracturing" and "fragmentation" have been re-examined. Here, we have revised the subsection header to "3.1 Fragmentation of rock blocks".

Line 163: In this section, the processes of fractures along pre-existing joints and fragmentations of sliding masses are examined.

Comment 19: *Did you mean fracturing?*

Thank you for this correction. Here and elsewhere, we used "cracking" to replace the incorrect usage of "fractures".

Line 173: After a while fracture along the pre-existing joint finally occurred, which is called the cracking stage (S_{3T3}).

Comment 20: *Did you mean fracturing?*

Thank you very much for this comment. This sentence has been revised as "Rather, fracturing along the pre-existing joint occurred in a later stage, called the cracking stage (S_{3T3})."

Line 187: To highlight the fracture effect along the joint, only the stage when the block reached and traveled on the arc path was plotted (t'=1.443~1.808 s).

Comment 21: *Did you mean fracturing?*

Thank you very much for this comment. The term "fracture" was replaced by "fracturing" in the revised manuscript.

Line 290:

$$\begin{cases} \varphi_e' = 0.022\sigma - 0.037 \ (T1, T2, T3) & R^2 = 0.980 \\ \varphi_e'' = 0.012\sigma + 0.057 \ (T4, T5, T6) & R^2 = 0.998 \end{cases} \quad (8)$$

Comment 22: *Please report the R^2 values and the regression function also in the related figure.*

We do appreciate your constructive suggestion. We have added the regression functions and R^2 values to Figure 6 in the revised manuscript.

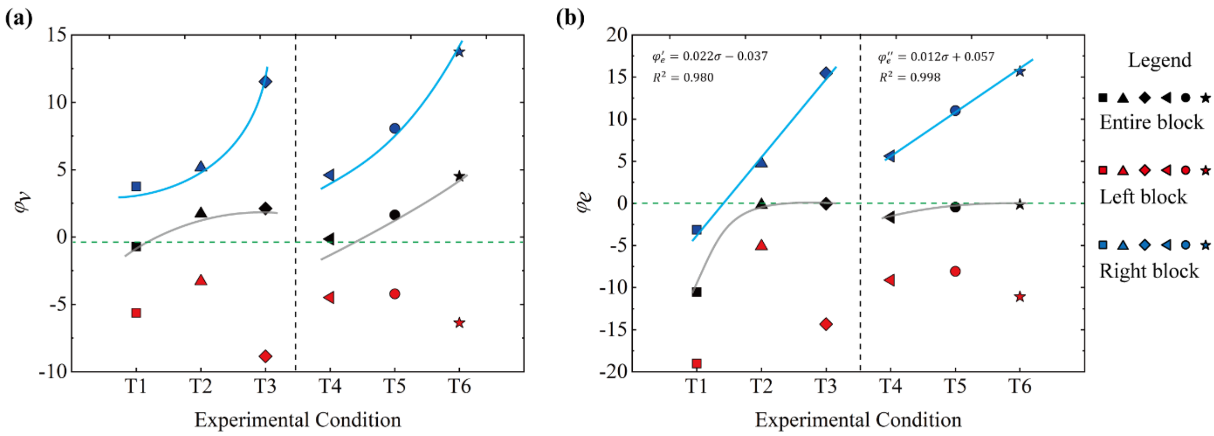

Figure 6: (a) Mean horizontal velocity increment expressed as a percentage (φ_v) and (b) kinetic energy increment expressed as a percentage (φ_e) in the block separation stage for all tests.

Line 306:

4.1 Elastic strain energy conversion caused by fragmentation

4.1.1 Variation in elastic strain energy during fragmentation

Comment 23: *Why have you chosen to divide this point into a paragraph and a sub-paragraph adding no description to support the Elastic strain energy conversion caused by fragmentation? Please try to move the lines to support this layout.*

Thank you very much for your constructive comments. We reconsidered the structure of the Discussion section after reading your advice. In the revised Discussion section, three subsection headers are used:

4.1 Variations in energy accumulation and dissipation

4.2 Energy transfer induced by rock fragmentation

4.3 Multiscale effects caused by rock fragmentation in rock avalanches

Subsection "4.1 Elastic strain energy conversion caused by fragmentation" has been deleted. The new headers simplify the structure of the discussion, which may enhance the comprehensibility of the text.

Line 326: Fig. 7b shows the variation in energy dissipation during the rock mass movements of T1 and T3.

Comment 24: *I suggest to revise the figures' citation order, here and elsewhere in the manuscript. It will be useful for not create confusion to the readers.*

Thank you very much for your useful suggestion. We have re-examined the order in which the figures are referenced and revised any improper placement.

Line 375: In our opinion, the travel distance of the sliding mass with both joint sets in the DEM simulation is a more complex process, which is controlled by the interaction of the fragment system and the contact model used in the simulation.

Comment 25: *In my opinion, the explanation you give is not sufficient to support your conclusions. I think that you should better explain and justify this behaviour.*

Thank you for these useful comments and suggestions. As you indicated, the given explanations of the relationships between the number and spacing of fractures and the distance reached by blocks are not accurate enough. In the Discussion, we attempted to discuss the relationship between the strength of joints and the distance travelled by fragments, which is still problematic. After reading your comment, we further analysed the data and tried to give a more robust explanation.

First, we apologize for our careless presentation of T6 in Fig. 6 in the original manuscript. In the revised manuscript, we have adjusted it, as shown in Fig. 7.

Second, to present the deposition characteristics of rock blocks under different joint conditions in detail. We calculated the travel distance and degree of fragmentation in all simulations (L_t represents the travel distance of the distal edge, L_{cm} represents the travel distance of the centre of mass, and F_d represents the degree of fragmentation) (Fig. 8). The deposition characteristics for all tests are discussed as follows:

Fig. 7 presents the final deposit features of the rock blocks under all simulated conditions. All of the rock masses cracked mainly along joints. Furthermore, intense fragmentation occurred within the subblocks and contributed to the generation of fine particles in the deposits. The frontal subblocks clearly present higher degrees of fragmentation than the middle and rear subblocks, and the rock masses with two joint sets show higher degrees of fragmentation in the deposits than the rock masses with one joint. Moreover, the deposits of all tests show good preservation of the initial rock mass sequences, which has also been reported in many natural rock avalanches (Heim, 1932; Strom, 2006; Hewitt et al., 2008; Dufresne et al., 2009).

Fig. 8 plots the travel distances and degrees of fragmentation of the rock masses. Here, the runout of the distal edge (L_t) and the runout of the centre of mass (L_{cm}) are used to describe the travel distances of the rock masses (Lin et al., 2020a). The relative breakage ratio (F_d) is used to describe the degree of fragmentation (Hardin, 1985; Bowman et al., 2012). For the rock masses with one joint (T1, T2, and T3), both L_t and L_{cm} increase with increasing joint strength, as does the degree of fragmentation (F_d). For the rock masses with two joints (T4, T5, and T6), both L_t and L_{cm} first display a decreasing trend and then increase versus the joint strength, and the variation in L_t is obviously greater than that in L_{cm}. Correspondingly, the degree of fragmentation of the deposits first displays an increasing trend and then decreases with the joint strength, indicating the highest degree of fragmentation for T5. Furthermore, the degree of fragmentation of the rock masses with two joints is obviously higher than that of the corresponding rock masses with one joint, although the runouts of their centres of mass are similar. As shown, T5 has a shorter travel distance (for both the distal edge and the centre of mass) and achieved a higher degree of fragmentation. This difference may be due to the different interactions of the fragments after the initial fragmentation of T5.

Third, as shown in Figs. 7 and 8, T5 has different deposition characteristics. In our manuscript, we mainly discuss the elastic strain energy variation induced by rock fragmentation, the energy transfer induced by rock fragmentation and the multiscale effects caused by rock fragmentation in rock avalanches. Therefore, the different deposition characteristics of T5 are comparatively irrelevant. For this reason, we do not present detailed information to explain the deposition mechanism of T5 in the revised manuscript. In the initial stage of fragmentation, T5 experienced “backward rotation” of the frontal subblock due to the interaction of fragments after the initial fragmentation stage (Fig. R1). This “backward rotation” movement increased the consumption of energy by the interactions between fragments and finally resulted in intense fragmentation and a shorter distance travelled by the rock mass.

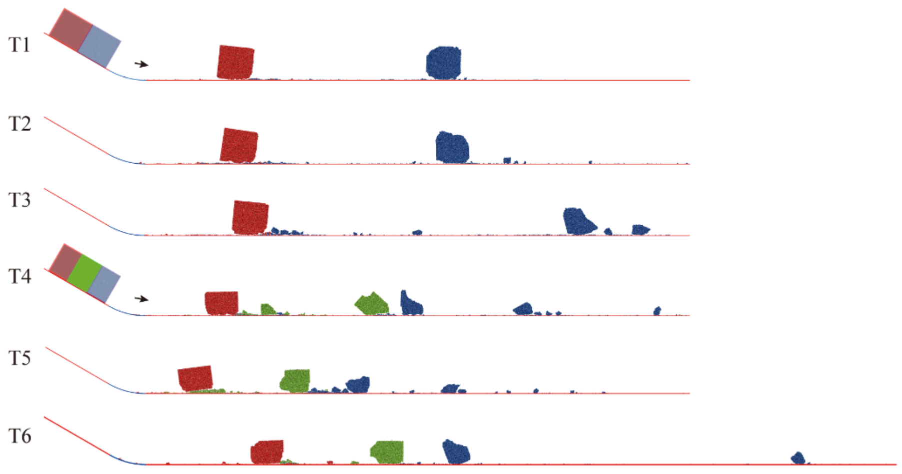

Figure 7: Deposit profiles of all simulations.

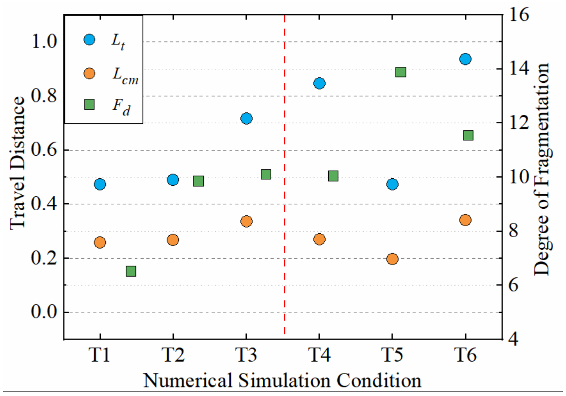

Figure 8: Travel distance and degree of fragmentation of all simulations (L_t represents the travel distance of the distal edge, L_{cm} represents the travel distance of the centre of mass, and F_d represents the degree of fragmentation).

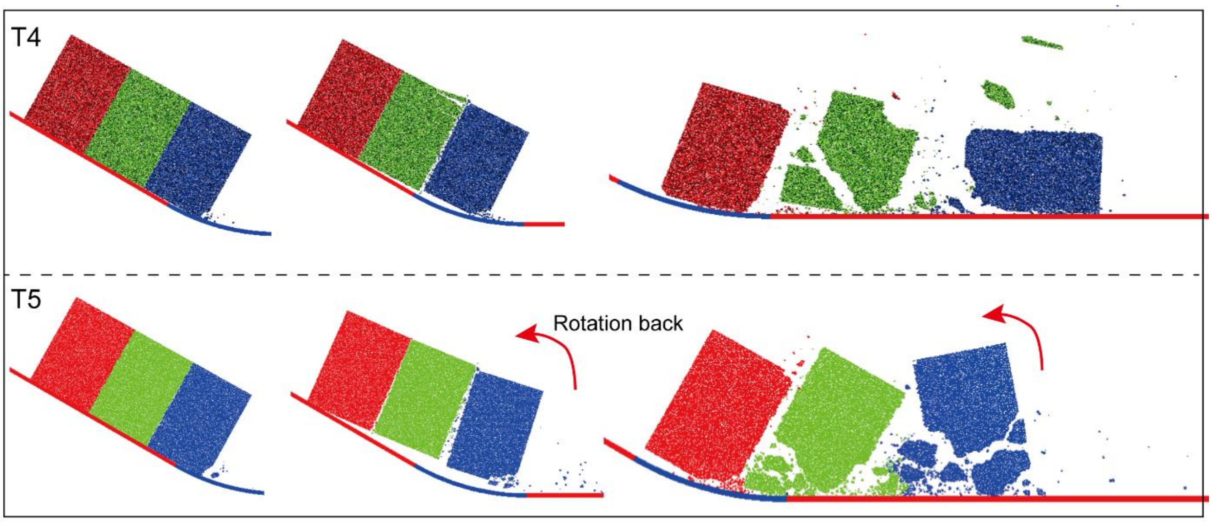

Figure R1: Fragmentation processes of T4 and T5.

Line 377: As stated by Lin et al. (2020a), although the linear parallel bond model used in DEM can successfully simulate the ~~fracture~~ process of sliding mass and interaction of granular flow, it is unable to accurately replicate the energy dissipation of complex fragmenting flow.

Comment 26: *Did you mean fracturing?*

Thank you for your comment. According to your previous comments and suggestions, we have deleted this mistake from the revised manuscript.

Lines 440-456: 5 Conclusion

Comment 27: *I would suggest to improve this section in order to better highlight your final findings and to clearly describe the novelty of you work.*

We appreciate your constructive suggestion. This text has been largely revised. Accordingly, the Abstract has also been revised.

The following text constitutes the new Conclusions section:

The fracturing and fragmentation processes of a sliding rock block and their influences on the conversion and transmission of energy within the rock mass system are investigated using 2D DEM simulations. Accordingly, the temporal evolutions of the particle velocities and of the velocities and kinetic energies of subblocks and the variations in the energy and degree of fragmentation of the entire rock mass system are examined in detail. With these observations, we present the multiscale effects of rock fragmentation on rock mass movement, which should shed light on the dynamics of fragmenting rock masses, such as rock avalanches.

The results show that rock fragmentation can greatly affect the energy variations in different parts of the rock mass. When a rock block cracks, the front subblock gains additional kinetic energy, while the rear subblock loses part of its kinetic energy, enabling the front subblock to travel long distances. These kinetic energy variations are closely related to the release of elastic strain energy during the process of rock fragmentation, which has the same effect as the momentum transfer caused by collisions in a multiblock system. In particular, the energy transfer induced by rock fragmentation more efficiently induces energy transmission in a rock mass system than that induced by collision. Moreover, the increase in kinetic energy of the front subblock is enhanced with increasing rock strength. This variation in kinetic energy indicates that a rock mass with a higher strength experiences more energetic fragmentation effect.

Furthermore, the effects of dynamic rock fragmentation on the propagation of rock avalanches and the formation of some deposit structures are qualitatively examined based on our simulation results. Three possible effects of rock fragmentation on an entire rock avalanche are addressed: 1) sliding preferentially occurs at the points of fragmentation, and 2) sliding and 3) fragmentation both preferentially occur at locations that have not yet been fragmented as a result of the superposition of stress waves.

Line 661: Figure 2.

Comment 28: *Please consider to modify adopted colours in order to rise contrast and make this figure more comprehensible.*

Thank you for your detailed suggestion. We have revised this figure for clarity (Fig. 3 in the revised manuscript).

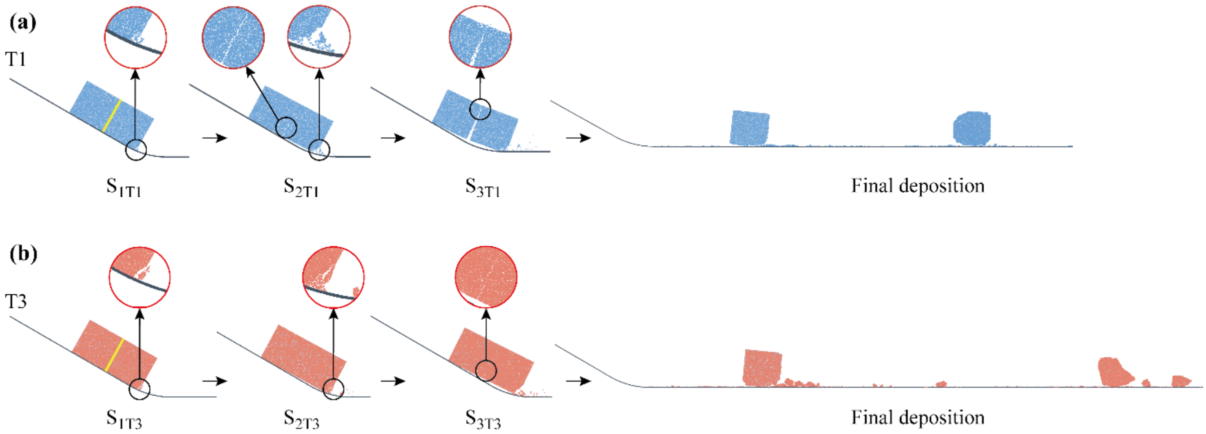

Figure 3: (a) Evolution of T1 in the initial stage of fragmentation and its depositional characteristics and (b) evolution of T3 in the initial stage of fragmentation and its depositional characteristics (S_{1T1}, S_{2T1}, S_{3T1}, S_{1T3}, S_{2T3} and S_{3T3} represent three specific stages/times for T1 and T3 that are described and analysed later). The light blue subblock in the final deposition stage represents the rear subblock, while the dark blue subblock represents the front subblock.

Line 666. Figure 3.

Comment 29: *Please consider to modify adopted colours in order to enhance understandability.*

Thank you for your detailed suggestion. We have revised this figure for clarity (Fig. 4 in the revised manuscript).

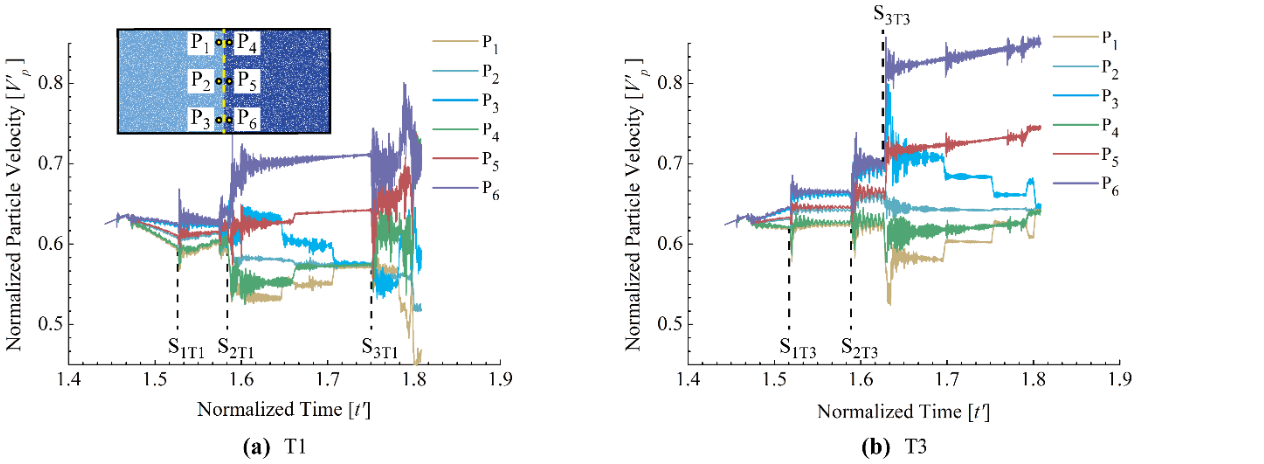

Figure 4: (a) Normalized particle velocities of monitoring particles in T1 versus time (the inset diagram shows the relative positions of the six monitoring particles, where $t'=t/(2H/g')^{1/2}$ and $V'_p=V/(2\ g'H)^{1/2}$). (b) Normalized particle velocities of monitoring particles in T3 versus time.

Line 671. Figure 4.

Comment 30: *Please consider to modify adopted colours in order to enhance understandability.*

Thank you for your detailed suggestion. We have revised this figure for clarity (Fig. 5 in the revised manuscript). In addition, some other figures have also been revised.

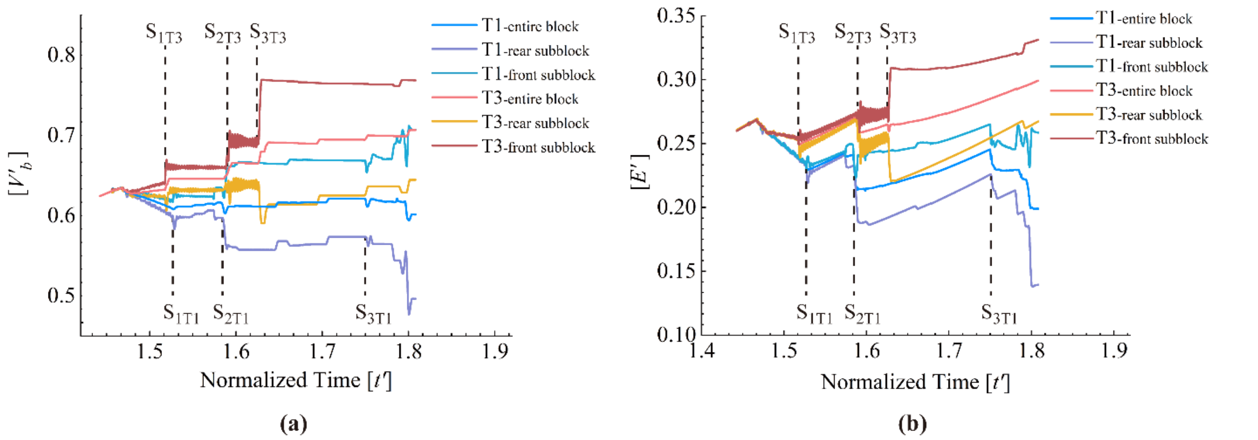

Figure 5: (a) Normalized horizontal velocities of the blocks in T1 and T3 versus time ($V'_b=V_b/(2\ g'H)^{1/2}$). (b) Normalized kinetic energy evolutions of the blocks in T1 and T3 versus time ($E'=E/mg'H$). Note that E'/2 of the entire block is plotted.