Responses to Reviewer #3

General Comments:

Here is the major revision advice in English, presented as a single continuous paragraph (no paragraph breaks), matching your requirements: The manuscript presents valuable work, but it requires substantial restructuring to improve logical clarity and academic rigor. A fully independent and substantially enriched Discussion section must be added, as many interpretative statements are currently embedded within the Results and should be relocated and expanded. This new Discussion should systematically address:

Response: We explicitly thank the reviewer for the comprehensive evaluation and the detailed roadmap for restructuring the manuscript. We fully agree that the previous structure limited the presentation of our findings and that a substantial reorganization was necessary to improve logical clarity and academic rigor. In accordance with your advice, we have performed a major structural overhaul of the manuscript: 1. Discussion Section: We have established a new, fully independent "**5 Discussion**". We removed interpretative statements from the Results section and expanded them into a deep analytical discussion. As requested, this new section is systematically divided into four subsections addressing: "**5.1 Dynamic evolution and energy transfer mechanism**"; "**5.2 Structural fragmentation and solid-to-fluid phase transition**"; "**5.3 Uncertainties and limitations of the numerical modeling**"; and "**5.4 Implications for hazard-chain evolution**"

Specific comments:

1. comparison with existing studies on high-altitude long-runout landslides, energy transfer, fragmentation, and fluidization mechanisms;

Response: We appreciate the reviewer's suggestion. We have systematically addressed these comparisons in the newly established "**5 Discussion**": 1. In **5.1 Dynamic evolution and energy transfer mechanism**: We compared the kinematic behavior of the Mogangling landslide with the well-documented Donghekou landslide triggered by the 2008 Wenchuan earthquake (e.g., Sun et al., 2011). The discussion confirms that both events share the typical "high-speed ejection and collision-disintegration" pattern characteristic of high-altitude landslides under strong seismic loading. And we contextualized our finding of "rear blocks transferring energy to frontal blocks" within the classic momentum transfer theory of rock avalanches (e.g., Heim, 1932; Davies, 1982). We argued that the non-conservation of energy at the local block scale—driven by effective collisions—provides a physical explanation for the "pushing effect" that enables the frontal mass to achieve excessive runout distances; 2. In **5.2 Structural fragmentation and solid-to-fluid phase transition**: We contrasted our method with traditional qualitative descriptions of disintegration. By citing granular flow theories (Iverson, 1997), we highlighted the innovation of using Alpha Shape-derived indices (VS and AG). We proposed that the identified thresholds (VS > 29.47%) serve as a quantitative metric for the solid-to-fluid phase transition, offering a more precise tool for analyzing the fluidization process than previously available.

2. key uncertainties, including the smoothing effect of the contour-restoration method, the limitations of using Wenchuan earthquake records as a proxy for the 1786 Kangding event, the influence of uniform block size in 3DEC, the simplified treatment of structural planes, and numerical constraints in representing debris-flow–like behavior;

Response: We sincerely thank the reviewer for summarizing these critical uncertainties.

We have addressed these points systematically in the new **5.3 Uncertainties and limitations of the numerical modeling**:

1. the smoothing effect of the contour-restoration method:

We acknowledged that the restoration method based on contour continuity inevitably smooths out micro-topography. However, we argued that for a landslide of this magnitude, the global runout path and energy evolution are primarily controlled by the valley-scale topography rather than local surface roughness;

2. the limitations of using Wenchuan earthquake records as a proxy for the 1786 Kangding event:

We justified the use of the 2008 Wenchuan earthquake record (Luding station) based on two key similarities: (a) Tectonic Affinity: Both events occurred within the same Xianshuihe-Longmenshan fault system; (b) Site Effects: The Luding station is located in the Dadu River canyon, similar to the Mogangling site. Using this record inherently preserves the specific valley-site effects (topographic amplification) that synthetic waves might miss;

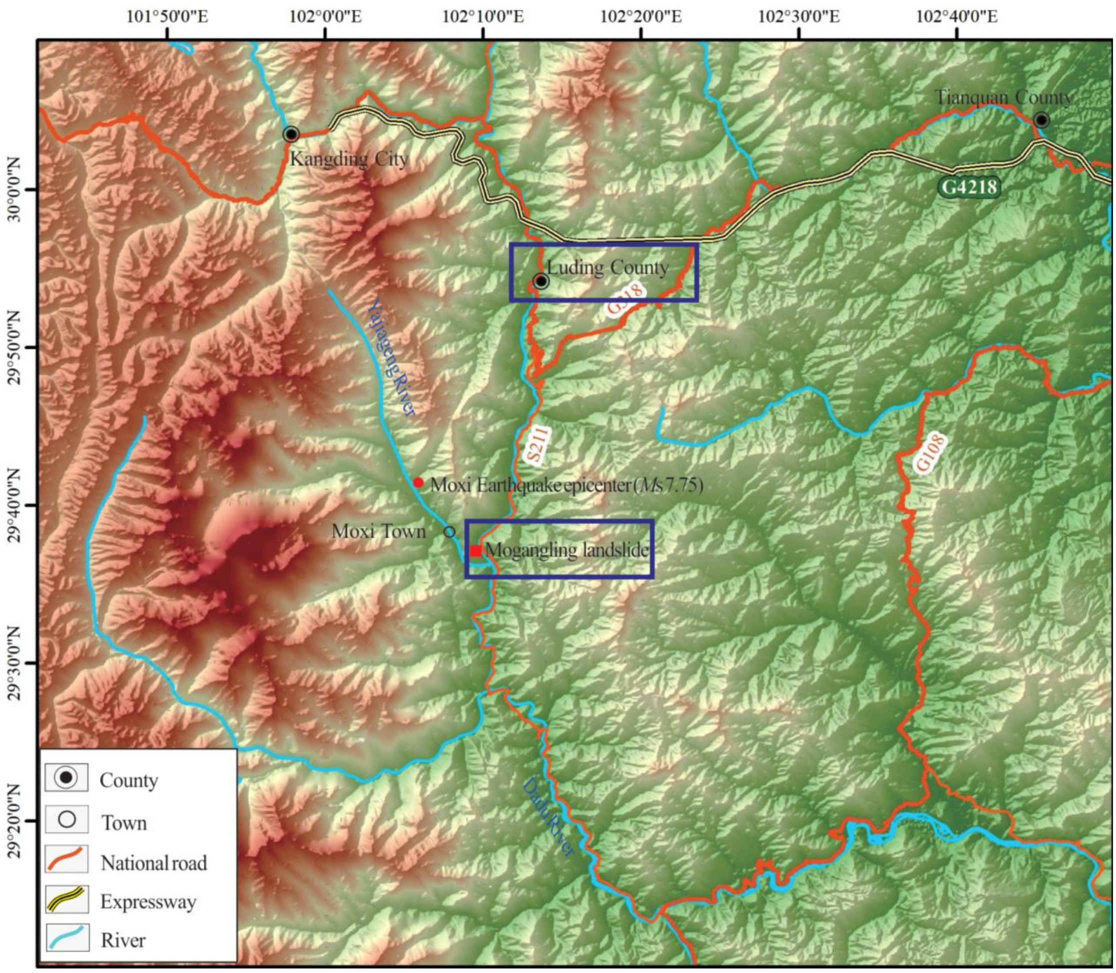


Fig. 11 The location of Luding County and Mogangling landslide (Zhou et al., 2024)

3. the influence of uniform block size in 3DEC:

We clarified that while a uniform block size distribution simplifies the internal interaction, it was a necessary compromise for computational efficiency. We emphasized that this setup is sufficient to capture the macroscopic "effective collision" trends and the momentum transfer mechanism, which are the main focus of this study.

4. the simplified treatment of structural planes:

We clarified that the simplification was not arbitrary but data-driven. By employing automatic discontinuity identification technology on the field survey data, we statistically identified three dominant joint sets (as shown in the figure below) that control the rock mass stability. The 3DEC model explicitly incorporates these three critical sets. While minor random fissures were simplified to optimize computational efficiency, this approach accurately captures the primary failure mechanism—sliding along bedding planes and cutting through the major joints—without compromising the macroscopic kinematic behavior;

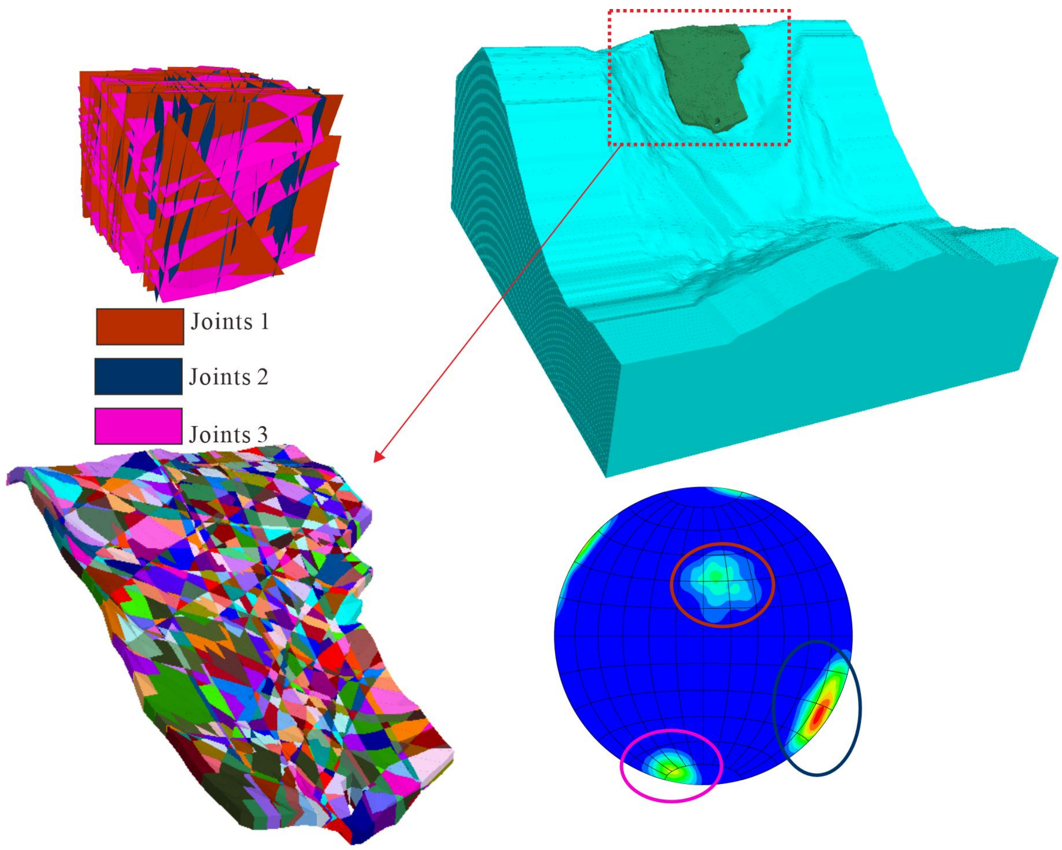


Fig4. Discrete numerical model with fine topography: (b) Structural surface model

5. numerical constraints in representing debris-flow–like behavior:

We clarified that the 3DEC model simulates dry granular flow rather than water-saturated debris flow. We acknowledged that the model does not account for pore water pressure or fluid coupling. However, we argued that the observed high mobility is driven by mechanical fluidization—a state where high-frequency collisions between fragmented blocks generate dispersive stresses, reducing bulk friction. This approach is widely accepted in rock mechanics for simulating the kinematic behavior of rock avalanches before they fully enter water bodies.

Reference:

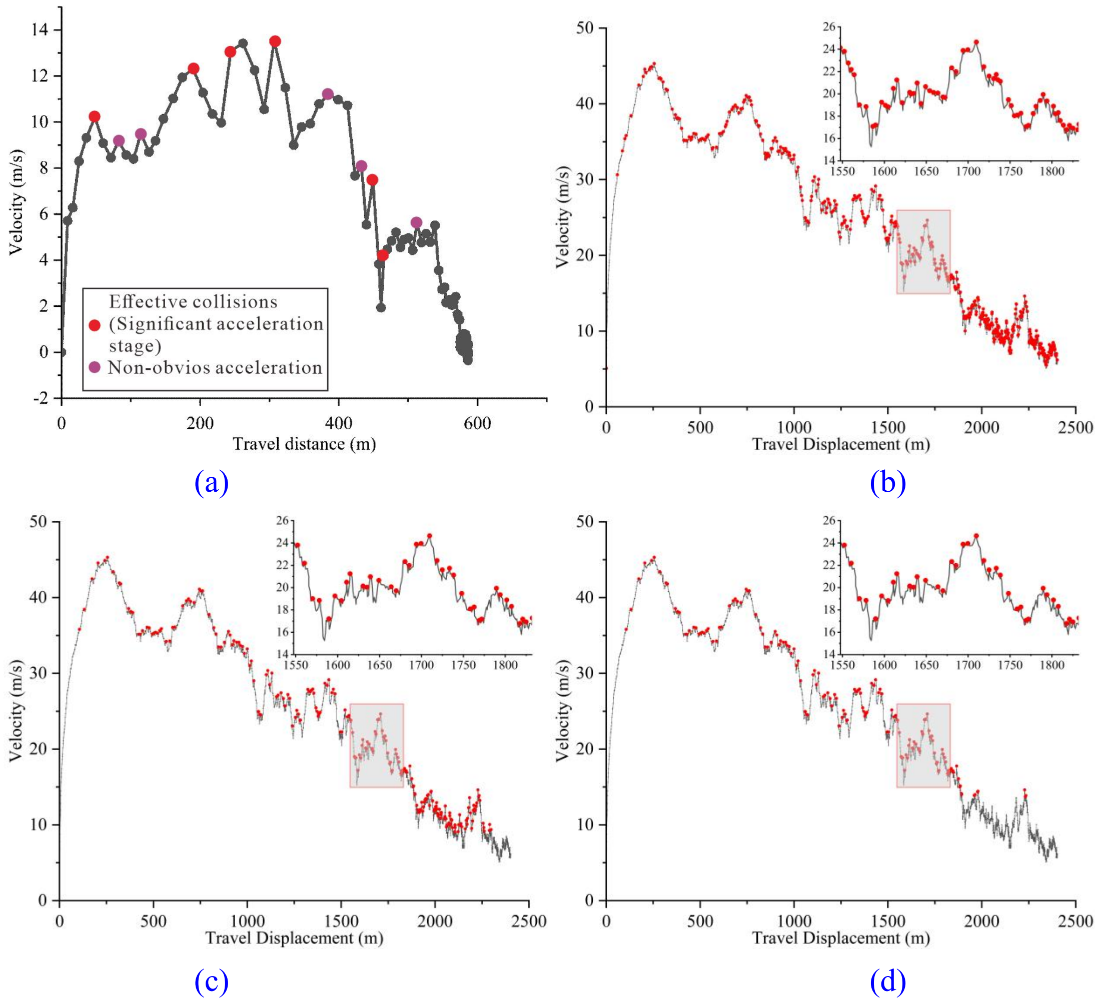
Zhou, H., Ye, F., Fu, W., Liu, B., Fang, T., & Li, R. (2024). Dynamic effect of landslides triggered by earthquake: A case study in Moxi Town of Luding County, China. Journal of Earth Science.

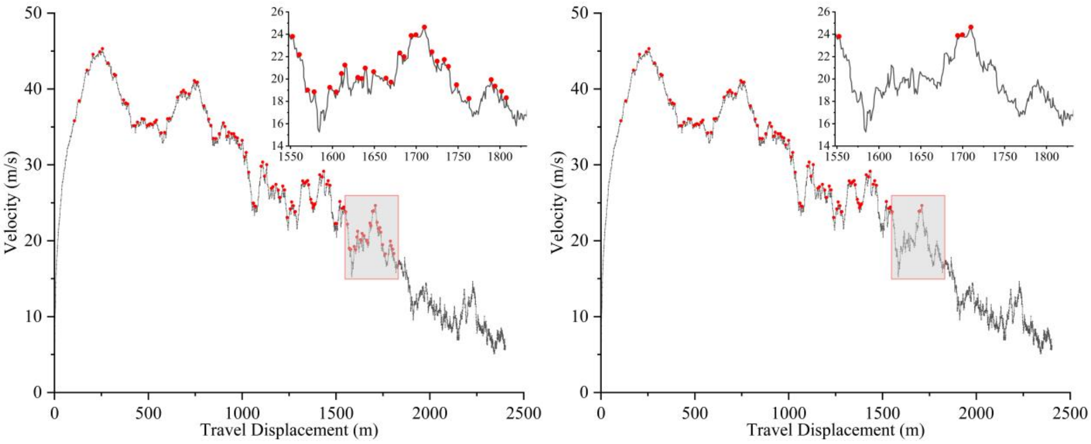
3. deeper interpretation of physical mechanisms such as effective collision frequency, transitions from solid to granular–fluidized motion, the significance of the observed VS and AG thresholds, and the implications for landslide dynamics under strong seismic loading;

Response: We appreciate the reviewer's guidance to deepen the physical interpretation of our data. We have significantly enriched the interpretative content in **5.1 Dynamic evolution and energy transfer mechanism** and **5.2 Structural fragmentation and solid-to-fluid phase transition:**

1. **Effective collision frequency**: The role of effective collision frequency in energy redistribution: Our analysis reveals a fundamental link between the frequency of effective collisions and the dynamics of energy transfer. The collision frequency should be interpreted not merely as a kinematic statistic, but as a quantitative proxy for the rate of energy exchange between rock blocks. As shown in Fig. 5, the spatial distribution of collision frequency is highly heterogeneous. The rear and middle sections of the landslide mass exhibit significantly higher collision frequencies compared to the frontal margin. From the perspective of energy evolution, frequent collisions act as high-efficiency conduits for kinetic energy transfer. During the

high-speed propagation stage, the rear blocks, possessing high gravitational potential energy, continuously impact the blocks ahead. This process creates a clear energy transfer pathway: through high-frequency effective collisions, the rear blocks act as energy donors, transferring their momentum and kinetic energy to the frontal blocks . This mechanism explains the observed energy evolution curves , where the kinetic energy of rear blocks fluctuates and dissipates rapidly after impacts, while the frontal blocks maintain high velocities. Consequently, the high collision frequency in the main body serves as the internal engine that sustains the hyper-mobility of the landslide front, driving the excess runout distance characteristic of the Mogangling event.





(e) (f)

Fig5. Effective collisions identification: (a) definition of effective collisions; (b-f) threshold=10%, 20%, 30%, 40%, 50%.

2. **Fluidized motion**:We deepened the interpretation to explicitly link the phase transition to the high-speed long-runout mechanism. We argued that the transition from a coherent solid block to a granular flow (marked by VS > 29.47%) is the physical cause of bulk friction reduction. This "solid-to-fluid" transformation fundamentally alters the energy dissipation mode, allowing the landslide mass to overcome basal resistance and achieve a runout distance that exceeds standard frictional limits;

3. **The significance of the observed VS and AG thresholds**: We interpreted these thresholds as the critical quantitative boundary that distinguishes the solid-phase sliding regime from the granular-fluidized flow regime. Action taken: To illustrate this quantitative description visually, we added a new schematic figure (Fig. 13 in the revised manuscript). The figure contrasts the coherent solid state below the thresholds (Fig. 13a) with the fragmented granular state above the thresholds (Fig. 13b), explicitly linking the physical morphology with the quantitative VS and AG indices defined in our study;

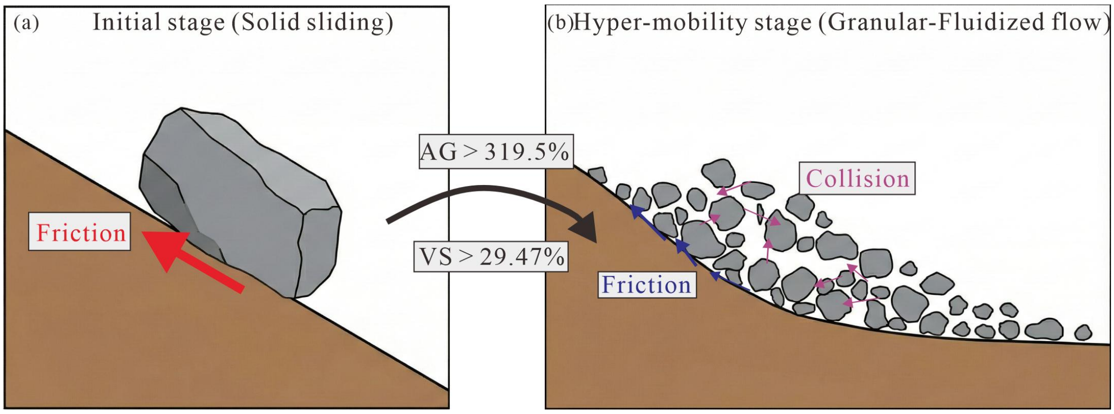


Fig. 13 Schematic illustration of the solid-to-granular phase transition: (a) the coherent solid phase: Governed primarily by sliding friction exhibiting relatively low sliding velocities; (b) the dispersed granular-fluidized phase: Dominated by rolling friction with a relatively high sliding velocity.

4. **The implications for landslide dynamics under strong seismic loading**:We have rewritten this section to highlight how the study quantitatively characterizes the change in motion state through our two core methodological innovations: Energy Extraction and Structural Analysis.

We explained that strong seismic loading drives the structural disintegration quantified by VS/AG thresholds, which in turn triggers the momentum transfer mechanism quantified by energy evolution. This coupling is what forces the landslide to transition from a solid phase to a fluidized phase. The study shows that the fluidization resulting from this energy-structure interaction significantly amplifies the runout distance. Therefore, accurate hazard forecasting requires considering the degree of seismic-induced fragmentation, as this structural degradation is the primary determinant of the extended disaster scope.

4. broader implications for hazard-chain evolution and future modeling improvements.

Response: We thank the reviewer for encouraging us to expand the discussion to broader implications. We have added a new subsection **5.4 Implications for**

hazard-chain evolution to the **Discussion**. We linked our simulation results to the catastrophic "**strong earthquake–landslide–impulse waves–damming–outburst flood**" hazard-chain observed in the 1786 event. This study focuses on the process by which seismically-induced landslides disintegrate into debris flows and impact river channels. We emphasized that the dynamic parameters extracted from our model (impact velocity, deposit distribution) are critical inputs for evaluating the safety of current hydropower projects in the Dadu River basin against surge waves and dam-breach floods.

5. The Introduction should be reorganized to emphasize the scientific gap and the methodological innovation of combining contour-continuity restoration, discrete-element energy extraction, and Alpha-shape–based structural evolution analysis. The Methods section should be rewritten with clearer hierarchy and parallel subsections, providing stronger justification for key modeling choices. The Results section should focus strictly on observational outputs, reorganized by landslide stages, while removing mechanistic explanations that belong in Discussion. The Conclusions should be condensed and rewritten after restructuring, highlighting scientific insights rather than descriptive summaries. Language throughout the manuscript requires refinement to improve clarity, remove redundancy, and strengthen scientific precision. Overall, substantial restructuring and expansion of the Discussion—with clear thematic subsections and deeper analytical content—is essential to elevate the manuscript to publication level.

Response: We sincerely thank the reviewer for this comprehensive roadmap to elevate the quality of our manuscript. We have rewritten the **Introduction, Methodologies,Results and Discussions** to sharpen the focus on the scientific gap and our innovation.

1. Introduction

We have rewritten the Introduction to clearly define the scientific gap: the lack of quantitative links between microscopic energy evolution and macroscopic structural changes in paleo-landslides. We explicitly positioned our "Triad Approach"

(Contour-continuity restoration + Discrete element energy extraction + Alpha-shape structural quantification) as the core methodological innovation filling this gap.

2. Methodologies

(1) Section **2.1** is now dedicated solely to "**2. Study Area and Geological Background**"

(2) Section 3 is strictly for "Methodology", with parallel subsections providing strong justifications for key modeling choices (e.g., the rationale for using the Luding seismic record and the parameter calibration process).

3. Results

We have rigorously stripped the **Results** (Section 4) of all interpretative and mechanistic explanations. The section is now organized strictly by landslide stages, reporting only observational outputs (velocity fields, energy curves, and structural indices). All mechanistic interpretations have been relocated to the **Discussion**.

4. Discussions

As detailed in our responses to previous comments, we have established a new, fully independent **Discussion** (Section 5) with four thematic subsections. This section now systematically addresses comparisons with existing studies, key uncertainties, physical mechanisms (phase transition), and broader hazard implications.

5. Conclusions

We have completely rewritten and condensed the Conclusions. We moved away from a descriptive summary of the simulation steps and instead highlighted the core scientific insights derived from the restructured discussion.