Buried and displaced: moving characteristics of building fragments in debris flows, egusphere-2025-5236

Reply to reviewers' comments

(*C and R denote comment and reply, respectively*)

Reviewer 1 (RC1)

C0: The study of debris flow-structure interaction is a complex topic, since many physical processes are involved. Given the recent high frequency of large debris flows, rock-ice avalanches, and snow avalanches in Europe and high mountain Asia, this study is a very timely research towards understanding this complex and practical problem. This manuscript carried out flume experiments to investigate the trajectory of building fragment under the action forces of debris flows. IMU was adopted to monitoring the state of block; PIV technology was used to reveal the velocity field prior interacting with the block. Analytical approach is further adopted to predict the deposition position of the displaced block. I have the following comments for further consideration on the limitation (simplification) of this study.

R0: Thank you for the constructive comments. This manuscript focuses on complicated debris flow and block movement processes, and aims to gain understanding based on appropriate simplification. We have made revisions on a point-by-point basis. Please see our detailed reply to comments below.

C1: A simplified scenario for a complicated interaction problem. I appreciate the efforts in tackle this problem using an analytical approach and in a dimensionless form. The simplification of the problem has to be clearly elaborated, e.g., the flat and straight channel (rather than on a deposition fan), the rotation of block (which is captured by the IMU), and the mono-sized particles in the modelled debris flows, etc.

The leading-edge model for decelerating debris flow. This is a special case for debris flow deposition on a flat area, by which the block movement model is built on. Therefore the applicable scenario and limitation should be discussed in the conclusion.

R1: Thank you for pointing out the limitation (simplification) of this study. As already mentioned in the manuscript, "Without a deep understanding on the mechanisms of a simplified scenario, it is pessimistic to further forward our understanding into the complicated real-world cases." We have made further clarification on these issues (Page XX, Line XX-XX):

> *"Nevertheless, substantial simplification has been made to achieve the above findings. Specially, the modelled building block lies in a 2D deposition zone, rather than a deposition fan. By modelling a high-density flat block contacting the channel bed, the rotation along the flow direction is constrained. In terms of the modelled debris flow, the mono-sized spherical particles mixed with Newtonian fluid is an idealization of prototype debris flows. The analytical model is built on a uniform deceleration model, which only reflects a specific scenario on the deposition area. Only the prediction of a single building fragment position in debris flow deposition is provided, rather than the distribution range of building fragments, which is*

> *beyond the capacity of deterministic analytical models. Further study, including large-scale experiments and well-calibrated numerical modelling, is needed to shed light on this complicated problem."*

C2: The analytical model has too many parameters and many possible solutions (due to different combination of states of parameters). This would result in confusion in practice. Moreover, it is found that, no matter the states of the block, the final position of block seems mainly determined by the basal sliding velocity of debris flow. What is the implication for this finding?

R2: Thank you for the pertinent concern. The number of parameters and possible solutions reflects the complicated interactions among the debris flow, the block, and the channel bed. The first endeavour of this study is to rule out some of the forces through non-dimensionalization of the governing equation. It is further revealed that the basal sliding velocity exerts a dominating control on the block deposition. This indicates that the property (flow regime) of debris flows is the key to determining the final deposition of building block.

C3: Equation (6). The viscous drag is neglected in the formulation, and the authors use the friction number to elaborate this. More information is needed to make it clear.

R3: Thank you for the critical comment. The fluid viscous force might not be a dominant one. We adopt the Friction number (N_{fric}, Iverson 2015) to quantify the relative contribution of frictional and viscous forces:

$$N_{\mathrm{fric}} = \frac{\sigma_e}{\dot{\gamma}\eta}$$

where σ_{e} is the effective stress, and can be deduced from the measured total stress and pore pressure (see **Figure 4**); γ is the shear rate, and can be deduced as a ratio of the flow velocity and flow depth; η is the viscosity of the fluid, 0.01 Pas in this study. The calculated values of this study are all above 100. This indicates that the contribution of viscous force is quite limited. We have made a clarification in the manuscript.

C4: I agree that this manuscript provides important findings for this complicated interaction problem, and derives some simplified tool for quantify the final deposition of single building block. At this stage, it is still far away to say that it provide "actionable guidance". Please tune down the description of these findings.

R4: Thank you for the kind suggestion. We fully agree that current findings on the mechanism are insufficient for practical emergency rescue. We have changed the "actionable guidance" to "useful reference".

C5: Line 94. Why a 5 degree slope is chosen for deposition of debris flow? Does this represent the prototype condition?

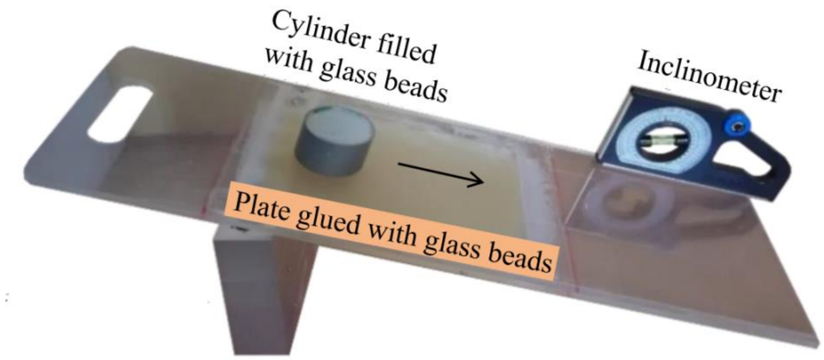
R5: Yes. The buildings and infrastructure are mainly located on the deposition area of debris flow catchment, and 5 degree is a typical slope for the deposition area. We have made clarification accordingly.

C6: Why the IMU results (through integration of the acceleration) is not directly adopted to measure the displacement of the block?

R6: This is a theoretically-feasible but technically-infeasible issue. Theoretically, it is easy to integrate the acceleration to derive the velocity and displacement (double integration). Technically, the bias drift and noise along with the long-time block motion would accumulate with integration, and result in error of displacement up to 200% (Harding et al. 2014). Nevertheless, the acceleration from IMU is still adopted to derive the initial velocity of the block, through a very short time of 0.2 s.

C7: Table 4. How are the particle friction coefficient and the block bed coefficient measured? Can it be directly measured through the measured normal stress, shear stress, and pore pressure?

R7: The particle friction coefficient can be estimated through the measured normal stress, shear stress, and pore pressure. However, errors might be introduced through the accuracy of transducers (normal and shear forces, pore pressure) and the steadiness of the flow. Specially, a steady flow state is very hard to be reached in physical experiments, and it may be further disturbed by secondary roll waves. Therefore, in practice we measure the particle friction coefficient through tilt test. The key procedure is as follows (see the figure below). First, put a cylinder filled with glass beads on an inclined plate glued with the same glass beads. Gradually increase the inclination of the plate, until the cylinder starts to move. This angle of inclination is the inter-particle friction angle.



Setup of tilt test.

Reviewer 2 (RC2)

C0: This study investigates the physical mechanisms associated with the movement of building fragments within debris flows through an integrated experimental-theoretical approach. The authors conducted controlled flume experiments to capture the force and kinematic responses of the moving blocks within debris flows. On this basis, they developed an analytical dynamics model formulated within a leading-edge framework, introduced a set of dimensionless groups (e.g., D^*, K^*, G^*), and proposed the criterion αFr^2 to distinguish the dominant mechanical regimes. Model predictions were quantitatively evaluated against the ratio L^*/S^* (block displacement versus depositional front displacement). The experimental and theoretical results exhibit good overall agreement across three debris flows with different solid concentrations. They found that the deposition position of building fragments is predominantly governed by the basal sliding velocity of debris flow. The study is innovative and well-designed; however, major revisions are required regarding the model assumptions, parameter sensitivity analysis, and the scalability of the proposed framework. Please refer to the following comments for detailed suggestions.

R0: Thank you for helping us to improve our manuscript with constructive comments. We have made revisions on a point-by-point basis. Please see our detailed reply to comments below.

C1: The study treats the building fragments as passive blocks that do not exert feedback on the surrounding flow, and it represents the depositional region as a single body undergoing uniform deceleration within a leading-edge framework. This approximation may be valid under the experimental scales and parameter ranges provided by the authors. However, at field scale, or when the block size ratio, the number of blocks, or the block volume becomes significantly larger, the feedback of the blocks on local flow velocity and pore-pressure distribution may become important. Therefore, the authors should specify the parameter ranges in which this approximation remains applicable, such as the block-to-flow depth ratio or the areal ratio of the block. Also, they should discuss the limitations of this approximation in the manuscript.

R1: Many thanks for the critical comment. Indeed, the one-way coupling (debris flow on block) hypothesis requires a very high ratio between the mass of debris flow and the mass of block. We have amended the manuscript as follows (Page X, Line XX-XXX):

> *"Based on the aforementioned leading-edge model, we developed a model where the kinematic behavior of building blocks is exclusively governed by the debris flow dynamics, with negligible feedback effects on the flow regime. This hypothesis generally requires the ratio between mass of debris flow (discharge) and the mass of block to be higher than 10."*

Regarding the number of blocks and the deceleration leading-edges model, we have made further discussion (Page X, Line XX-XXX):

> *"Nevertheless, substantial simplification has been made to achieve the above findings. Specially, the modelled building block lies in a 2D deposition zone, rather than a deposition fan. By modelling a high-density flat block contacting the channel bed, the rotation along the flow direction is constrained. In terms of the modelled debris flow, the mono-sized spherical particles mixed with Newtonian fluid is an idealization of prototype debris flows. The analytical model is built on a uniform deceleration model, which only reflects a specific scenario on the*

deposition area. Only the prediction of a single building fragment position in debris flow deposition is provided, rather than the distribution range of building fragments, which is beyond the capacity of deterministic analytical models. Further study, including large-scale experiments and well-calibrated numerical modelling, is needed to shed light on this complicated problem."

C2: The authors relate the ratio of D^* to K^* to the Froude number and introduce αFr^2 as a criterion. However, the selection of parameters within α (such as C_d, k_a, k_p, λ, and h/H) is not sufficiently transparent for both the experimental and field conditions. The authors should perform a parameter sweep for the key variables (C_d, k_p-k_a, λ, h/H, and $1/n$), or at least provide sensitivity curves showing how uncertainties in their magnitudes influence the prediction of L^*/S^*. This would help demonstrate the robustness of the conclusions to variations in these parameters. In addition, the manuscript contains many symbols. A complete notation table at the end of the paper would assist readers in checking definitions.

R2: The model depends on the proposed dimensionless parameters (D, K, G, αFr^2) to predict the position of the block. However, the dimensionless parameters only reply on the terms like physical properties (ρ, μ, h/H), physical coefficients (C_d, k_p-k_a) which have very narrow ranges, or directly measured parameters (λ, m, $1/n$). Moreover, the comparison between the model prediction and experimental results confirm the dominance of the basal sliding velocity on the L/S. Sensitivity analysis may not be necessary. We have now added a notation at the end of the main text.

C3: Regarding the IMU data, the authors acknowledge that direct integration of acceleration can lead to significant errors, as cited from Harding et al. (2014). Nevertheless, they use short-time integration over the initial 0.2 seconds to obtain the initial block velocity m (0.9-1.0). If the IMU signals were filtered through some approaches, the authors should describe the full processing procedure in this manuscript.

R3: Thanks for these pertinent comments. We have added further clarification of the data processing (Page X, Line XX-XXX):

"During the analysis of the sensor measurement data, filtering was applied to signals from selected sensors. For the basal measurement modules, the raw data from the load cells and the pore pressure transducers exhibited substantial noise. To facilitate data visualization and comparison, a moving average filtering was employed to smooth these datasets. The raw data from the inertial measurement unit, which contained minimal noise, were retained without filtering."

C4: The authors conclude that the depositional position of the block is controlled by the basal sliding velocity of the debris flow. This conclusion may result from the assumptions used in the theoretical model, where the block is submerged in the flow and remains in contact with the bed. In addition, the experimental block has a density greater than that of the debris flows. In real events, however, building fragments may be carried within the debris-flow front and may not remain in direct contact with the bed. The authors should clarify this distinction in the discussion.

R4: Thanks for the pertinent comment. We agree that the higher density of the block than the density of debris flow is the prerequisite for the influence of basal sliding velocity. We have amended the discussion as follows (Page X, Line XX-XXX):

> *"By modelling a high-density flat block contacting the channel bed, the rotation along the flow direction is constrained."*

C5: In the experiment, the authors attached particles at the flume bottom that were identical to the solid phase of the debris flow. In dry granular flows, this approach is commonly used to approximate a no-slip boundary. It is unclear, however, what the intended effect is in two-phase debris flows. If the purpose is similarly to enforce a no-slip condition, the presence of substantial slip velocities in the reported velocity profiles raises questions. Clarification or discussion of this apparent discrepancy would strengthen the manuscript.

R5: Thanks for this pertinent comment. Adopting roughened bed surface to reduce basal slip is widely used in dry and two-phase flow experiments. However, the effect of the roughened bed surface is hard to be (has rarely been) quantified. Furthermore, the field observation at the Lattenbach catchment (Tyrol, Austria) further confirmed the existence of basal slip velocity in the natural condition (Nagl et al., 2025). This calls into question the no-slip assumption of traditional rheological models and underscores the significance of basal slip in the dynamics of debris flows. We have revised the manuscript as follows (Page X, Line XX-XXX):

> *"Based on high-speed photography, Particle Image Velocimetry (geoPIV8, Take, 2014) analysis is conducted to determine the velocity profile within the debris flow (Figure 3b-d). The results reveal distinct basal sliding, evidenced by non-zero flow velocities in the near-bed region. The basal slip has also been observed at the Lattenbach catchment, Tyrol, Austria, particularly during surge phases and granular flow fronts (Nagl et al., 2025)."*

Nagl, G., Ender, M., Klein, F., McArdell, B., Boss, S., Aaron, J., Zott, F., Hübl, J., Kaitna, R. (2025). Brief communication: First field observations of basal slip velocities in natural debris flows. EGUsphere, 2025, 1-9.

C6: Line 25: The reference "F Zhao et al., 2025" should be formatted in accordance with the journal's reference style.

R6: The revision has been made.

C7: Line 25: The conjunction "However" is inappropriate here because the preceding and following sentences do not express a contrast relationship. Please choose a more suitable transition or remove it.

R7: We have removed "However".

C8: In line49: "debris flow mobility" should be changed to "debris-flow mobility".

R8: The revision has been made.

C9: In line 57: The citation should be: "For both dry granular (Faug, 2015) and two-phase granular-fluid flows (Sturm et al., 2018)".

R9: The revision has been made.

C10: Lines 63-66: The manuscript cites studies of boulder transport in tsunamis but does not explain how those studies inform debris-flow boulder transport. This citation appears abrupt, I recommend reorganizing the text to clarify the relevance or removing the citation.

R10: Thanks for the comment. The proposed theoretical models for boulder movement under tsunami traction also provide useful reference for the study of building fragment movement. Therefore, we have clarified this as follows (Page X, Line XX-XXX):

> *"In coastal engineering, the movement of individual blocks by tsunamis has been well studied, and the proposed theoretical models for boulder movement under tsunami traction also provide useful reference for the study of building fragment movement."*

C11: Figure 2: "flume set up" should be revised to "flume set-up".

R11: The revision has been made.

C12: line 117: Replace "liquid phase" with "fluid phase" to maintain consistency with the terminology used elsewhere in the manuscript.

R12: The revision has been made.

C13: Figure 4: "pore water pressure" should be revised to "pore-water pressure".

R13: The revision has been made.

C14: line 215: "coefficient of friction" should be changed to "friction coefficient".

R14: The revision has been made.

C15: Figure 8: for state 1, the inequality shown as "$v_b > v_d/n$" is incorrect and should be "$v_b < v_d/n$". Please revise this label carefully so it is consistent with the textual description in lines 258-262.

R15: The revision has been made.

C16: Line 263: Equation (6) represents the block motion equation, not the debris-flow motion equation. Consider rephrasing, for example: "Substituting Equation (7) into the block-movement governing Equation (6)".

line 265: The equation reference is incorrect; "Equation (7)" should be "Equation (6)".

R16: We apologize for the typo here. It should be

"Substituting the debris-flow movement governing Equation 4 into the block's movement Equation 6"

C17: line 289. There is an extraneous left parenthesis "(". Please remove it. line 294: "**Table 2**)" should be removed.

R17: We apologize for the typo here. This is due to the improper hyperlink to Table 2. We have corrected it accordingly.

Reviewer 3 (RC3)

C0: The manuscript presents laboratory experiments investigating the transport and deposition behavior of building fragments in debris flows. An analytical model is applied to predict the deposition locations of these fragments. Overall, the manuscript is well-structured and clearly written, though some sections could be more concise. The methods section would benefit from additional experimental details. Specific comments are provided below:

R0: Thank you for helping us to improve our manuscript with constructive comments. We have made revisions on a point-by-point basis. Please see our detailed reply to comments below.

C1: Line 75: Would the displacement of objects by snow avalanches also be considered by this assumption? Some object like cars?

R1: Thanks for the pertinent comment. The dynamics of debris flow shares similarity with that of rock avalanches and snow avalanches. Specially, by adopting the parameter degree of liquefaction, the model could consider the case of dry flows (λ=0). We have revised the manuscript as follows (Page XX, Line XXX-XXX):

> *"This study has significant practical implications for post-disaster emergency rescue, particularly in locating the positions of buried buildings within debris flow deposits. Moreover, findings of this study could have practical implications for locating the position of other objects (e.g., cars) in rock avalanches or snow avalanches."*

C2: Line 95: how many basal sensing modules?

R2: There are in total 4 modules, and we have updated the manuscript now.

C3: Line 105: Is the IMU sensor time triggered? Is the system synchronized with the other setup?

R3: The IMU sensor has to be switched on and off manually. Also, it is not synchronized with the data logger. However, we can ensure timeline alignment through the response of the IMU sensor and the images captured by the high-speed camera. We have clarified the setup of IMU sensor as follows (Page XX, Line XXX-XXX):

> *"The IMU can be switched on and off manually before and after the experiments. Through the images captured by the high-speed camera, the response of IMU can be manually synchronized with the flow depth and stress measurements."*

C4: Why did you use this shape of the imu block? Please describe.

R4: We apologize for the misleading information. "40 mm × 40 mm × 10 mm" is the dimension of the block and we have now moved it to Section 2.1 Experimental model setup. We do not specify the size of the commercial IMU, but we have to make sure the mass of IMU is uniformly distributed within the block. The revision is as follows (Page XX, Line XXX-XXX):

> *"A flat aluminium block is positioned 0.75 m downstream from the smooth transition zone (Figure 2a). To ensure that the block only moves by sliding rather than rolling and saltation,*

the block is designed as a flat shape, and the edges are rounded. The dimension of the block is 40 mm × 40 mm × 10 mm (Figure 2b).”

C5: Line 100-105: Company of the sensors and camera is missing, please specify.

R5: We have now supplemented the information (company, measurement range, and resolution, etc.) of sensors and camera as follows (Page XX, Line XXX-XXX):

> *“each module is equipped with a triaxial load cell (LH-SZ-02, 50 N, ± 0.1% BSL) located at the center of the force plate (Figure 2b). These load cells are used to measure normal and shear stresses. Additionally, each module has a pore-water pressure transducer (PPT, OMEGA PX409, 6.9 kPa/34.5 kPa, ± 0.08% BSL) upstream of the force plate (Figure 2b) to measure pore-water pressure. Above each basal sensing module, there is an ultrasonic sensor (BANNER U-GAGE T30UXUA, 0.1–1.0 m, resolution 0.1% of distance) to measure the flow depth. The whole data acquisition system (National Instruments) is set to a sampling rate of 500 Hz. To derive the frontal velocity prior to contact, a high-speed camera (PHONTRON FASTCAM Mini WX50) with resolution of 1280×1024 pixels is placed at the sidewall of the flume. The frame rate of the high-speed camera is set at 250 fps. Three video cameras (DJI Osmo Action 4, resolution 3648×2736 pixels, 120 fps) are used to capture the movement kinematics. Owing to the incomplete transparency of the modeled debris flow, the block movement is not easily observable by eye. Therefore, employing a micro inertial measurement unit (IMU) is imperative for analyzing its movement mode (Curley et al., 2021; Maniatis, 2021). A commercial IMU (WITMOTION, WT901SDCL) is embedded into the block. It has an acceleration range of ±16 g with accuracy of 0.0005 g/LSB (least significant bit), and an angular velocity range of ±2000°/s with resolution of 0.061 (°/s)/LSB. The sampling rate of the IMU is 200 Hz.”*

C6: Line 117: how do you keep the viscosity constant? What fluid did you use?

R6: As mentioned in the manuscripts, “A solution of glycerol and water is used as the fluid phase.” The rheological behaviour of this fluid is Newtonian. By changing the content of glycerol, the viscosity can be accurately controlled.

C7: Line 119: What is L (liter)?

R4: Yes, liter. We have now revised the manuscript accordingly.

C8: Table 1: Was this the maximum flow depth?

Table 1: Is this the solid concentration by volumetric or the mass? Please specify

R8: We did not model a dam-break release of the debris. Rather, the opening of the gate is controlled, so that a (relatively) steady flow could be generated, as shown in Figure 4. We have now clarified this as follows (Page XX, Line XXX-XXX):

> *“A steady flow with relatively constant height is generated by adjusting the opening of the gate.”*

It is the volumetric solid concentration, and we have now clarified this.

C9: Line 129: What PIV program did you use?

R9: We used the geoPIV8 developed by Andy Take and David White. We have now clarified this in the manuscript.

C10: Please describe the data processing (e.g. filtering).

R10: Thanks for the kind suggestion. The data of load cell and PPT are filtered, and the data from IMU are not filtered. We have now added clarification on the data processing (Page XX, Line XXX-XXX):

> *"During the analysis of the sensor measurement data, filtering was applied to signals from selected sensors. For the basal measurement modules, the raw data from the load cells and the pore pressure transducers exhibited substantial noise. To facilitate data visualization and comparison, a moving average filtering was employed to smooth these datasets. The raw data from the inertial measurement unit, which contained minimal noise, were retained without filtering."*

C11: Movie S3 is not working at the end

R11: Our apology for the inconvenience. We have reedited Movie S3 and uploaded it at https://www.msdc.ac.cn/#/datadetails?id=105

C12: Describe the other datasets of test 53-40, B2 and B3 (or are the corrupt) (Figure 4).

R12: In total, there are 4 basal sensing modules. For test 53-40, the debris flow only reached B1 (can be cross-confirmed in Figure 5a). The word "responsive" is misleading, and we have now clarified it in the manuscript (Page XX, Line XXX-XXX):

> *"For the experiment with a 53% concentration, which has low mobility (low degree of liquefaction), only basal sensing module B1 is covered by debris flow (Figure 4f). For the experiment with a 50% concentration, which has intermediate mobility, basal sensing modules B1 and B2 are covered by debris flow (Figure 4d-e)."*

C13: Line 160 and Figure 5 describe L/S.

R13: We have now marked the block displacement distance (*L*) debris-flow deposit length (*S*) in Figure 5a. We have further added a notation at the end of the main text to clarify the definition of the symbols.

C14: Line 179: How do you adopt?

R14: We use measured acceleration to infer the state of the buried block. Specially, the rotation along the flow direction is constrained. Otherwise, the performance of the proposed model in Section 3, without consideration of rotation along the flow direction, cannot be validated. The angular velocity is actually not used in the analysis, and we have removed it from the text. We have reorganized the manuscript as follows (Page XX, Line XXX-XXX):

> *"We adopt the measured acceleration to infer the real-time state of the displaced block. At the moment of contact, the y-axis acceleration increases sharply, resulting in downward block movement. Meanwhile, the z-axis maintains a constant upward acceleration of 1 g throughout*

the entire process, indicating that the direction of the z-axis does not change during the whole process. That is, the block does not roll over (y-direction). For Test 45-40, after debris-flow deposition, the accelerations of the x- and y-axes are swapped (Figure 6a), indicating that the block rotated 90° around the z-axis. For Test 50-40, the x- and y-axes exhibit similar accelerations after deposition (Figure 6b), indicating that the block rotated 45° around the z-axis from its original position."

C15: Table 2: The variables (G*, Gd*, and so on) should be described in the text.

R15: Thanks for the kind suggestion. There are more than 40 parameters, including their dimensional and dimensionless forms. To make this clear, we have added a notation at the end of the main text to clarify the definition of the symbols.