Review of "Mobility of dry granular debris flows over erodible beds: Experimental insights into the influence of flow–bed inertia" by Wetterauer et al.

21 May 2026

Erosion is an important process in both dry and water-rich landslides, as it can strongly affect volume and momentum growth. Although several erosion experiments have been carried out in the past, the present study provides a new dataset for dry granular flows by varying the composition of the erodible bed. To the best of my knowledge, dry granular flow experiments involving three contrasting bed material compositions have not previously been reported in this way. This is therefore welcome. The experimental dataset itself is interesting and potentially valuable. In particular, the analysis of deposit morphology is insightful, and the dataset may also prove useful as a benchmark for advanced numerical models.

However, the present framing and mechanistic interpretation of the experiments are incorrect, as I already explained in my community comment CC2 and as discussed in Issler et al. (2024). In Section 1 below, I briefly restate why the current interpretation cannot be maintained and indicate how it could be amended. In Section 2, I discuss the major changes that are required to reframe the manuscript. In Section 3, I provide more specific and line-by-line comments. Given the extent of the necessary reframing, I recommend **major revisions** and a further round of review before the manuscript can be reconsidered. My condition for further consideration is that the authors fully remove their reliance on the fundamentally incorrect model of Pudasaini and Krautblatter (2021) and instead frame and interpret the experiments using a mechanically sound framework.

1. Why the current interpretation is not valid

I agree, in general, with the remark by Reviewer 1 that in geosciences one often uses simplified, approximate, or partly empirical frameworks that can still be useful in practice. For example, in depth-averaged landslide modelling, empirical entrainment laws have been proposed (e.g., Eglit and Demidov, 2005; McDougall and Hungr, 2005) that relate entrainment rate to flow variables such as depth, velocity or momentum through (non-physical) calibrated coefficients. Although such laws are not derived from first principles, their use is legitimate because they are explicitly empirical, and because they avoid the need to characterize bed material properties in the field, which may be a reasonable parsimonious strategy for large-scale hazard mapping. It is therefore meaningful to test against experiments whether they can reproduce observed erosion and mobility (see however also the opinion in Iverson and Ouyang, 2015). The situation is fundamentally different for Pudasaini and Krautblatter (2021). That model is not approximate or empirical, but the result of an incorrect mathematical derivation (Issler et al., 2024). The conclusions that follow from that derivation are therefore also incorrect. For this reason, the current attempt to frame the experiments as supporting or testing the legitimacy of the PK interpretation is not acceptable. Although the errors are already explained in Issler et al. (2024) and in my CC2, it is useful to restate the point here using a very simple mass-block model, analogous to the examples discussed by Iverson et al. (2011) and Iverson (2012), which I will extend to consider different flow and bed bulk densities and a possible finite initial bed velocity u_b.

Consider a moving slide block of initial mass (per unit basal area) $\rho_m h_m$, where h_m is the initial landslide thickness and ρ_m is the landslide bulk density, travelling downslope with initial velocity u_m. This block overrides and entrains a basal layer of mass $\rho_b \Delta z_b$, where ρ_b is the bed bulk density and Δz_b is the (pre-defined) entrained depth. The momentum change of the combined system (moving block plus newly entrained bed material) is then

$$(\rho_m h_m + \rho_b \Delta z_b)(u_m + \Delta u_m) - (\rho_m h_m u_m + \rho_b \Delta z_b u_b), \tag{1}$$

where Δu_m is the change in the whole landslide speed. Dividing by the time interval Δt over which these processes occur, and equating the result to the sum of the forces acting on the entire system, yields the momentum balance

$$(\rho_m h_m + \rho_b \Delta z_b)\frac{\Delta u_m}{\Delta t} + \rho_b(u_m - k \cdot u_b)\frac{\Delta z_b}{\Delta t} = (\rho_m h_m + \rho_b \Delta z_b) g \sin\theta - \tau_b, \tag{2}$$

where $k = 1$ (Issler et al., 2024; Iverson, 2012), and τ_b is the shear stress acting at the base of the slide plus the newly entrained bed material (see derivation in Iverson, 2012; Issler, 2014). This form is well established and has been rigorously derived and discussed in the literature (Hungr, 1990; Erlichson, 1991; Fraccarollo and Capart, 2002; Iverson et al., 2011; Iverson, 2012, 2013; Iverson and Ouyang, 2015; Issler et al., 2024). By contrast, Pudasaini and Krautblatter (2021) incorrectly derive $k = 2$ (see Issler et al., 2024, for an explanation of the origin of this error), thereby violating momentum and energy conservation. They then propagate this error into further equations and conclusions concerning the influence of flow–bed density contrast on mobility. These conclusions on flow–bed density contrasts therefore cannot be used as a valid framework for the interpretation proposed by Wetterauer et al.

At the level of the simple block model, Eq. (2) already allows one to discuss the influence of bed density on both landslide mobility and mass growth. The net driving force (right-hand side of Eq. 2), must be allocated between accelerating the landslide system and entraining the bed material (i.e., accelerating it from u_b to u_m). Because Δz_b is prescribed in this example, that partitioning depends explicitly on ρ_b, as seen on the left-hand side of the equation. That said, this simple rigid mass-block analysis assumes that the entrained bed block fails along a pre-defined interface located at depth Δz_b, which may be the case for a competent rock layer sliding on a discontinuity, or of a granular material failing along a pre-defined weak layer. For a continuous granular material, however, the situation is more subtle. As $\Delta t \to 0$, depth-averaged models contract the entrainment layer to an infinitesimal layer $\mathrm{d}z_b$, whose thickness is no longer prescribed in advance but is instead regulated by the available driving force. In that limit, the shear stress jump across the bed interface determines the mass of bed material that can be accelerated from u_b to u_m in a unit time:

$$\rho_b E_b = \frac{\max(0, \tau_m - \tau_b)}{u_m - u_b}. \tag{3}$$

In the limit $\Delta t \to 0$, Eq. (2) then becomes[1]

$$\rho_m h_m \frac{\mathrm{d}u_m}{\mathrm{d}t} + \rho_b(u_m - u_b)E_b = \rho_m h_m g \sin\theta - \tau_b. \tag{4}$$

A small ρ_b will imply a large entrainment rate E_b (cf. Eq. 3), but this does not change how the net

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[1] It is interesting to note that, in the Eulerian form of the depth-averaged momentum conservation equation, ρ_b does not appear explicitly (Iverson and Ouyang, 2015), because the inertial effects of entrainment are already accounted for implicitly on the left-hand side of the equation. If dilatancy effects are neglected, the (depth-integrated) flow density may change when an erodible bed with a different bulk density is entrained and the newly entrained material does not adapt its density to that of the flow. In that situation, determining the evolving (depth-integrated) flow density requires conservation of both mass and volume (see Eqs. 3 and 4 in Vicari and Issler, 2025). Combining these relations with the Eulerian momentum balance (Eq. 6 in Vicari and Issler, 2025) precisely yields Eq. (4). By contrast, if granular dilatancy occurs during entrainment, a granular bed with a porosity different from that of the flow may adapt its density during the entrainment process, which will also affect the momentum balances (Iverson and Ouyang, 2015).

driving force is partitioned between entrainment and acceleration, nor does it alter the momentum of the whole landslide (cf. Eq. 4). Nonetheless, a larger entrainment rate E_b leads to higher flow depths and larger flowing volumes, which may in turn generate a stronger downslope thrust through large longitudinal pressure gradients at the flow front ($-g\, h_m\, \partial_x(\rho_m\, h_m \cos\theta)$, omitted in the simplified block-model example of Eq. 4).

At the same time, Eqs. (2) and (4) also show that the shear strength within the erodible bed, τ_b, plays a primary role in determining the net driving force. If one assumes that the resisting stress follows a Mohr–Coulomb failure criterion, then in the dry case

$$\tau_b = (\rho_m h_m + \rho_b \Delta z_b) g \cos\theta \tan\varphi_b, \tag{5}$$

where φ_b is the internal friction angle of the erodible bed. Weak beds with low φ_b can therefore strongly increase the net driving force in Eqs. (2) and (4), thereby promoting erosion and mobility. This is precisely what Wetterauer et al. observe when comparing the *low-friction* Glass beds with the *higher-friction* Quartz and Magnetite beds. By contrast, Pudasaini and Krautblatter (2021) incorrectly posit that the basal shear stress of the flow, τ_m (dependent on the flow friction angle φ_m), applies instead of τ_b. That assumption does not permit a correct explanation of the mobility pattern observed in the experiments (see also my CC2).

In real landslides, and also in flume experiments, the influence of bed density on mobility may nevertheless be more complex than the simple interpretation of Eqs. (2) and (4). For example, entrainment of lighter particles may induce density segregation, so that sediments originating from the erodible bed are transported away from the flow base, and subsequent mobility may then be controlled more strongly by the frictional properties of the original flowing material. Likewise, entrainment of particles finer than the flow material may promote basal sorting and enhance mobility through rolling effects (Makris et al., 2024). This is to say that qualitative interpretation of such experiments against simplified depth-averaged theories is not straightforward.

2. Major remarks

Mechanistic framing. My main comment is that the manuscript must be reframed. The following major changes are required:

- **Remove all reliance on Pudasaini and Krautblatter (2021).** Any citation to Pudasaini and Krautblatter (2021), and any interpretation based on their inertia-contrast framework, should be removed. This also applies to subsequent erosion models by Shiva Pudasaini that build on the same underlying error. If the authors wish to interpret their results with respect to a depth-averaged entrainment theory, they should instead refer to the rigorous and correct formulations of Iverson (2012) and Iverson and Ouyang (2015). (However, note that jump conditions had already been proposed earlier by Norem and Schieldrop (1991), Gray (2001) and Fraccarollo and Capart (2002).) Given the seriousness of the PK errors, I do not consider the manuscript acceptable unless all reliance on Pudasaini and Krautblatter (2021) is removed. This reframing will actually go in the authors' favor, because it will provide a physically sound interpretation of the experimental results and thereby make the manuscript stronger and more convincing.

- **Reframe the experiments around bed properties, not "density contrasts" alone.** The manuscript should not present the experiments primarily as a test of bed particle density or of "flow–bed inertia". The experiments simultaneously vary both particle density and internal friction, and the results strongly suggest that bed friction is the dominant control on erosion and mobility. In the current manuscript, this only appears as a secondary caveat in Section 4.2, but in the landslide literature it is already well established that bed shear strength is a primary control on erosion and mobility through analytical theory (Iverson, 2012), depth-resolved modelling (Crosta et al., 2009), and experiments (Crosta et al., 2009; Iverson et al., 2011; Roelofs et al., 2023). This should be the central framing of the manuscript.

- **Refer to the bed configurations by material composition.** Throughout the manuscript, I suggest referring to the erodible bed configurations by their composition (Glass, Quartz, Magnetite), rather than by "inertially weak/neutral/strong" terminology. This would more honestly reflect the experiments, since both density and friction vary between these materials.
- **Rewrite the abstract, introduction, and main interpretation accordingly.** The manuscript should be reframed as a study of erosion of dry granular flows over beds with differing sediment properties, especially frictional properties, and secondarily differing densities. A possible title could be: "Mobility of dry granular flows over erodible beds: Experimental insights into the influence of varying bed sediment compositions". The introduction could then motivate the study as follows: previous dry-flow experiments have mostly considered similar bed and flow materials (Mangeney et al., 2010); other studies (Farin et al., 2014) have examined the effect of bed porosity on erosion and mobility; but few studies have explored distinctly different bed sediment compositions, combining differences in density and friction. The manuscript could then highlight that such experiments provide a useful dataset for benchmarking advanced numerical models, including depth-resolved continuum simulations and discrete element simulations. To facilitate this, it would be highly useful if the authors could provide, through a repository, a digital elevation model of the flume and release volume, the scanned deposit surfaces, and an organized dataset of the main experimental results, which could then be used by other researchers to benchmark their models.
- **Move the discussion of density to a secondary level.** The main interpretation in Section 4.1 should focus first on the effect of bed internal friction. The discussion of density may then be retained as an additional possible control, but framed using the correct framework discussed in Section 1 above.
- **Acknowledge previous work on erosion.** The role of bed bulk density is not new. Farin et al. (2014) already performed experiments on erodible beds of differing porosities, and thus differing bulk densities.
- **Experiments with limestone beds.** Because density and friction vary simultaneously in the current experiments, their individual effects cannot be isolated precisely. It could therefore be very valuable if the authors chose to perform their proposed additional tests using limestone beds, which would have lower density than quartz but similar frictional properties. Even a limited number of such experiments could significantly strengthen the manuscript. I fully understand, however, that this would require substantial additional work, and I therefore leave it entirely to the authors whether they wish to pursue this extension.

Applicability to which type of landslides. The manuscript is currently motivated primarily in terms of debris flows. However, the experiments involve dry materials on very steep slopes. I therefore suggest shifting the emphasis from debris flows toward *dry granular flows*, rock avalanches, or dry debris avalanches.

The introduction currently devotes substantial space to physical mechanisms of erosion in debris flows. I suggest shortening this part and placing greater emphasis on erosion in dry granular flows and debris avalanches. In the field, erosion of dry coarse-grained sediments has been documented by Hungr and Evans (2004), although in many rock avalanches extreme mobility is also associated with the avalanche encountering saturated sediments on flatter areas (Hungr and Evans, 2004; Aaron and McDougall, 2019). On the other hand, significant erosion of fully dry sediment can also occur on steep slopes when the bed is metastable (Mangeney et al., 2010; Mangeney, 2011). A very intuitive example is the familiar experience of "scree running", where steep coarse-grained slopes can be easily mobilized under the weight of hikers, creating the feeling of "skiing the gravel" (see `https://teara.govt.nz/en/photograph/9871/scree-running`). Dry sediment on steep scree slopes may therefore be quite erodible if its friction angle is not much higher than the slope angle (see the Boua digl Cof channel described in Vicari et al., 2026).

Dry granular flow experiments (with pasta and rice particles) were also conducted by Crosta et al. (2009), who found that the presence of an erodible layer could decrease mobility when flow and bed had similar density. Such mobility reduction may be related to their horizontal experimental geometry (consistent with the results of Mangeney et al., 2010).

Because dry granular flows are less sensitive to some scaling effects than wet flows, a discussion of scaling would be useful (see Iverson, 2015; Makris et al., 2024). For example, the Savage number might help characterize the flow regime – although it may be difficult to evaluate reasonably the shear rate on the smooth rigid bed if substantial basal slip occurred.

Depth-resolved models. The manuscript currently places strong motivation on validating depth-averaged model assumptions. However, with modern computational resources, fully three-dimensional depth-resolved simulations are now feasible even at slope scale (Cicoira et al., 2022; Kyburz et al., 2025; Zhu et al., 2025). In such models, the flowing mass and erodible bed are represented explicitly through constitutive laws, and erosion and entrainment emerge naturally without the need for separate closure assumptions for fluxes and boundary stresses during entrainment. A strong motivation for the present study could therefore be that it provides a valuable benchmark dataset for such numerical models. A key paper that should be discussed in this context is Crosta et al. (2009), who performed depth-resolved simulations while varying the internal friction angle of the erodible bed. Lower bed friction led to greater erosion and higher mobility, in qualitative agreement with the present experimental results. This study should be cited and discussed. Additional references on 3D erosion modelling are provided in my CC2.

3. Minor remarks and specific comments

- **Title (and elsewhere):** The landslide classification of Hungr et al. (2014) defines debris flows as "Very rapid to extremely rapid surging flow of saturated debris in a steep channel". The term "dry debris flow" is therefore problematic. I suggest using "dry granular flows" instead.

- **L3–7:** This passage will need to be fully reframed in line with my major comments above.

- **L28:** "mass and momentum transfer**, and bed weakening**".

- **L29:** Deceleration during erosion is not synonymous with reduced mobility. Farin et al. (2014), for example, found that erosion could strongly affect the deceleration phase while still enhancing overall flow mobility.

- **L31–32:** You should remove momentum production (that situation would only arise when the bed itself has an initial finite velocity; see Section 4.1 in Iverson (2012)), and instead add "application of the consistent basal shear resistance in the presence of eroding beds (Iverson, 2012; Iverson and Ouyang, 2015)". The reason is well explained by Iverson and Ouyang (2015), for example: "In depth-integrated models, decreased basal shear resistance can be the only source of flow momentum gains that sometimes accompany entrainment."

- **L32:** The current discussion on entrainment implementation in numerical models is incomplete. Depth-averaged models often assume basal shear-dominated erosion, but more general frameworks can also include slope-normal momentum jumps (Iverson and Ouyang, 2015) and alternative frontal ploughing mechanisms (see Issler, 2020, and references therein). Depth-resolved models should also be discussed.

- **L34:** I am not sure de Haas et al. (2020) is the best reference here, as that paper does not itself compare depth-averaged entrainment models. Shen et al. (2020) and Lee et al. (2022) may be more appropriate.

- **L42:** In addition to basal shear, recent studies have also examined the influence of collisional stresses on erosion (de Haas et al., 2022; Zheng et al., 2025).

- **L42:** I would avoid stating that erosion increases *linearly*; a more cautious wording would be that erosion increases or is positively correlated with the relevant variable.

- **L49:** Replace "reduced effective basal friction" with "reduced bed internal friction".

- **L55–56:** This statement is insufficiently supported. I suggest removing it.

- **L57–80:** This section needs to be fully reframed in line with my major comments above.

- **L86–95:** This section also needs to be reframed. It should state clearly that both bed density and bed internal friction are varied simultaneously, and that bed friction is expected to exert a major control on erosion and mobility (Iverson, 2012; Crosta et al., 2009; Iverson et al., 2011). The influence of bed density can then be addressed, building on the discussion presented in Section 1 above.

- **L96–101, Table 1, and elsewhere:** Reframe the scenarios in terms of Glass, Quartz, and Magnetite beds, and state more explicitly, and with greater emphasis, that each bed differs in both solid density and frictional properties. In Table 1, the column "Relative inertia of bed to slide" should be replaced by "Scenario", with the corresponding entries indicated, for example, as "Low bed friction and low bed density", "High bed friction and intermediate bed density", and "High bed friction and high bed density".

- **L98–100:** Please specify clearly that these are *solid* particle densities.

- **L103–105 and Table 1:** Please clarify what the labels "/f" and "/c" refer to. As written, it is not fully clear whether the fine and coarse fractions apply only to the erodible bed materials, to the initially released quartz slide material, or to both the slide and bed materials within each experimental series. Are both Qtz/f and Qtz/c used for the initial sliding material? I also suggest avoiding the wording "sand" and "gravel" here, or at least explicitly defining it as particle-size terminology. Because sand and gravel seem to refer to grain-size classes, but sand and gravel may themselves be composed of quartz, this wording could be confused with the material composition, especially since quartz is also one of the tested materials. Please specify the relevant particle-size ranges directly, e.g., "fine fraction, 0.25–2 mm" and "coarse fraction, 0.25–8 mm".

- **L125:** In addition to the release mass, do you have an estimate of the release volume? This would allow calculation of the initial slide porosity.

- **L129–131:** I appreciate the methodology used to allow gradual erosion. You could add a reference to de Haas and van Woerkom (2016), where strong erosion instead occurs near the upstream edge of the erodible bed.

- **L142:** Please specify whether the 4–5% water content is by mass or by volume.

- **L145 and later:** You refer to flow *heights* as being measured slope-normal. Later, you refer to erosion *depth* (L162): is this quantity also measured slope-normal? Please use consistent terminology throughout the manuscript.

- **L160 and Section 3.1.4:** It would be more informative to calculate the front velocity separately for each consecutive section (e.g., reservoir flap to us1; us1 to us2; etc.). This would better highlight where along the flume the flow accelerates or decelerates.

- **L281 and Table 2:** Because the long runout in the coarse cases seems dominated by dispersed particles, it would be useful also to report the runout distance of the deposit center of mass on the runout plane.

- **Figure 5:** A summary plot of deposit volume as a function of scenario would be helpful to visualize the results more quickly than reading Table 2.

- **L308–311:** This will need to be removed in line with my major comments above.

- **L316–320:** This will need to be reframed in line with my major comments above.

- **L320:** The longer runout in the Glass scenario may also be related to increased flow volume through larger erosion (see my comment above on the role of longitudinal pressure gradients).

- **L325:** Please add a reference to density segregation.

- **L326–327 ("Strikingly"):** This is not at all surprising, since the Quartz and Magnetite beds have similarly high friction.

- **L330–338:** This section will need to be fully reframed in line with my major comments above. In particular, it should describe the role of bed internal friction in controlling erosion and entrainment, and discuss the role of bed density with reference to the established theory of Iverson (2012), or the framework I provided above.

- **L342–344:** This is not always the case in erosive situations; weakening of the bed can also lead to acceleration (Iverson et al., 2011).

- **L355:** Modify to "or low material friction and, possibly, low density".

- **L355–359:** You may also compare your erosion rates with those measured at Illgraben by Berger et al. (2011), and with those measured in the dry granular flow experiments of Barbolini et al. (2005). This latter study would also be worth citing and discussing in the manuscript.

- **L361:** The manuscript refers to segregation of coarse particles toward the front, but the results seemed rather to highlight density segregation, with lighter particles concentrating near the front. Maybe I am not understanding correctly your argument here?

- **L370:** Add a reference to Farin et al. (2014) on the role of packing.
- **L375–376:** Could the more dispersed coarse deposits also be related to stronger collisional stresses (Choi and Goodwin, 2021)?
- **L392–399:** This will need to be reframed in line with my major comments above.
- **Section 4.2:** I suggest presenting all possible controls in the same section, beginning with the most important one, namely bed internal friction. The potential role of density can then be discussed as a secondary effect (based on the framework I discussed above in my Section 1), followed by the other factors already mentioned in the manuscript such as roundness, compaction, and segregation.
- **L436:** Add Farin et al. (2014) on the role of packing.
- **L485–493:** A method similar to that proposed by Berger et al. (2010) could also be used; see also its simpler adaptation to flume experiments by Vicari et al. (2022).
- **L499–501:** This passage should be removed.
- **Conclusions:** These points will need to be fully reframed in line with my major comments above. The conclusions should state that the study investigates contrasting erodible bed materials differing in both friction and density. The role of friction appears consistent with previous theoretical (Iverson, 2012), numerical (Crosta et al., 2009), and experimental (Iverson et al., 2011) work. Particle density may also influence how easily eroded material is accelerated to the flow speed. You may also highlight more succinctly your finding that Glass particles segregate toward the deposit front and margins.

Best regards,
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