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

30 April 2026

The manuscript by Wetterauer et al. presents a set of experiments of dry erosive granular landslides, in which the particle materials of the erodible bed are varied in order to investigate its influence on erosion, flow mobility, and deposit characteristics. In general, erosion is a key process in landslide dynamics because it can strongly affect volume growth and runout. Controlled experiments are therefore highly valuable for improving physical understanding and for constraining models. In this respect, the dataset presented here is potentially important. In particular, the analysis of deposit morphology and internal structure is insightful, and the dataset may also prove useful as a benchmark for advanced numerical models. For these reasons, I believe that the manuscript has the basis for becoming a useful contribution. However, the current framing and mechanistic interpretation cannot be maintained, because they are built around an incorrect theoretical basis. I elaborate on these points below.

1. Context

As a preface to my comments, I wish to disclose that two years ago I co-authored a paper published in the “Matters Arising” section of *Nature Communications* (Issler et al., 2024) (hereafter IGTV), in which we identified a serious error in the derivation of the landslide entrainment model proposed by Pudasaini and Krautblatter (2021) (hereafter PK). Because PK is used centrally in the interpretation of the experiments presented in this manuscript by Wetterauer et al. (of which Pudasaini and Krautblatter are also co-authors), I believe it is important to clarify several issues that invalidate the mechanistic interpretation of the results.

In IGTV, we showed that PK made an error in deriving the Lagrangian form of the depth-averaged momentum conservation equation for entraining landslides. Specifically, their derivation counts the momentum influx associated with the initial velocity of the erodible bed material twice the correct amount, because they include this contribution also in the external force F, even though it is already explicitly accounted for outside F as the particle-borne momentum flux into the flow. This double counting is what produces the erroneous factor of two in PK’s equation of motion. This leads to an incorrect equation of motion and, critically, to violation of energy conservation. Owing to this error, PK further conclude that entrainment from an inertially neutral bed causes no change in mobility, entrainment from an inertially weaker bed enhances mobility, and entrainment from an inertially stronger bed reduces mobility. These are precisely the expectations that are also stated and tested in the manuscript of Wetterauer et al. However, once the erroneous factor of two is corrected, as shown in IGTV, these conclusions no longer follow, and the central claims of both PK and the present manuscript are no longer physically valid. Instead, the resulting equations reduce to the standard and physically correct depth-averaged conservation laws for entraining landslides, as derived by Iverson (2012) and Iverson and Ouyang (2015)[1]. This is not a minor technical point: if implemented in numerical tools for hazard assessment and mitigation, such a model could produce physically inconsistent results and (literally) far-reaching consequences.

---

[1] These models can already account correctly for erosive landslides with erosion velocities $u^b > 0$, but without introducing the erroneous factor of two; see Eqs. 27, 28 and Table 1 of Iverson (2012).

Despite these mathematical and physical issues, the present manuscript attempts to test and qualitatively support the PK theory through flume experiments of dry granular flows over erodible beds with differing solid (particle) densities, which the authors interpret as representing different inertial conditions. In my opinion, this approach is problematic for three main reasons. First, there is no meaningful point in attempting to validate PK as a physical theory, because that theory is already incorrect. A model that violates momentum and energy conservation cannot serve as a sound mechanistic basis for interpreting experimental results. Thus, the stated objective of evaluating or supporting PK is itself flawed from the outset. Second, even leaving PK aside, the scope for validating any depth-averaged entrainment model through the present experiments is limited unless the assumptions underlying depth integration are explicitly verified. Depth-averaged formulations often rely on strong assumptions, including (depending on the model) incompressible flow, negligible slope-normal accelerations, and assuming only shear acts at the flow-bed interface (see, e.g., the discussion of ploughing entrainment mechanisms in Issler, 2020). In the experiments of Wetterauer et al., these assumptions may not be automatically satisfied. Therefore, qualitative agreement between model expectations and experimental trends cannot by itself be taken as validation of the governing equations. Third, the authors' own results do not in fact support the trend predicted by PK across the full set of inertial scenarios.

2. Problems with the experimental framing

To clarify this last point, it is important to retain the manuscript's own definitions and stated expectations. The authors define their inertial scenarios explicitly near the beginning of the manuscript. As they write at L7, they impose

> "inertial contrasts by releasing a quartz slide of constant solid density over erodible beds with lower, equal, and higher solid densities representing inertially weak, neutral, and strong scenarios"

Accordingly, the manuscript refers to an *inertially weak* scenario when the flow solid density is larger than the erodible bed solid density, to an *inertially neutral* scenario when flow and bed have the same solid density, and to an *inertially strong* scenario when the erodible bed has larger solid density than the flow[2]. The manuscript then states its expectations with respect to PK at L61:

> "According to the Pudasaini and Krautblatter (2021) model, three distinct energy regimes arise from the inertial contrast between the moving slide and the erodible bed. Mobility remains unchanged when erosion proceeds under inertially neutral conditions, where the slide and bed material exhibit equal inertia and no net gain or loss of flow momentum and energy occurs. In contrast, mobility increases through the erosion of an inertially weaker bed, which introduces mechanically weaker material into the moving slide, enhancing flow momentum and energy."

This framing is problematic already at the theoretical level, because it relies on PK, whose derivation is incorrect for the reasons explained here and in Issler et al. (2024). But the framing is also not supported by the experimental evidence presented in the manuscript itself. The authors' interpretation relies on the claim that mobility should remain unchanged in the neutral case,

---

[2] Note that these definitions differ somewhat from those originally given in PK, where the solid volume fractions of both the flow and the bed were also taken into account by multiplying the respective solid densities, so that, in the dry case, it is the contrast in flow and bed *bulk* density that determines the inertial scenarios in PK.

increase in the weak case, and decrease in the strong case. However, the experiments only show an apparent increase in mobility for the weak case relative to the neutral case. The strong case does not exhibit the predicted mobility reduction, as the authors themselves acknowledge at L332 and L337.

This weakness becomes even clearer when one compares the authors' interpretation to the well-known erosion experiments of Iverson et al. (2011). In those experiments, the flow and bed materials had similar densities (see their Supplementary Table 1), yet some tests still exhibited substantial mobility enhancement. The mechanistic interpretation adopted by Wetterauer et al. and by PK would imply that under inertially neutral conditions mobility should remain unchanged. That prediction is contradicted by the results of Iverson et al. (2011). In that study, the key parameter controlling erosion and mobility was not the relative density of flow and bed, but the water content of the bed, which controlled bed pore pressure and therefore bed shear strength. Increasing bed water content led to higher pore pressures, reduced bed shear strength, enhanced entrainment, and increased flow mobility. This directly highlights that bed shear strength, rather than relative density, is a primary control on erosive landslide mobility. Similar considerations can be made for the dry granular experiments of Mangeney et al. (2010), where flow and bed materials were also similar, yet mobility cannot be explained in terms of relative density.

3. A more plausible mechanical interpretation of the experiments

This latter point on the influence of bed shear strength is especially important because it also reveals a second error in PK that was not the focus of IGTV (for the sake of conciseness) but is directly relevant here. In the Eulerian momentum conservation equation (their Eq. PK.2 and PK.34) and therefore also in the derived Lagrangian form (their Eq. PK.11), PK apply the wrong basal shear stress (see the second term on the right-hand side of these equations). They use the basal shear stress of the moving flow, τ^m, whereas it has been shown analytically that in the entraining case the relevant resisting stress is the shear stress within the erodible bed at the erosion interface, τ^b (see Iverson, 2012; Iverson and Ouyang, 2015)[3]. This point is also critically discussed in Iverson (2013, 2018). The correct application of τ^b is fundamental because it is the strength of the erodible substrate that controls whether entrainment is facilitated and whether momentum gains occur.

This second error in PK also suggests a more physically defensible interpretation of the experiments by Wetterauer et al., where mobility is enhanced in the inertially weak case relative to the inertially neutral case. However, between these two sets of tests, not only the bed density changes: the friction angle changes substantially as well. In Table 1, the inertially weak beds have markedly lower friction angles (29–31°) than the inertially neutral beds (37–39°). Lower friction corresponds to lower bed shear strength τ^b, which is therefore the most likely reason for the enhanced mobility observed in their so-called inertially weak experiments. This interpretation is consistent with the experiments of Iverson et al. (2011) and with the correct depth-averaged

---

[3] Note that the right-hand side of the momentum conservation equation can be written in alternative, but mathematically equivalent, forms (see Eq. 38 and the discussion following it in Iverson and Ouyang, 2015). In the physically correct form, the resisting basal traction is the shear stress within the erodible bed at the erosion interface, τ^b, and no entrainment-related momentum source term appears (except possibly the momentum influx $u^b E$ when the eroded material has a finite velocity u^b). If one instead writes the equation using the basal shear stress of the moving flow, τ^m, then an apparent momentum-gain term uE (with u the landslide velocity and E the entrainment rate) must also be added. This term is artificial physically: it arises only because τ^m is used instead of the correct resisting shear stress τ^b. The PK equations do not correspond to any of the valid forms described by Iverson and Ouyang (2015).

entrainment theory of Iverson (2012) and Iverson and Ouyang (2015), but it is inconsistent with PK, which incorrectly places τ^m rather than τ^b at the base of the erosive landslide. Although the authors briefly acknowledge in Section 4.2 that bed friction may play a role, the manuscript as presently written continues to frame the results primarily as support for PK theory.

More generally, while it is certainly possible that bed density also influences erosion and mobility, the present experiments do not isolate density from frictional effects. The low-density beds are not simply lower-density versions of the neutral beds; they also differ in grain shape and frictional properties. As a result, the observed trends cannot be attributed primarily to "flow–bed inertia" as framed in the manuscript.

4. Broader context and recommendation

In summary, once the errors in PK are corrected, the model reverts to the correct depth-averaged framework of Iverson (2012) and Iverson and Ouyang (2015), which already provides a sound basis for interpreting erosive landslide experiments. From that perspective, the results of Wetterauer et al. are qualitatively consistent with the established role of bed shear strength in controlling erosion and mobility. It cannot be ruled out that bed density also influences erosion and mobility, although not for the reasons claimed by PK.

More generally, the role of bed bulk density in erosion and mobility is not a novel question. Farin et al. (2014) already performed flume experiments on dry granular beds with differing solid volume fractions (and thus differing erodible bed bulk densities). They found that granular flows on more porous beds exhibited larger erosion and higher mobility than flows on less porous beds. At the same time, denser granular materials (i.e., lower porosity) are well known to exhibit dilatancy and therefore higher peak shear strength (Rowe, 1962; Bolton, 1986). From this perspective, the effect of erodible bed solid volume fraction may itself be interpreted through its influence on bed shear strength. It is also worth noting that the DEM simulations of Martin et al. (2024) instead found a negligible effect of bed porosity on flow mobility.

Seen in this broader context, the present manuscript does not establish a distinct or compelling mechanistic role for "flow–bed inertia" as framed by the authors. Rather, the wider literature increasingly points to bed shear strength as a primary control on erosion and mobility. In particular, an increasing number of researchers have now adopted fully three-dimensional, depth-resolved models for erosion by geophysical flows, thereby avoiding several of the strong (or, in the case of PK, erroneous) assumptions required in the derivation of depth-averaged formulations. These studies consistently indicate that the shear strength of the bed material is one of the key controls on erosion and flow mobility (Nikooei and Manzari, 2020; Li et al., 2022; Vicari et al., 2022; Goodwin et al., 2023; Cuomo et al., 2024; Zhu et al., 2025; Vicari et al., 2025).

Wetterauer et al. nevertheless provide a potentially valuable dataset. The manuscript has the basis for a useful contribution, but requires fundamental revision. The study should be reformulated as an investigation of dry granular flows over beds with differing frictional properties (beyond differences in density), rather than as a verification of the "flow–bed inertia" concept proposed by PK. Most importantly, citations to Pudasaini and Krautblatter (2021), and to subsequent erosion models by Pudasaini that build on the same erroneous concept, as a valid mechanistic basis for the present interpretation should be removed throughout. As long as the manuscript remains framed around that incorrect theory, it cannot be recommended for publication.

Best regards,
Dr. Hervé Vicari
ETH Zürich and SLF Davos

References

Bolton, M.D., 1986. The strength and dilatancy of sands. Géotechnique 36, 65–78. doi:10.1680/geot.1986.36.1.65.

Cuomo, S., Di Perna, A., Moscariello, M., Martinelli, M., 2024. Possible remediation of impact-loading debris avalanches via fine long rooted grass: An experimental and material point method (MPM) analysis. Landslides 21, 679–696. doi:10.1007/s10346-023-02178-5.

Farin, M., Mangeney, A., Roche, O., 2014. Fundamental changes of granular flow dynamics, deposition, and erosion processes at high slope angles: Insights from laboratory experiments. Journal of Geophysical Research: Earth Surface 119, 504–532. doi:10.1002/2013JF002750.

Goodwin, S.R., Lapillonne, S., Piton, G., Chambon, G., 2023. An SPH study on viscoplastic surges overriding mobile beds: The many regimes of entrainment. Computers & Geosciences 181, 105476. doi:10.1016/j.cageo.2023.105476.

Issler, D., 2020. Comments on "On a continuum model for avalanche flow and its simplified variants" by S. S. Grigorian and A. V. Ostroumov. Geosciences (Switzerland) 10. doi:10.3390/geosciences10030096.

Issler, D., Gauer, P., Tregaskis, C., Vicari, H., 2024. Structure of equations for gravity mass flows with entrainment. Nature Communications 15, 4613. doi:10.1038/s41467-024-48605-6.

Iverson, R., 2013. DISCUSSION: Numerical study on the entrainment of bed material into rapid landslides. M. PIRULLI and M. PASTOR (2012). Géotechnique 62, No. 11, 959–972, http://dx.doi.org/10.1680/geot.10.P.074. Géotechnique 63, 887–888. doi:10.1680/geot.12.D.007.

Iverson, R.M., 2012. Elementary theory of bed-sediment entrainment by debris flows and avalanches. Journal of Geophysical Research: Earth Surface 117, 1–17. doi:10.1029/2011JF002189.

Iverson, R.M., 2018. Discussion of "Shallow Water Hydro-Sediment-Morphodynamic Equations for Fluvial Processes" by Zhixian Cao, Chunchen Xia, Gareth Pender, and Qingquan Liu. Journal of Hydraulic Engineering 144, 07018009. doi:10.1061/(asce)hy.1943-7900.0001519.

Iverson, R.M., Ouyang, C., 2015. Entrainment of bed material by Earth-surface mass flows: Review and reformulation of depth-integrated theory. Reviews of Geophysics 53, 27–58. doi:10.1002/2013RG000447.

Iverson, R.M., Reid, M.E., Logan, M., LaHusen, R.G., Godt, J.W., Griswold, J.P., 2011. Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment. Nature Geoscience 4, 116–121. doi:10.1038/ngeo1040.

Li, X., Sovilla, B., Ligneau, C., Jiang, C., Gaume, J., 2022. Different erosion and entrainment mechanisms in snow avalanches. Mechanics Research Communications 124, 103914. doi:10.1016/j.mechrescom.2022.103914.

Mangeney, A., Roche, O., Hungr, O., Mangold, N., Faccanoni, G., Lucas, A., 2010. Erosion and mobility in granular collapse over sloping beds. Journal of Geophysical Research: Earth Surface 115, 1–21. doi:10.1029/2009JF001462.

Martin, H.A., Mangeney, A., Lefebvre-Lepot, A., Maury, B., Maday, Y., 2024. An optimization-based discrete element model for dry granular flows: Application to granular collapse on erodible beds. Journal of Computational Physics 498, 112665. doi:10.1016/j.jcp.2023.112665.

Nikooei, M., Manzari, M.T., 2020. Studying effect of entrainment on dynamics of debris flows using numerical simulation. Computers and Geosciences 134. doi:10.1016/j.cageo.2019.104337.

Pudasaini, S.P., Krautblatter, M., 2021. The mechanics of landslide mobility with erosion. Nature Communications 12, 6793. doi:10.1038/s41467-021-26959-5.

Rowe, P.W., 1962. The stress-dilatancy relation for static equilibrium of an assembly of particles in contact. Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences 269, 500–527. doi:10.1098/rspa.1962.0193.

Vicari, H., Tran, Q.A., Metzsch Juel, M., Gaume, J., 2025. The role of dilatancy and permeability of erodible wet bed sediments in affecting erosion and runout of a granular flow: Two-phase MPM–CFD simulations. Computers and Geotechnics 185, 107307. doi:10.1016/j.compgeo.2025.107307.

Vicari, H., Tran, Q.A., Nordal, S., Thakur, V.K.S., 2022. MPM modelling of debris flow entrainment and interaction with an upstream flexible barrier. Landslides 19, 2101–2115. doi:10.1007/s10346-022-01886-8.

Zhu, L., Tang, X., He, S., Yang, Z., Liang, H., Lei, X., Luo, Y., Zhang, L., 2025. Geomorphology and Sedimentology of the Nyixoi Chongco Rock Avalanche and Implications for Emplacement Mechanisms. Journal of Geophysical Research: Earth Surface 130, e2024JF007666. doi:10.1029/2024JF007666.