Author response to community comment CC3 by Dr. Dieter Issler

Manuscript: Mobility of dry granular debris flows over erodible beds: Experimental insights into the influence of flow–bed inertia

Dear Dr. Issler,

Thank you for taking the time to comment on our manuscript and for the thoughtful and constructive remarks. We appreciate the detailed discussion of the theoretical framework, terminology, and interpretation of the experimental results. Some of the points raised here overlap with comments made by the reviewers, while others provide valuable additional perspectives on the interpretation of the datasets and their broader implications. These comments will be carefully considered during the revision of the manuscript.

In the following we provide the community comments listed as [C1] to [C5] (black italic font) and our corresponding answers as [A1] to [A5] (blue normal font).

With kind regards,
The authors

This manuscript describes, analyzes and discusses chute experiments on granular flows over erodible beds of different bulk densities with the goal of testing the erosion theory of Pudasaini and Krautblatter (Nat. Comm. 12, 6793, 2021, henceforth called PK). In CC2 and RC2, Hervé Vicari pointed out that Issler et al. (Nat. Comm. 15, 4613, 2024) demonstrated that the results of PK hinge critically on counting the particle-borne momentum flux from the bed to the flow twice. If this error is corrected, the conclusions in PK revert to the standard formulation that has been known for decades.

This situation implies that the the present manuscript uses an interpretative framework that is not mathematically consistent. Accordingly, Vicari posits that all references to PK need to be removed and the discussion of the results reformulated before publication. I fully support Vicari's statement and also agree with him and the Reviewer #1 that the experiments described in the manuscript are interesting, valuable and do not depend on the interpretative framework of PK in any essential way. It should therefore be fairly straightforward to reformulate the analysis and discussion parts of the manuscript with an emphasis on the mass, momentum and energy balances and the associated stresses. There is hardly anything to add to Vicari's thorough and detailed review, but perhaps a few remarks from a different perspective could be useful in the revision of the paper.

Thank you for your detailed general comment and for your positive assessment of the experimental work. We appreciate that you consider the experiments interesting and valuable.

As stated in our response to Dr. Vicari, we acknowledge that the current manuscript overemphasizes the interpretation of the experiments in the specific framework of Pudasaini and Krautblatter (2021; hereafter called P&K). We will therefore substantially revise the manuscript and will describe the experiments primarily in terms of dry granular flows over low-, equal-, and high-density erodible beds with contrasting material properties. The interpretation will be broadened toward erosion, entrainment, mass and momentum exchange, bed resistance, shear strength, internal friction, particle shape, and grain-scale entrainment mechanisms.

At the same time, we do not consider it appropriate to remove all references to P&K. We acknowledge that Issler et al. (2024) provides a critical opposing statement to this model. However, P&K remains a peer-reviewed publication in Nature Communications, has not been withdrawn or retracted by the publisher, and remains part of the scientific record. Beyond this formal point, the publication is scientifically relevant to our study because it explicitly describes the potential consequences of contrasting bed inertia for erosion-induced changes in landslide mobility. This is the conceptual motivation behind our experimental design, in which a constant dry granular slide overrides erodible beds of lower, equal, and higher density. We therefore consider a limited and balanced citation of P&K, together with the critique by Issler et al. (2024), to be more appropriate than a complete omission of the study.

We also note that our experiments were not designed to discriminate between competing mathematical derivations of erosion-induced momentum exchange. Our measurements are mainly surface-based and do not directly resolve basal shear stress or the full slide-bed interface dynamics. We will therefore avoid using the data as evidence for or against a specific coefficient (you name it k) in a depth-averaged momentum balance. Instead, we will present the dataset as an experimental basis for future testing of different erosion and entrainment formulations, including depth-averaged and depth-resolved approaches.

Accordingly, the revised manuscript will be reframed as an experimental study of dry granular flow mobility over erodible beds with contrasting density, friction, and particle-shape properties. The role of P&K will be reduced to motivation and literature context, while the interpretation will be broadened to include the mechanically sound concepts and limitations highlighted in your comment and in Dr. Vicari's review.

[C1] *It would be helpful if the authors could summarize early on in which respect their experiments differ from other, similar experiments.*

[A1] Thank you for this suggestion. We agree that this would be beneficial and will more clearly emphasize the distinguishing features and novelty of our experiments in the introductory part of the revised manuscript.

[C2] *In my opinion, the emphasis on inertia in this context is problematic. The notion has a history spanning more than two millennia (see the Wikipedia article for an interesting summary) and played an important conceptual role in the Theory of Relativity, yet it has not been linked to a measurable physical quantity. Perhaps a vague description like "the property of a body causing it to maintain its velocity in the absence of external forces acting on it" comes close to the essence of the concept. In contrast, PK and the present manuscript seem to oscillate between identifying inertia with bulk density or momentum density. If the authors want to use the term inertia, they need to define it unambiguously (and preferably in line with conventional usage). In my opinion, it would be best to eschew it in favor of a well-defined, measurable quantity.*

[A2] Thank you for this broader conceptual clarification. We understand the concern that the term "inertia" can be ambiguous if it is not linked to a clearly defined and measurable quantity. In the revised manuscript, we will therefore avoid using "inertia" as a central interpretative term wherever possible and will instead refer more explicitly to measurable quantities such as solid particle density, bulk density, mass entrainment, and momentum balance. At the same time, we note that these quantities are, in a mechanical sense, still related to the resistance of a moving mass to changes in its motion.

Our original intention was to address how the mechanical response of a flow changes when material with different solid particle density is entrained from the bed. In a geomorphological context, such changes can affect the total momentum either through changes in mass at a given velocity or through changes in velocity at a given mass. In the present experiments, we focused on the first aspect by varying the density of the erodible bed material while keeping the released slide material and initial mass constant.

We also agree that the distinction between bulk density and solid particle density should be made clearer. In model equations, bulk density is often the directly relevant quantity. Experimentally, however, we prepared comparable particle-size distributions within each size fraction, so that porosity and solid volume fraction were intended to be broadly comparable. Under these conditions, differences in bulk density primarily reflect differences in the true density of the solid particles. We will clarify this point in the revised Methods and Discussion.

Finally, we will emphasize that these experiments are not intended to reproduce naturally occurring density contrasts one-to-one. Rather, they are controlled experiments for fundamental research designed to create clear contrasts in material properties and flow response. Their main value is to provide reproducible benchmark data for testing and improving numerical models of erosion, entrainment, and dry granular flow mobility.

[C3] *There are many passages throughout the manuscript where the authors mention important aspects of the experiments, like the effect of particle shape, the stability and shear strength of the erodible bed, and the energetics of entrainment. These are key elements that need to be analyzed carefully and quantitatively where possible if one wishes to understand the experimental results. In the present version, these questions are discussed mostly where some discrepancy between PK theory and the experimental results was encountered. Instead, it would be preferable to start from these aspects of the experiments and discuss what their consequences are. This should help in distinguishing between firm conclusions, plausible inferences and conjectures.*

[A3] Thank you for this valuable observation. In the revised manuscript, we will restructure the discussion to place greater emphasis on the experimental observations themselves and on the potential controls on erosion and mobility inferred from them, providing a more integrated assessment of the different influencing factors.

[C4] *It should be quite illuminating to clearly state (and if possible quantify) the connections between the entrainment rate , the mass balance and the momentum balance. An almost trivial but important point is that, in these experiments, the entrainable material is initially at rest and therefore does not increase the flow momentum when it is entrained. As the eroded material must be accelerated to the mean flow velocity or a fraction thereof, the entraining flow will accelerate less (or decelerate more) compared to the situation without entrainment (as has been known for a long time). Conversely, the entrainment rate is limited by the excess of the flow shear stress over the bed shear strength. For the granular materials used here, the shear strength can be estimated in terms of the difference between internal friction angle and slope angle and the bed-normal load. From the experiments without erodible bed, it should be possible to estimate the bed friction and to check whether the mass and momentum balances of the flow work out with the estimated entrainment rates. If the flow decelerated less than estimated, it could mean that the entrainment rate was lower than expected or that the eroded material is not thoroughly mixed into the flow but remains near the bed with lower velocity. Stronger deceleration could indicate deep failure of the substrate, i.e., a sudden, very high erosion rate; this could occur in the case of the Glass substrate since it is only meta-stable and is likely to fail throughout its depth once disturbed by the flow.*

[A4] Thank you for outlining these important considerations. We will evaluate whether the available data allow us to relate the apparent entrainment rates more explicitly to the mass and momentum balance. In the revised manuscript, we will take this into account and discuss the possible implications for the different bed materials, especially the meta-stable Glass substrate.

[C5] *It is intriguing that entrainment has a decelerating effect on the flow, yet entraining flows can be significantly more mobile than non-entraining ones. Perhaps one could shed some light on this with one or two series of tests without entrainment, using mixtures of quartz and glass, and of quartz and magnetite. The fraction of glass or magnetite mass could be chosen to roughly correspond to the entrained mass in the reported experiments. In this way, the effect of the erosion and entrainment process on the momentum can be separated from the effect of the density and shape differences as well as the poly-dispersity.*

[A5] Thank you for this very interesting suggestion. We agree that such experiments could provide valuable additional insight, because they would help to separate the effect of the erosion and entrainment process itself from the effects of density, particle shape, friction, and polydispersity in the final moving mixture.

We consider this a highly relevant direction for future work. However, adding such experimental series to the present manuscript would require substantial additional testing, analysis, and discussion, and the manuscript is already extensive. We therefore decided not to include these additional experiments in the current study. We have, however, now explicitly incorporated this aspect into our ongoing experimental program and plan to address it systematically in a dedicated future study, where the mixture composition, entrained mass fractions, and non-erodible reference cases can be analyzed in sufficient detail.

I wish the authors success in the revision process and look forward to seeing the revised paper published.