Author response to Referee #1, anonymous

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

Dear Referee,

Thank you for taking the time to review our manuscript and for your constructive and thoughtful feedback. We appreciate your positive assessment of the experimental design and the study's scientific value for the debris-flow and granular flow community. Our manuscript will certainly benefit from your comments, and the suggested clarifications will help us to further improve both the scientific interpretation and the clarity of the presentation.

In the following we provide the review comments listed as [C1] to [C12] (black italic font) and our corresponding answers as [A1] to [A12] (blue normal font).

With kind regards,
The authors

Language

[C1] *The Paper needs revision in writing style genuinely before publication. Reading the paper suffers through e.g.*

- *Long, heavily subordinated sentences.*
- *Noun-heavy constructions such "the mechanical complexity of flow–bed interactions"*
- *Paragraph structure. The paragraphs tend to be very long and try to cover multiple subtopics It will be very understanding if the writers use more focused paragraphs with a clearer topic sentence.*

As an example, the sentence:
"Besides, variations in bed clay content appear to influence the contraction–dilation behavior of the bed, with an optimum clay content at which undrained loading conditions and liquefaction of the upper bed layer produce maximum erosion (Roelofs et al., 2023)."

It tries to deliver four separate subjects and ideas in one sentence:

1. *Clay content variations influence bed behavior*
2. *There is an optimum clay content*
3. *At that optimum, undrained loading and liquefaction occur together*
4. *This combination produces maximum erosion*

In plain and easily readable text, this would typically be split into at least two sentences, something like (if I understood it correctly!):

"Variations in bed clay content influence the contraction–dilation behavior of the bed. At an optimum clay content, undrained loading conditions trigger liquefaction of the upper bed layer, resulting in maximum erosion (Roelofs et al., 2023)."

[A1] Thank you for this helpful comment. We will carefully revise the manuscript to improve readability by simplifying sentence structure, phrasing, and improving paragraph organization where appropriate.

The terminology problem

[C2] *Takahashi's framework, which is the standard reference in debris flow science, clearly distinguishes between debris flows (which requires a fluid phase, typically water, to mobilize and transport sediment) and dry granular flows, which are essentially a different phenomenon governed by different mechanics. Dry granular flows and debris flows behave fundamentally differently in terms of erosion mechanics, momentum transfer, and mobility. The authors acknowledge it very briefly in introduction, stating that when they use the term "debris flow" it specifically denotes dry granular single-phase flows.*

The entire theoretical framework of experiments is based on the work of Pudasaini & Krautblatter (2021), which was developed for landslide mobility broadly, but the applicability to dry granular flows specifically versus water-bearing debris flows needs much more careful justification in the paper.

[A2] Thank you for this valid remark. We realize that our terminology remains potentially misleading despite pointing at the dry nature of our experiments. To avoid misunderstandings, we will replace the term "debris flow" by "dry granular flows" whenever we refer to our experiments in the revised manuscript. This change is also consistent with the recommendation by Reviewer #2 (see [C9]).

We agree that this aspect requires further clarification and will discuss the applicability to dry granular flows versus water-bearing debris flows in more detail in the revised manuscript. Even though the model of Pudasaini and Krautblatter (2021) was developed for landslide mobility in a broader sense, it explicitly includes the limiting case of a “pure dry granular flow” when no fluid phase is present and the solid volume fraction approaches unity. Our first experiments were designed to investigate this simplified end-member case, in which the mechanical response to erosion-induced changes in bed inertia can be isolated from additional effects related to pore pressure, fluid viscosity, or phase interactions.

Comment of Mr. Hervé Vicari

[C3] *It would be useful to address the points of Mr. Hervé Vicari in his discussion about the validity of Pudasaini & Krautblatter (2021).*

However, in geoscience and fluid mechanics, we use many simplified or partially incorrect theoretical frameworks that still provide useful working approximations. The fact that Pudasaini & Krautblatter (2021) has a mathematical flaw does not automatically invalidate your experimental study inspired by it.

Therefore, it is important to discuss the comment of Mr. Hervé Vicari in the paper. Especially in your discussion you mention the point that the observation did not support the hypothesis proposed by Pudasaini and Krautblatter (2021).

[A3] Thank you for the recommendation. We address these concerns in detail in our responses to the corresponding comments of Reviewer #2 and will revise the manuscript accordingly.

Experimental method

[C4] *In nature the density range is much narrower. Natural bed materials in the mountain torrents, where debris flow occurs, typically range from about 1200-1500 kg/m³ for highly porous or organic-rich soils (if exist), through 1600-1800 kg/m³ for typical alluvial sediments, up to about 2600-2900 kg/m³ for dense crystalline rocks like granite or basalt.*

So my question is: If you use such extreme density contrasts, which is understandable from an experimental strategy perspective, what about the relevance and transferability? If the inertial effect is only clearly detectable at such large density contrasts, how does is its importance in natural debris flows?

[A4] Thank you for this important question. We agree that the relevance of the observed effects for natural systems deserves further discussion. While the aim of the experiments was not to reproduce natural debris flows directly, but to compare relative differences between controlled laboratory scenarios based on strong contrasts, we will further elaborate on the transferability of this approach in the revised manuscript.

The observed similarity in mobility and runout of the inertially neutral and inertially strong scenarios suggests that even exaggerated density contrasts alone were insufficient to produce measurable differences under the tested conditions. Consequently, our results indicate that smaller density contrasts, more typical of natural systems, are unlikely to exert a stronger influence on mobility and runout and would likely result in similar behavior. We will incorporate this perspective into the revised discussion.

However, we would like to highlight that, as noted in [A4] correctly, the large density differences result from our experimental strategy. We intentionally imposed pronounced solid particle density contrasts to generate clearly observable changes in flow mobility. The manuscript is part of a project funded by the German Research Foundation (DFG) that aims to contribute to fundamental research and to provide experimental data for the validation of theoretical models. From this perspective, the experiments are not primarily intended as a direct reproduction of natural debris-flow conditions. Rather, they represent controlled end-member test cases. Such test cases are commonly useful for model validation because they produce distinct and interpretable responses while minimizing the superposition of additional effects. In principle, a theoretical or numerical model that correctly captures the governing mechanics should be able to reproduce the experimental results when supplied with the corresponding initial and boundary conditions. Although this approach may appear less application-oriented at first glance, it provides a robust basis for testing the fundamental assumptions of the inertia-based mobility concept.

[C5] *The slope which is selected for experiment is about 75%. It is practically out of range for a torrent with debris flow. We speak in such cases mostly about rock avalanches. Mountain torrents with debris flow have normally a slope range of 25 to 45% (14° - 25°). Lanzoni et al., 2017 used this range of slope, which is reasonable. It needs to justify why this extreme slope is representative for such study.*

[A5] We thank for this comment and agree that the selected flume inclination is steeper than typical channel gradients of torrent debris flows.

In the present study, the flume inclination was not varied systematically, and the experiments were not designed to assess the influence of slope angle on debris-flow mobility. We fully acknowledge that higher slopes generally promote higher mobility. The selected inclination resulted from the specific experimental requirements for this dry granular setup. Because no water was present, the material had to be mobilized solely by gravity and had to remain sufficiently mobile to interact with the erodible bed and reach the runout area. Therefore, the inclination had to exceed the relevant basal and internal friction angles of the dry materials. At lower inclinations, the dry granular flow would either not have developed sufficiently or would have deposited before passing the erodible section and reaching the runout area.

We further agree that this differs from natural torrent debris flows, where motion at lower channel gradients is commonly enabled by substantial water contents, pore-pressure effects, and fluid-solid interactions. For this reason, we have adjusted the terminology throughout the manuscript and now refer more specifically to “dry granular flows”. With this clarification, the selected slope is better understood as an experimental requirement for studying dry granular flow mobility on steep slopes, rather than as a typical torrent-channel gradient.

The maximum inclination was also constrained by the internal stability of the erodible bed material and by safety considerations associated with operating a relatively large experimental flume. Thus, the selected slope represents a compromise between ensuring sufficient motion and erosion in a dry granular system, while maintaining initially stable, safe, and reproducible experimental conditions.

[C6] *Rough coated plywood: information about roughness is missing. It is important to have this information.*

[A6] Thank you for pointing this out. We will add the missing information.

Measurements

[C7] *Flow-front velocity was calculated from the ratio of the traveled distance from the reservoir flap to each sensor and the respective time of flow-front arrival. This is not the front velocity (instant front velocity), it is the average velocity of the front from flap to the sensor. The (instant) front velocity can be diverted from the average over the whole distance.*

[A7] We apologize, this term was expressed in a misleading way - thank you for pointing this out. We will revise the terminology to use “average front velocity from flap to sensor”.

Results

[C8] *I would suggest that chapter 3 needs a brief introductory paragraph.*

[A8] We adopt your suggestion, thanks, and include a few introductory lines.

[C9] *My second suggestion: chapter 3.1.2 consists almost entirely of descriptive reporting of numbers presented sequentially scenario by scenario without any interpretive thread connecting them. The Discussion (chapter 4) does provide physical interpretation of these descriptions. However, the Results and Discussion are so completely separated that the reader has to hold a large amount of raw numbers in their head from Chapter 3 before getting any interpretive context in Chapter 4 or has to jump often between these two chapters. Maybe you can reconstruct the chapter to replace pure numerical reporting with an interpretive approach that guides the reader toward the key findings.*

[A9] Thank you for this helpful suggestion. We understand the concern that Sect. 3.1.2, in its previous form, was strongly descriptive and required the reader to retain many numerical details before the physical interpretation was provided in the Discussion. We agree that the key findings should be guided more clearly already within the Results section. At the same time, we would like to maintain a clear separation between Results and Discussion, as a complete interpretive restructuring of Sect. 3.1.2 would substantially shift discussion points into the Results section and would also create considerable overlap with Sect. 4. We therefore will revise Sect. 3.1.2 in a moderate way. Specifically, we will add short guiding sentences that highlight the main contrasts between the scenarios, and introduce the most important mechanical links already at the descriptive level. This will help the reader to recognize the key pattern before the full physical interpretation is developed in the Discussion.

[C10] *Regarding my last comment related to the front velocity, the increase of your front velocity is interesting. Our observations show that the instant front velocity of debris flows (with water and fine part) does not increase in a channel. This is physically reasonable, because of the equilibrium of forces. Therefore, it is important to emphasis that the velocity measured in your experiment is the average velocity for the distance segment.*

[A10] Thank you for sharing your observations. We will revise the terminology to use “average front velocity from flap to sensor”.

[C11] *The missing introductory text for chapter 3.2 is repeated here again. Section 3.2.1 represents an improvement in terms of scientific explanation of the results, which is worth acknowledging fairly. But again here, as it is discussed above, the reader must jump always between chapter 4 and 3.*

[A11] We adopt your suggestions, thanks.

Discussion

[C12] *The Discussion would benefit substantially from the inclusion of comparative diagrams, e.g. using non-dimensional parameters, to place the experimental findings in the context of existing literature. Even a simple statistical summary of key parameters across repetitions would strengthen the quantitative basis of the conclusions.*

[A12] We thank the reviewer for this useful suggestion. We agree that additional comparative and quantitative diagrams would strengthen the discussion and place our experiments more clearly in the context of previous studies.

Regarding non-dimensional parameters, the options are somewhat limited for our dry granular flow experiments, because many commonly used dimensionless numbers require properties of a fluid phase that is absent in our setup. We will therefore focus on parameters that are meaningful for dry granular flows, in particular the Savage number, and compare them with values reported in the literature where available.

In addition, we will strengthen the statistical basis of the results by reporting the variation across repetitions for key parameters listed in Table 2. This will make the variability around the selected representative runs more transparent. We will also compare mobility-related parameters, such as L/W, initial volume, and inundated area, with previous experimental data, extending the comparative framework presented by Baselt et al. (2022). Due to the already long manuscript, we might shift some of these diagrams to the Supplement.