We are grateful for the constructive and detailed comments of Prof. Shiva P. Pudasaini and Reviewer 2. In accordance with their helpful and insightful recommendations, we have modified the original manuscript to both improve the presentation and strengthen the discussion on the limitations and potential of the results derived from our reduced-scale flume tests.

Below, we provide our responses to the specific comments and questions received from the reviewers. The comments of the reviewers are shown in italics and different colors (i.e., those of the Associate Editor, Reviewer 1, and Reviewer 2 are presented in green, brown, and blue, respectively), while our responses are provided in normal black text.

Associate editor COMMENTS AND AUTHOR RESPONSE

AE comment:

thank you for the revised paper. I have received two further reviews by the original reviewers. Reviewer #1 is largely satisfied with your changes and merely makes a few language suggestions. Reviewer #2 is more critical and makes a few important points. I'd like to highlight two (related) comments. First, there is little discussion about how your experimental results scale up to natural debris flows and their fans. Please add a section in the discussion on this topic, possibly also the mentioning the limited range of conditions that you tested and the small number of data points. Second, most of the analysis and discussion focusses on the scaled parameter values. Reviewer #2 rightly points out that normalized parameters might yield slightly different interpretations and may be more easily generalizable (relating to point 1).

I think you can address the comments at various levels, most easily by revising and expanding the discussion. It might strengthen the paper, however, to come up with a suitable non-dimensional framework to present the data.

Overall, I think the necessary revisions are moderate. I have decided on major revisions, as I would like reviewer #2 to have another look at the revised manuscript.

Please address all of the comments and submit a detailed rebuttal with your revisions. I am looking forward to seeing your revised paper and wish you a very nice weekend.

All the best, Jens Turowski

Reply to AE comment: We greatly appreciate the time and effort of the editors and reviewers in providing constructive and insightful feedback, which has helped us improve our manuscript. We sincerely agree with the comment and indications received from Reviewer 2. We have added a new subsection in the discussion section to explain how the experimental results represent the properties of natural debris-flow fans (**P15 L474-516**). In this subsection, we discuss the similarities between experimental and natural debris-flow fans in terms of qualitative observations and geometrical comparisons (**Figure 19**). On the basis of these similarities, we suggest that the four experimental runs likely exhibited representative results for our experimental setup with adequate reproducibility. At the end of this subsection, we also note the limitation of our flume tests in that they focus only the aspect of the effects of grain-size distribution within debris flows on fan-formation processes, and we emphasize the need for comprehensive assessment using further accumulated field data.

Additionally, to support our interpretation, we investigated changes in the normalized avulsion distance (i.e., the ratio between the distance from the flume outlet to the occurrence point of the avulsion and the distance of the runout of the solid phase) (**Figure 14**) and differences in the surface slope of the final fan morphology (**Figure 16**) between the monogranular and multigranular flows. The results, which do not alter our interpretation and discussion, further highlight that different runout distances can result in different fan morphology (**P11 L321-325** and **P11 L340-351**).

All related figures and text are mentioned in **Reply to R2 Overall comment**. We hope that these responses satisfactorily address all issues and concerns regarding our original submission and that our manuscript might now be considered suitable for publication in Earth Surface Dynamics.

Reviewer 1 COMMENTS AND AUTHOR RESPONSE

R1 General comment 1:
The ms has been thoroughly revised, enhancing its quality and clarity. I appreciate the authors for their work. However, in parts, the writing is incomplete, or inconsistent. The description could still be made better, including the mechanisms of erosion and phase separation with respect to the available mechanical models.

Reply to R1 General comment 1: We sincerely appreciate your thorough and helpful review of our manuscript. To improve the presentation, we have carefully revised the manuscript in accordance with your comments. Moreover, in accordance with the comments from the Associate Editor and Reviewer 2, we have added some new results and additional discussion (please see **Reply to AE Comment**) to further improve both the quality and the clarity of the manuscript.

R1 Specific comment 1: *L63: "fluctuation of inertia" --> "change of inertia"*

Reply to R1 Specific comment 1: We have made the suggested changes, thank you (**P2 L63**).

R1 Specific comment 2: *L67: It is better to call "interstitial water and colloidal sediment particles"*

Reply to R1 Specific comment 2: We have made the suggested changes, thank you (**P3 L68**).

R1 Specific comment 3: *L128: --> "This phenomenon has been explained by Pudasaini and Krautblatter (2021) with their mechanical erosion model for debris flows involving the state of excess energy during the erosion process."*

Reply to R1 Specific comment 3: We have added the suggested sentence, thank you (**P5 L137-139**).

R1 Specific comment 4: *L175-184: Not clear, which velocity you are talking about, solid, water, or both? Please make it clear.*

Reply to R1 Specific comment 4: We apologize for the confusion. Because we measured the velocity of either the solid or the water or both, the sentence has been revised as follows (**P7 L190-191**):

P7 L190-191: the paired image sets were processed to estimate the vectors of the flow velocity of either the solid or the water or both at the surface of the deposition area.

R1 Specific comment 5: *L201: This definition of the index is applicable only for the geometry, any physically less representative, but there are other asymmetries too! E.g., depth, density, particle-fluid distribution, etc. Please discuss.*

Reply to R1 Specific comment 5: We sincerely appreciate this important comment. As you correctly highlighted, asymmetries of the physical (dynamic) properties of debris flows in the deposition area are also crucial regarding changes in fan morphology. However, unfortunately, we could not quantitatively measure such properties after the flow runout. This is an obvious limitation of our flume tests, which we have discussed in relation to the general experimental limitations (**P16 L497-516**, please see **Reply to AE Comment**).

R1 Specific comment 6: *L266-273: You could improve descriptions in connection to the figure panels.*

Reply to R1 Specific comment 6: According to this comment and R2 Comment 12, we have revised the lead sentence of this paragraph (please see **Reply to R2 Comment 12**).

R1 Specific comment 7: *Fig. 5-6: Panels b-f: are these vertical sections?*

Reply to R1 Specific comment 7: We apologize for the confusion. To indicate the flow direction, we have revised Figs. 5 and 6 (please see **Reply to R2 Comment 13**).

R1 Specific comment 8: *Fig. 7-8 (etc.): The quality is poor.*

Reply to R1 Specific comment 8: To improve clarity and quality, we have indicated the location of the point of the avulsion in Figs. 8–13.

Figure 8:

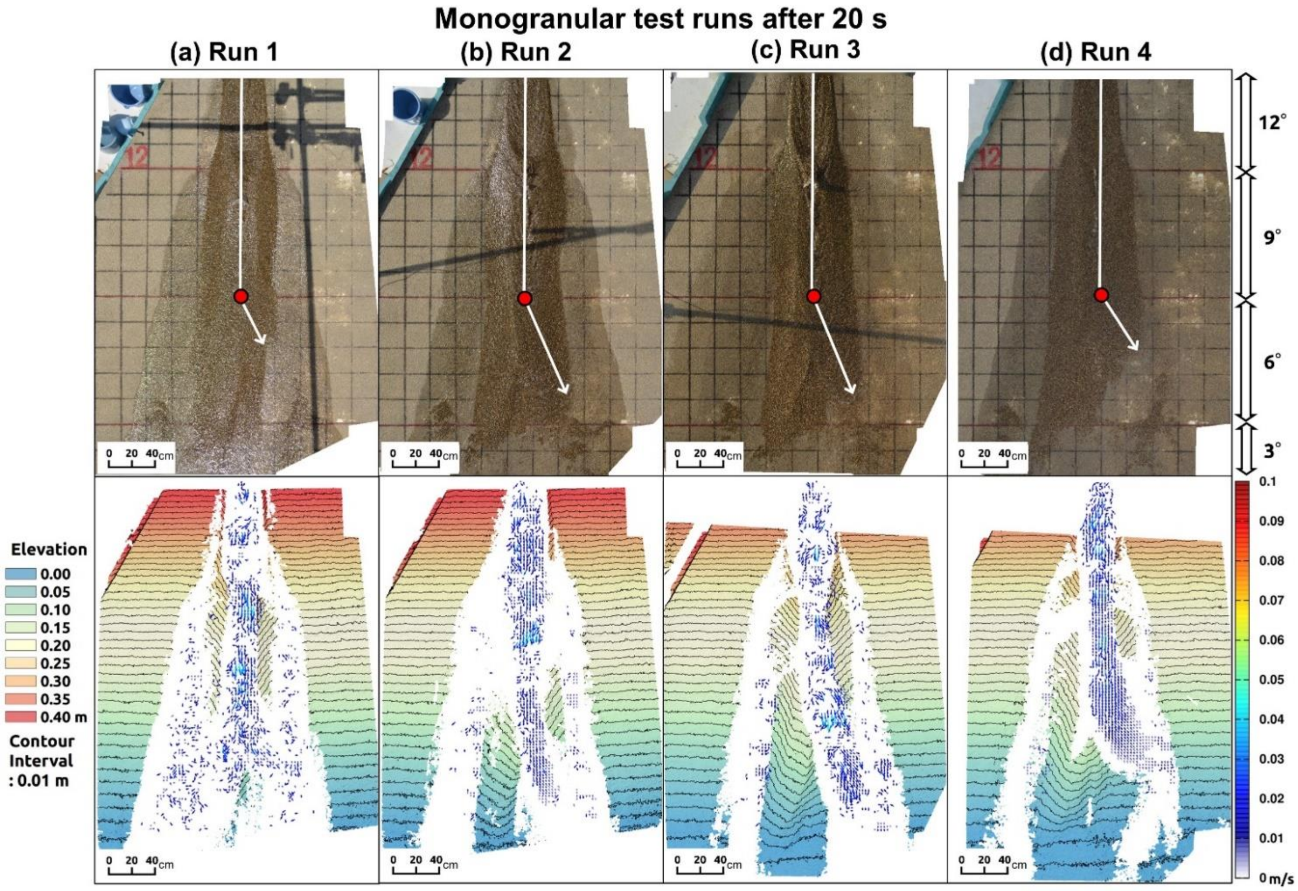

Figure 8: Fan morphology 20 s after the start of runout of the monogranular flows. The upper and lower panels show orthophotos and digital elevation models (DEMs) with flow vectors, respectively. Respective sets of the upper orthophoto and lower DEM represent corresponding results of each experimental test run. The white arrows on the orthophotos indicate the assumed principal direction of flow descent. The red points in the orthophotos indicate the assumed occurrence point of the avulsion. The elevation of the DEMs is depicted assuming that the area with a 3° slope (i.e., the area furthest downstream from where the slope angle changed from a 6° to 3° slope) has elevation of zero.

R1 Specific comment 9: *L371: "Numerical simulations" --> "Numerical simulations based on the mechanical model"*

Reply to R1 Specific comment 9: We have made the suggested changes, thank you (**P13 L416-417**).

R1 Specific comment 10: *L386: "for the variation in the fluidity" --> "for the state of the erosion induced excess energy and the mobility"*

Reply to R1 Specific comment 10: We have made the suggested changes, thank you (**P14 L432-433**).

R1 Specific comment 11: *L390: “deposition range.” --> “deposition range that can be achieved with the mechanical erosion and mobility model (Pudasaini and Krautblatter, 2021).”*

Reply to R1 Specific comment 11: We have made the suggested changes, thank you (**P14 L436-437**).

R1 Specific comment 12: *L434: “Despite similarities in the flow properties before the start of debris-flow runout”: You can’t say this in general. You only have similarity in flow depth. But, you don’t know the internal structure, mechanics and dynamics. So, I would re-phrase it and say it ‘the debris mixture hydrograph’. Also, in the main text.*

Reply to R1 Specific comment 12: We appreciate this comment. We have revised the related sentences to avoid such speculation (**P1 L16, P3 L86, P5 L127,** and **P17 L526-527**).

R1 Specific comment 13: *L437-438: “The short runout distances of the multigranular flows were responsible for sediment deposition closer to the flume outlet”: two parts of this sentence are the same. This is not the reason. Please explain it physically.*

Reply to R1 Specific comment 13: We appreciate this comment. We have revised the related sentences to explain the reason on the basis of the newly added results (**P17 L530-531**).

P17 L528-529: The short runout distances of the multigranular flows were responsible for changes in the location at which the avulsion occurred, which led to avulsion that markedly shifted the flow direction during fan formation.

R1 Specific comment 14: *References: Please check thoroughly with all necessary information as required by the journal, including doi, paper nr., etc.*

Reply to R1 Specific comment 14: We have carefully checked and revised the entries in the reference list to ensure that they provide all the required information in the correct format (**P18 L555-730**).

Reviewer 2 COMMENTS AND AUTHOR RESPONSE

R2 Overall comment: *Tsunetaka et al present the results of a set of flume experiments where they test the impact of debris flow grain size distributions on the morphology of debris flow fans. By comparing the results of 8 experiment runs, 4 monogranular and 4 multigranular, they discover that debris flows with coarser grains have shorter runouts due to early solid and fluid phase separation. Due to the shorter runout multigranular flows the fans are more complex as changes in direction can occur more frequently during the runout of the flow. While I believe this is an interesting result, in its current form it is difficult to apply it to real debris flow fans. Without this link it is not clear whether this manuscript represents a significant step forward in our understanding of debris flow fan formation.*

I believe the results of the manuscript are hard to apply to real debris flow fans due to three main reasons. I will describe these reasons briefly here and provide detailed section specific feedback below.

In the experiments described, the fans are produced by a single debris flow like surge resulting from a continual flow entraining sediment from the bed of the flume. However, in reality debris flow fans are produced by multiple flows depositing sequentially over the course of potentially thousands of years. Therefore, it is not currently clear how the deposits from the experiments can be compared to actual debris flow fans. Instead, it is likely these results can help us to decipher single events from fan stratigraphy.

Most of the analysis of the experiment is in terms of time and distance, both of which are highly specific to the experiment run and cannot easily be scaled up to a real debris flow or easily compared between model runs. Throughout the results and discussion, the authors describe how avulsions in multigranular flows occur earlier (both in terms of distance from the flume outlet and in time) than monogranular flows. However, as this result is likely due to the shorter runout distance of the multigranular flows it is not clear whether this result represents a significant difference in behaviour between the 2 types of flow. By normalising the runout length of the flow, it is possible to compare whether the avulsions in multigranular flows truly occur earlier in the evolution of the fan. If there is no difference in the normalised runs then grainsize is not a controlling factor on avulsion frequency or location. Normalising the runout length will also allow for comparison between the model results and actual debris flows and debris flow deposits.

Finally, there is surprisingly little reference to the changing slope of the runout area despite slope being a well-known control on the deposition of sediment. By analysing the slope at which the flows stop at the differences in friction between the flows can be quantified. Multigranular flows may stop in steeper slopes than monogranular flows which could allow for some calculation of the friction angle in the deposited sediment. This result would again help to link the experimental results to real debris *flow deposits.*

Reply to R2 Overall comment: We sincerely appreciate your insightful review and constructive suggestions. We agree that our experiment focused on the fan morphology formed by a single successive debris-flow surge rather than that formed by an accumulation of multiple debris-flow surges. This arose because of differences in the study objectives and intentions. We intended to investigate whether differences in the grain-size distribution within debris flows could lead to changes in fan morphology via differences in runout characteristics without considering differences in hydrographs and without considering the effects of geomorphology formed by previous debris-flow surges. To convey our intention and to clarify the study targets, we have revised the related sentences (**P3 L83-96**).

We also acknowledge that we performed only four experimental test runs for the respective grain sizes, and that our flume tests focused on a limited aspect of the effects of the grain-size distribution within the debris flows. On the basis of the similarities between experimental and natural debris-flow fans in terms of qualitative and geometrical comparisons, we suggest that despite the limited number of experimental runs, the experiments were well controlled and could have produced representative results under our experimental setup and operation (**Figure 19** and **P15 L475-496**). Additionally, we have emphasized and carefully discussed the limitations of our flume tests (**P16 L497-516**).

Moreover, we compared the normalized avulsion distance (i.e., the ratio between the distance from the flume outlet to the occurrence point of the avulsion and the distance of the runout of the solid phase) (**Figure 14**), which indicated that the avulsion of the multigranular flows occurred closer to the flume outlet in comparison with that of the monogranular flows (**P11 L321-325**). We also compared the surface slope of the final fan morphology between the monogranular and multigranular flows (**Figure 16**). The multigranular flows formed steeper slopes of the fan surface further upstream in comparison with the monogranular flows (**P11 L340-351**). These results support our interpretation and discussion that the short runout distance of the multigranular flows can lead to variations in fan morphology.

We believe that these revisions address all doubts and clarify the implications derived from our flume tests regarding the understanding of natural debris-flow fans.

P3 L83-96: The primary objective of this study was to assess how the grain-size distribution within a debris flow influences fan morphology, especially during debris-flow runout and inundation. We conducted reduced-scale flume tests to compare fan morphologies that resulted from single debris-flow surges with different grain-size distributions but with similar sediment mixture hydrographs. To investigate whether differences in the runout properties of both solid and fluid phases cause different sediment deposition patterns, we intended to avoid the effects of morphology resulting from previous debris-flow surges on the debris flow that runs out at the flume outlet. To achieve this, we focused on how a single successive debris-flow surge forms the fan-like morphology around the flume outlet without geomorphological effects arising from previous debris flows. Thus, in this study, debris-flow fans are defined as the sediment deposition formed by a single successive debris-flow surge rather than the accumulation of multiple debris-flow surges. Using photogrammetry and video-image analysis, we investigated how differences in grain-size distribution within debris flows influence variations in runout characteristics and fan morphologies. The intention underlying this comparison was to interpret the differences in fan morphology in terms of known debris-flow mechanics. The final objective was to elucidate whether differences in grain-size distribution within debris flows could change fan morphology solely by influencing the runout process without variation of the dynamic properties of the debris flow in the channel.

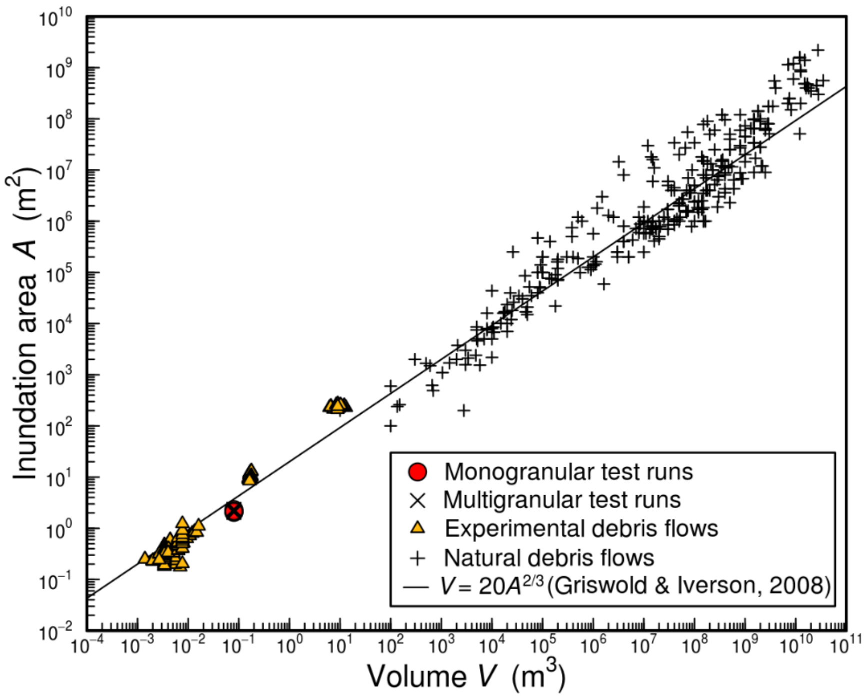

Figure 19: Debris-flow volume versus inundation area. Data concerning experiments (n = 454) are from Liu (1996), Major (1997), D'Agostino et al. (2010), De Haas et al. (2015b), Hürlimann et al. (2015), and Baselt et al. (2022). Data concerning natural debris flows (n = 323) are from Abele (1974), Li (1983), Crandell et al. (1984), Siebert (1984), Francis et al. (1985), Siebert et al. (1987), Hazlett et al. (1991), Hayashi and Self (1992), Siebe et al. (1992), Stoopes and Sheridan (1992), Iverson et al. (1998, 2015), Capra et al. (2002), Berti and Simoni (2007), Griswold and Iverson (2008), D'Agostino et al. (2010), Dufresne et al. (2019), Fan et al. (2019), and Friele et al. (2020). Note that the monogranular and multigranular test runs of this study are overlain in the log-log plane, and that the flow volume was approximated as 0.08 m3 on the basis of the supplied sediment volume. The solid black line is the best-fit regression carve (V = 20$A^{2/3}$) derived by Griswold and Iverson (2008).

P15 L475-496: It should be noted that the flume tests conducted in this study were operated under limited conditions that considered only two types of grain-size distribution. Therefore, the extent to which the obtained experimental results represent the properties of natural debris-flow fans should be assessed with caution. The observations of the grain-size profiles of the multigranular flows (Figs. 6 and 7) indicate that the grain-size segregation of the sediment particles was similar to that of natural debris flows (e.g., Iverson, 1997; Zanuttigh and Lamberti, 2007; Johnson et al., 2012). Additionally, the wide-ranging grain-size distribution of the debris flows caused horizontal widening of the deposition range (Fig. 15). This relationship between horizontal deposition characteristics and grain-size distribution is also observed in stratigraphic records of natural debris-flow fans (Pederson et al., 2015). Thus, in terms of qualitative observations, our flume tests can be considered representative to a certain extent of the properties of natural debris-flow fans.

In terms of a geometrical scaling relationship, we compared the relationships between the volumes of the debris flows (V) and the inundation areas of the sediment deposits (A) similar to De Haas et al. (2015b) and Baselt et al. (2022) (Fig. 19). The inundation areas of the monogranular and multigranular test runs were ~2.224 m^2 and ~2.159 m^2, respectively (Table S1), which highlights that when the hydrograph and velocity of debris flows are similar before the start of runout, the effects of grain-size distribution within the debris flows on fan formation are reflected in change in the horizontal shape of the sediment inundation range but without substantial variation in the gross area. Owing to this similarity in the inundation area regardless of the grain-size distribution, all experimental runs were plotted in almost identical locations on the log-log *V*-*A* plane, and just below the best-fit regression curve for natural debris flows derived by Griswold and Iverson (2008) (Fig. 19). The *V*-*A* scaling relationships indicate that our experimental results are geometrically within the range of natural debris flows, and that our flume tests were well-controlled experiments across all experimental runs, especially regarding the resultant inundation areas. Given this reproducibility of the inundation area, although we performed only four test runs for both the monogranular flows and the multigranular flows, we believe that the obtained observations adequately reflect the representative behavior of experimental debris flows under the operation and setup of our flume tests.

P16 L497-516: In addition to these qualitative and geometric similarities between the experimental and natural debris flows, the similar flow depths suggest that the experimental debris flows were well-controlled in terms of their hydrographs, at least in the flume (Fig. 3). However, some dynamic properties, such as flow resistance (Egashira et al., 2001), sediment erosion and entrainment rate (McCoy et al., 2012; De Haas et al., 2022), and flow friction (Pudasaini and Miller, 2013; Lucas et al., 2014), are strongly governed by the scales of grain size and flow volume. Thus, especially for the experimental debris flows after their runout, our flume tests might not have completely met the dynamic similarity law of debris flows, similar to many other reduced-scale flume tests (e.g., De Haas et al., 2015b; Iverson, 2015). In this regard, our flume tests focus on a limited aspect of the effects of the grain-size distribution within debris flows. Although the effects of fine sediment (e.g., silt and clay) were intentionally excluded in our experiments to control the hydrograph and the velocity of the debris flows in the flume, fine sediment might alter the resistance and stress structure of natural debris flows (Kaitna et al., 2016; Sakai et al., 2019; Nishiguchi and Uchida, 2022). Because these changes in the resistance and stress of debris flows might affect the rate of separation between the solid and fluid phases (Pudasaini and Fischer, 2020; Baselt et al., 2022), our flume tests could not identify the extent of phase separation on the scale of natural debris flows that comprise wide-ranging sediment particle size from silt to large boulders. In nature, various factors (e.g., phase separation) associated with particle size and grain-size distribution interact, and therefore the behavior of debris flows becomes increasingly complex (e.g., De Haas et al., 2018b). This is reflected in the wide-ranging variation in the *V-A* relationship of natural debris flows (Fig. 19). Our flume tests demonstrate that differences in the grain-size distribution within debris flows can change fan morphology, and likely support interpretation of the formation processes of fan morphology resulting from a single successive debris-flow surge. However, comprehensive assessment of the extent of the respective effects in relation to grain-size distribution within natural debris flows will require further accumulated field data.

Figure 14:

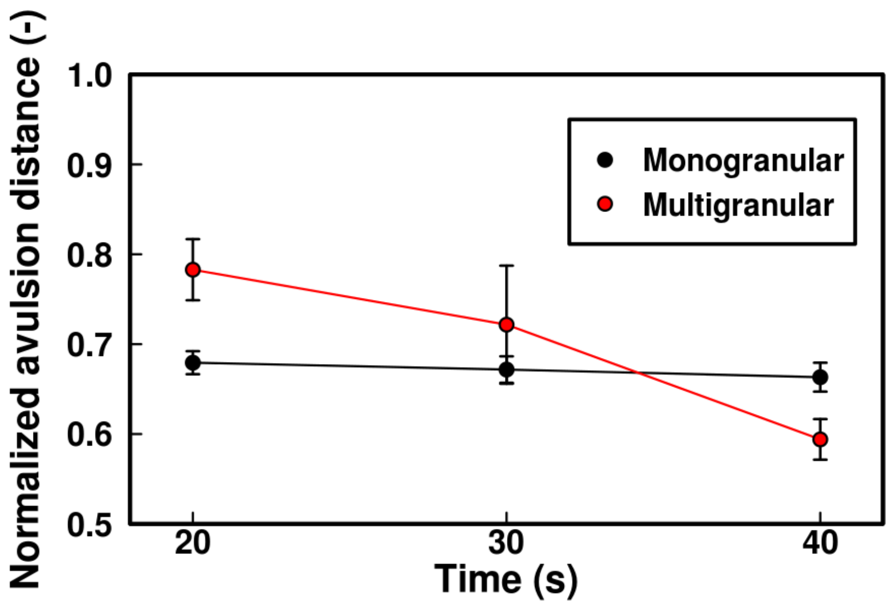

Figure 14: Change in normalized avulsion distance with time. The error bar indicates the standard deviation between the four experimental runs.

P11 L321-325: The normalized avulsion distances of the monogranular test runs were almost constant at approximately 0.67 from after 20 s to 40 s from the start of flow runout (Fig. 14). Unlike this fixed position of the avulsion of the monogranular flows, the normalized avulsion distance of the multigranular test runs gradually decreased from ~0.78 to ~0.59 from after 20 s to 40 s from the start of flow runout (Fig. 14). This highlights the difference in the trend of the inundation processes between monogranular and multigranular flows.

Figure 16:

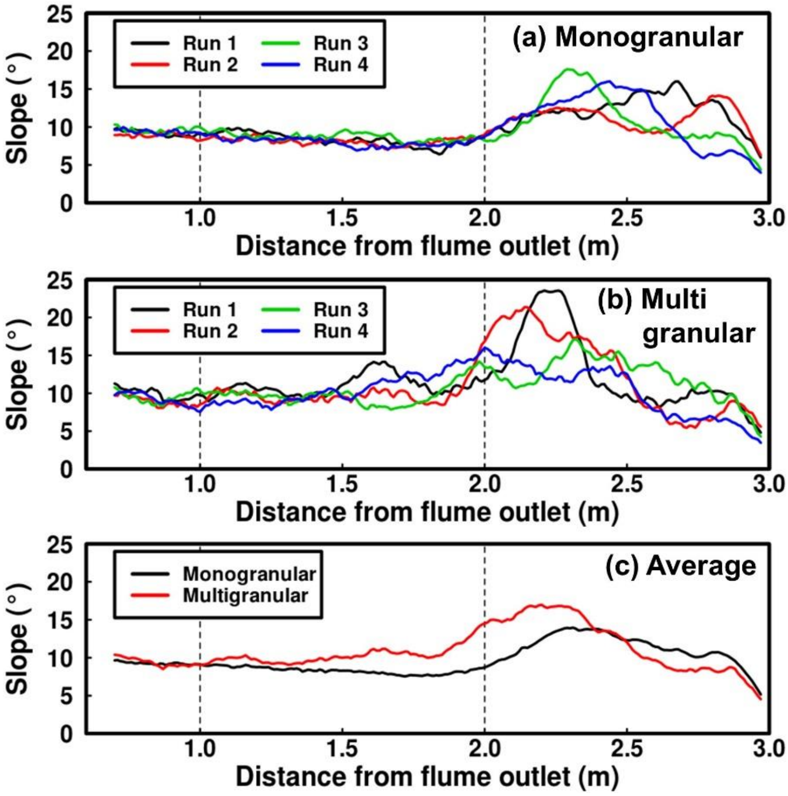

Figure 16: Slopes along the center of the final fans. The slope values were averaged over 0.2 m intervals. The upper, middle, and lower panels indicate monogranular flows, multigranular flows, and their averages, respectively. Vertical broken lines indicate the boundaries of bed slope (i.e., the change points from 12° to 9° and from 9° to 6°).

P11 L340-351: Corresponding to the difference in the runout distance of the solid phase (Fig. 5), the surface slopes along the center of the final fan morphology were different between the monogranular and multigranular flows (Fig. 16). The slopes of the monogranular test runs were similar at ~10° from the flume outlet to ~2 m downstream, but they increased to a maximum of ~15° and became somewhat varied further downstream between experimental runs (Fig. 16a). Similarly, the slopes of the multigranular test runs were similar at ~10° from the flume outlet to ~1.5 m downstream (Fig. 16b). However, the slopes of the multigranular test runs started to increase further upstream in comparison with the monogranular test runs; the slopes increased to a maximum of ~23° from ~1.5 to ~2.2 m downstream (Fig. 16b). These differences, reflected in the averaged slopes, indicate steeper surface slopes of the multigranular-fan morphology (Fig. 16c). Note that beyond 2.5 m downstream, the deposition thickness of the multigranular test runs was close to zero (Fig. 15b), indicating that the slope values do not represent the surface slopes of the final fan morphology. Indeed, in the section from 2.5 to 3.0 m downstream from the flume outlet, the slopes of the multigranular test runs were gentler (i.e., ~6°–8°) and closer to the surface slope of the deposition area (6°) in comparison with the monogranular test runs (Fig. 16c).

R2 Comment 1: *Line 16: This line is confusing to readers as it is not currently clear how a debris flow can have a flow depth before it starts to runout.*

Reply to R2 Comment 1: We agree with this comment and we have added some additional information to improve clarity (**P1 L11-19**):

P1 L11-19: Therefore, using a flume connected to a deposition area (inundation plane), this study conducted fan-morphology experiments to assess the effects of differences in grain-size distribution within debris flows on changes in fan morphology. Two types of debris-flow material, i.e., monogranular particles comprising monodispersed sediment particles and multigranular particles comprising polydispersed sediment particles, were used to generate monogranular and multigranular experimental debris flows, respectively. By adjusting the average grain size coincident between the monogranular and multigranular flows, we generated two types of debris flow with similar debris mixture hydrographs but different grain-size distributions in the flume. Although the flow depths were mostly similar between the monogranular and multigranular flows before the start of the debris-flow runout at the deposition area, the runout distances of the front of the multigranular flows were shorter than those of the monogranular flows.

R2 Comment 2: *Lines 69&61: Which processes are being referred to here?*

Reply to R2 Comment 2: We appreciate this question. We have revised the related sentences to improve clarity (**P2 L60-62** and **P3 L69-71**):

P2 L60-62: Moreover, the velocity that erodes channel deposits is susceptible to the influence of both grain-size distribution and slope of the channel bed (Egashira et al., 2001; Takahashi, 2007), and this erosion velocity differs fundamentally from the velocity that entrains the eroded sediment (Pudasaini and Krautblatter, 2021).

P3 L69-71: When debris flows leave the channel outlet, the relative difference in velocity between the solid and fluid phases increases and leads to phase separation (Pudasaini and Fischer, 2020; Baselt et al., 2022).

R2 Comment 3: *Line 68: It is not clear what is meant by "Discharge around". Perhaps "when debris flows leave the channel outlet…" would work better*

Reply to R2 Comment 3: We have made the suggested changes, thank you (**P3 L69-71**, please see **Reply to R2 Comment 2**).

R2 Comment 4: *Line 71: Unclear what is meant by "The progress of phase separation continues"*

Reply to R2 Comment 4: We agree with this comment. We have revised the related sentences to improve clarity (**P3 L71-72**):

P3 L71-72: Around the channel outlet, the solid phase eventually translates into sediment deposition, but the fluid phase continuously descends with the progress of phase separation.

R2 Comment 5: *Line 73: How is runout distance defined in this circumstance? Is it defined by the runout of the solid phase?*

Reply to R2 Comment 5: Your assumption intimated in the second question is correct in relation to the first. We intended to describe the runout distance of the solid phase and we have revised the related sentence accordingly (**P3 L72-75**):

P3 L72-75: The extent of the phase separation might vary in response to the grain-size distribution within a debris flow (Major and Iverson, 1999; Pudasaini and Fischer, 2020), potentially resulting in further difference in runout distance of the solid phase, in addition to the effects attributable to sediment erosion and entrainment processes in the channel.

R2 Comment 6: *Line 77: Unclear what "runout around the channel outlet means"*

Reply to R2 Comment 6: We appreciate this comment and we have revised the related sentence to improve clarity (**P3 L76-78**):

P3 L76-78: In other words, the grain-size distribution can influence the characteristics of both the debris-flow development in the channel and the runout distance after debris flows leave the channel outlet.

R2 Comment 7: *Line 84: There needs to a definition of what the authors consider a debris flow fan to be and how their experiment replicates this definition. Currently the experiments do not seem to result in a fan as defined by the references discussed in the references of the introduction.*

Reply to R2 Comment 7: To convey our intention and to explain why we designed the experiments to focus on fan morphology formed by a single continuous debris flow, we have included additional clarifying sentences (**P3 L83-96**, please see **Reply to R2 Overall comment**).

R2 Comment 8: *Line 118: What are these "similar flow properties"? Perhaps these need to be defined before discussing the differences between the flows.*

Reply to R2 Comment 8: We agree with this comment. To avoid such vague explanation, we have used the phrase "similar sediment mixture hydrographs" in the revised manuscript (please see **Reply to R1 Comment 12**).

R2 Comment 9: *Line 173: How are the solid and fluid phases identified and defined?*

Reply to R2 Comment 9: To improve clarity, we have added new figures (**Figures S1 and 2**) and referred to them as appropriate in the main text (**P6 L179-186**):

Figure S1:

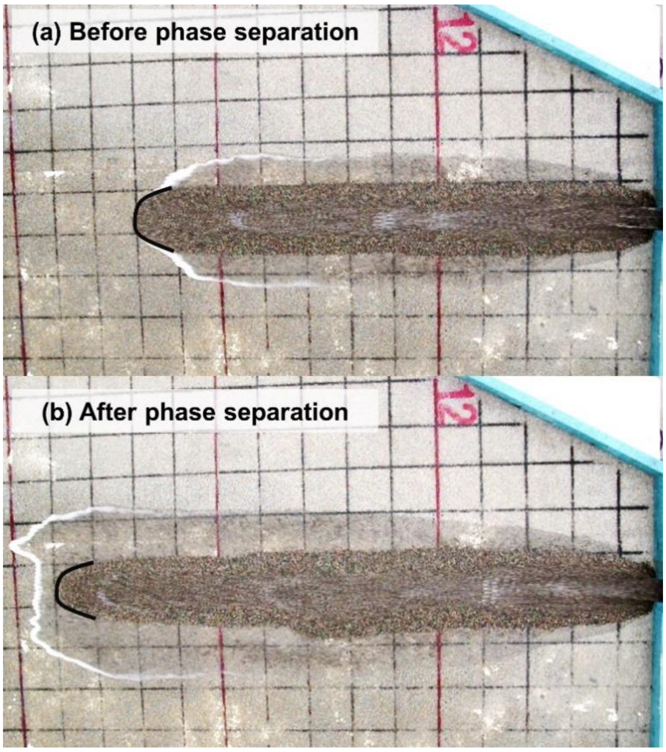

Figure S1: Images extracted from the captured video with respect to flow runout of the monogranular test run4: (a) before the start of phase separation and (b) after the start of phase separation. Drawn grid lines indicate a square grid (0.2 × 0.2 m). The black line indicates the front of the solid phase, whereas the lower edge of the fluid phase is captured by the white line in the video. In (a), the solid and fluid phases are shown descending synchronously; in (b), the fluid phase has reached further downstream owing to phase separation.

Figure 2:

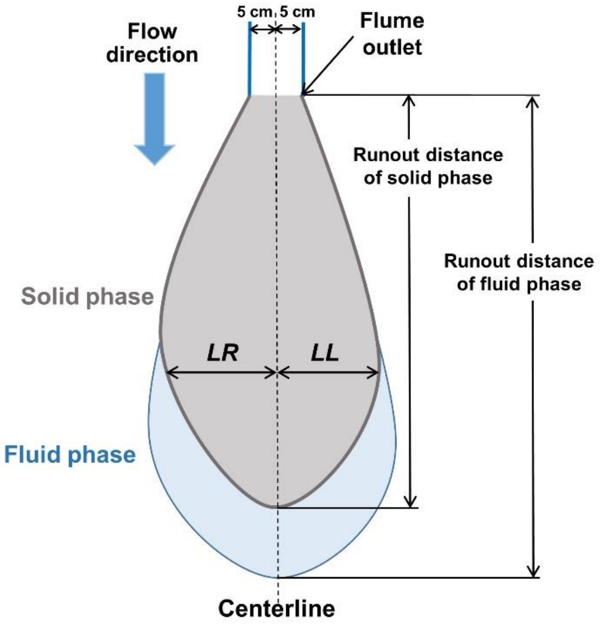

Figure 2: Sketch showing definitions of measurements associated with the flume experiments. The centerline is drawn as an extension of the central longitudinal axis of the flume.

P6 L179-186: We measured changes in the runout distance of the fronts of the generated debris flows with temporal resolution of 0.1 s using the captured video and the grid lines drawn in the deposition area. During the early stage of debris-flow runout, the solid phase (sediment particles) and fluid phase (clear water) descended synchronously as a complete granular–water mixture flow (Fig. S1a), but then they flowed separately with different velocities in accordance with the deceleration of the solid phase (Fig. S1b). Because the timing of the phase separation was clear in all experimental cases, we measured the fronts of both the solid and the fluid phases after separation to compare the extent of phase separation between the monogranular and multigranular flows. The runout distances of the solid and fluid phases were defined as the distance from the flume outlet to the front of the solid and fluid phases, respectively (Fig. 2).

R2 Comment 10: *Lines 200 – 205: The calculation of this metric could be better explained by diagram, currently it is not clear how the mid line is defined or what "the length of the fan from the midline to the edge…" describes.*

Reply to R2 Comment 10: We appreciate this comment. We have added a new figure to explain the definitions (**Figure 2**, please see **Reply to R2 Comment 9**) and we have revised the related sentences that describe these definitions (**P8 L224-228**):

P8 L226-230: Additionally, to investigate the differences in the shape of fans derived from both the monogranular and the multigranular flows, we proposed an index that focuses on fan-shape symmetry. The proposed symmetric index (*SI*) is defined as follows:

$SI = LL/LR$ (1)

where *LL* and *LR* represent the length of the fan from the centerline of the flume to the edge of the left-bank side and to the edge of the right-bank side of the fan shape, respectively (Fig. 2).

R2 Comment 11: *Line 237: How is the runoff distance measured and defined? Does the runout begin in the flume or once it enters the deposition zone?*

Reply to R2 Comment 11: We appreciate these questions. We have added a new figure (**Figure 2**, please see **Reply to R2 Comment 9**) and additional sentences (**P4 L108** and **P6 L185-186**) to clarify both the measurement method and the definition of runout distance:

P4 L108: In this study, debris-flow runout is defined as the descent of the debris flow downstream from the flume outlet.

P6 L185-186: The runout distances of the solid and fluid phases were defined as the distance from the flume outlet to the front of the solid and fluid phases, respectively (Fig. 2).

R2 Comment 12: *Line 266: It is unclear what is meant by "following multigranular test runs 2 and 3". Perhaps "the grain size of the deposits of test runs 2&3 were observed…" works better*

Reply to R2 Comment 12: We have made the suggested changes, thank you (**P10 L292**):

P10 L292: The grain sizes of the deposits of multigranular test runs 2 and 3 were observed (Figs. 6 and 7).

R2 Comment 13: *Lines 267-270: It is not clear what a depth of 1-2cm from the surface of the deposition area means. Are the coarser grains 1-2 cm above the base or 1-2 cm below the surface of the deposit? It is also not clear whether the deposit is fining upwards or has reverse grading.*

Reply to R2 Comment 13: We appreciate this comment. We have revised the related sentences to improve clarity, and we have modified Figs. 6 and 7 to indicate the direction of the measurement profiles (**P10 L292-294** and **Figures 6 and 7**).

P10 L292-294: At all observation points, relatively large particles were deposited above the base of the deposition area (i.e., zero on the ruler) to thickness of ~1–2 cm (Figs. 6b–f and 7b–f).

Figure 6:

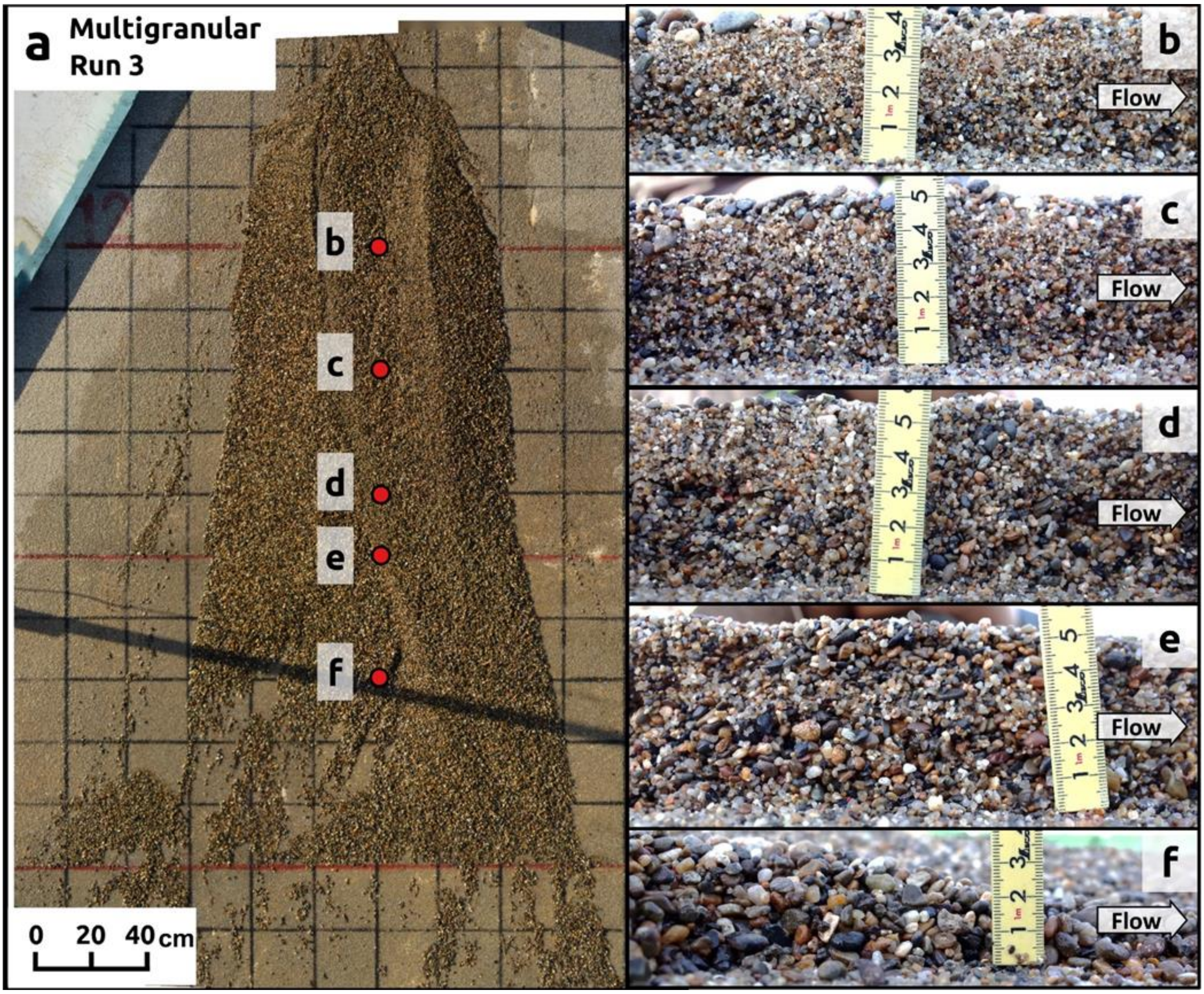

Figure 6: (a) Orthophoto of the debris-flow fan formed by the multigranular flow in test run 3. The red circles indicate the points at which the images were taken. Images of the longitudinal profile from the right-bank side view: (b) 1 m downstream from the flume outlet (slope change point from 12° to 9°), (c) 1.4 m downstream from the flume outlet, (d) 1.8 m downstream from the flume outlet, (e) 2 m downstream from the flume outlet (slope change point from 9° to 6°), and (f) 2.4 m downstream from the flume outlet.

R2 Comment 14: *Line 307: Deposition depth is not intuitive, I would use deposit thickness.*

Reply to R2 Comment 14: We agree with this comment and we have changed the term "deposition depth" to "deposit thickness" (**P10 L293**, please see **Reply to R2 Comment 13**).

R2 Comment 15: *Line 347: The locations of the avulsions cannot be compared between runs due to* *the difference in runout length. Normalising the runout length may indicate that the locations of the avulsions are fairly similar across all of the experiment runs.*

Reply to R2 Comment 15: We appreciate this comment. Comparison of the normalized avulsion distances indicated that the locations of the avulsions were different between the monogranular and multigranular flows (**Figure 14** and **P11 L321-325**, please see **Reply to R2 Overall comment**).

R2 Comment 16: *Line 363: The lack of consideration of the change in slope in the discussion of runout length is strange. An important confirmation of the coarse grains enhancement of friction would be if the multigranular flow stop on steeper slopes than the monogranular flows. This would also allow for easier comparison with real examples of debris flows.*

Reply to R2 Comment 16: We appreciate this comment. Comparison of the surface slope of the final fan morphology indicated that the multigranular flows resulted in a steeper surface slope in comparison with that of the monogranular flows. This aspect is reflected in the revised manuscript (**Figure 16** and **P11 L340-351**, please see **Reply to R2 Overall comment**).

R2 Comment 17: *Line 408: There has been no discussion on how coarser grains may cause avulsions other than by increasing the friction of the front of the debris flow. Therefore, it is not clear why a model which considers the friction of debris flows will not be able to replicate fan morphology.*

Reply to R2 Comment 17: We apologize for the confusion. We have revised the related sentences to improve the clarity of this discussion (**P14 L446-457**):

P14 L446-457: Importantly, in comparison with monogranular fans, the extent of asymmetry of the multigranular fans differed substantially between test runs (Figs. 17 and 18). The variations in the asymmetry of the multigranular fans suggest that debris flows with wide-ranging grain-size distribution can randomly shift their descent direction when the flows behave as unsteady flows that are freed from horizontal constraints owing to the channel-like topography. Some models assume that multigranular debris flows can be approximated to monogranular debris flows with the same average grain size (e.g., Egashira et al., 1997; Takahashi, 2007). Despite this assumption, such models allow estimation of debris-flow properties such as flow velocity and depth, especially under a steady flow state (Egashira et al., 1997; Takahashi, 2007). Indeed, in the flume, experimental results exhibited similar flow velocity and depth as debris flows with the same average grain size but with different grain-size distributions (Fig. 3). However, given that natural debris flows generally consist of wide-ranging grain-size sediment particles (e.g., Zanuttigh and Lamberti, 2007; Johnson et al., 2012), the use of debris-flow models that involve grain-size approximation could result in errors in the estimated runout distance of debris flows owing to unsteady behavior during flow runout. This likely leads to inevitable uncertainty in the estimation of fan morphology formed by debris-flow runout.

R2 Comment 18: *Line 416: How much of this phase separation is resulting from the lack of very fine sediment in the flow? Clay particles significantly increase pore pressures in the flow and could prevent phase separation and possibly increase the runout length of the flow.*

Reply to R2 Comment 18: We appreciate this comment. As you correctly highlighted, our flume tests could not reveal the effects of fine sediment on phase separation and runout characteristics. We have explained these limitations of our flume tests in the revised manuscript (**P16 L497-516**, please see **Reply to R2 Overall comment**).