Reviewer comments in black

Author response in blue

"text changes"

Anonymous Referee #2

General Comments

In summary, the present "short communication" (from now on: SC) displays the textpart (introduction, methods, results and discussion, conclusion) of a previous open access publication of experimental data (Haug et al. 2020). Additionally, the present SC constitutes a follow up article to the authors previous publication Haug et al. 2016. The scientific results and conclusions are presented in a clear, concise, and well structured way.

The present SC addresses fragmentation, a generally observed feature of rock avalanches, and its role within the still not thoroughly understood emplacement of highly mobile rock avalanches, despite more than a century of research. Fragmentation itself became a field of interest in rock avalanche research, about two decades ago and remained a promising attempt since then. Rock avalanches, because of their size, violent dynamics and nevertheless overall scarce occurrence (luckily), pose a huge challenge in their investigation at laboratory scale or to be addressed within the limits of available computational power, as the authors correctly state in the SC.

The present SC presents and discusses the results of so called 1g laboratory experiments. The drawback of these experiments is, that governing velocities and stress states are reduced by 2 to 3 orders of magnitude compared to the natural prototype model. Furthermore, the model boundaries have to be set so close, that the models resemble not even a millionth of the natural volumetric scale. Other fields of science experience similar problems: Especially physics faces since decades a growing gap between theories proposed by theoretical physics and the (even theoretical) ability of experimental physics to put these theories to observable and repeatable tests which threatens their epistemological validity. Inventing to a certain degree simple but useful experiments for big theoretical questions displays a main quest in physics today. Hence, 1 g experiments (and corresponding, relatively small-scale numerical models) are, what is currently available to many research groups, after reviewing further publications on the current topic. In this sense the present SC matches the, let's call it "relative state of the art", as defined by the cited articles. In that way the SC can be considered a good contribution to scientific progress.

But on the other hand, it shall be stated, that more rigorous publications on the present topic already exist which are more or less ignored by the SC. Especially the publication of Imre et al, 2010 *) not only presents data derived from a physical modelling environment of much higher velocities and stress states, such as much closer to natural situation, but also suggests quantities of energy dissipated by fragmentation. They also suggest what fragmentation due to inter-particle collisions actually may cause – C2 ESurfD Interactive comment Printer-friendly version Discussion paper the dispersive stress model and show, applying a numerical model, how the spreading of a rock avalanche – hence the rapid propagation of the front at minor propagation of the center of mass, emerges from the dispersive stress model. Since velocities and stress states within their physical model applied still not fully resembled the natural model, they present in Imre et al, 2011 **) an brittle analogue material together with a rigorous scaling of all properties of the analogue material according to the physical modelling applied within. Based in these, dependencies are derived how physical properties of natural rock materials, like strength, pre-fracturing etc., governs the run-out of rock avalanches which may became a truly useful tool in practical hazard mitigation in future.

These topics are alle covered or sometimes at least scratched within the SC also, but within Haug et al. 2016, Imre et al., 2010 just serves as yet another reference on fragmentation in rock avalanches without referring to any details. Within the present follow up SC this publication is completely ignored by the authors. To be clear, there is no intention to advocate the work by Imre et al. They applied a complicated and expensive physical modelling environment and it may become useful to refer to 1g experiments instead to speed up research on rock avalanches as I stated above on physics in general. But scientific progress can be achieved only if something which is proposed as a valid attempt, is thoroughly discussed, in its strengths and weaknesses, to its predecessor, or in the case of Imre et al., 2010, to a model which is by physics much closer to the natural situation than the 1g experiment presented within the SC.

Since the present SC lacks such a proper discussion, the SC is considered just a fair overall contribution to scientific progress, although the scaling law presented is innovative. The fact that currently a number of research groups apply 1g experiments of the kind presented within the SC, proofs by its own their popularity but not necessarily their suitability for lasting progress in rock avalanche research.

*) Imre, B., J. Laue, and S. M. Springman (2010), Fractal fragmentation of rocks within sturzstroms: Insight derived from physical experiments within the ETH geotechnical C3 ESurfD Interactive comment Printer-friendly version Discussion paper drum centrifuge, Granular Matter, 12(3), 267–285, doi:10.1007/s10035-009-0163-1

**) Imre, B., Wildhaber, B., and S. M. Springman (2011), A physical analogue material to simulate sturzstroms. Int. J. of Physical Modelling in Geotechnics 2011 11:2, 69-86.

We thank the reviewer for this review sharing his view from a geotechnical perspective. We agree that experiments using real rock material (or closer to real rock like is “ETHAR”) under conditions closer to the prototype instead of weaker rock analogue material under downscaled laboratory conditions provide highly valuable and unique data. This is especially true for those cost-intensive experiments run in a centrifuge. However, an “analogue modelling” approach as used here should then be considered a different class of experiments equivalent to the distinction made in the geoscience community between rock mechanics experiments (e.g. using High pressure-high temperature deformation devices) and any deformation experiments using weaker (kPa instead MPa) analogue material under consistently (according to scaling laws) lower P-T conditions. Despite this downscaling issue, analogue models have some advantages beyond being cheap: They are also more accessible in terms of monitoring the deformation process more directly at high spatial and especially temporal resolution typically not realizable in geotechnical experiments using real rocks under close to real conditions. In the end, we think both, experiments using quasi-real rock material and those with weak analogue rock material, should be considered complementary with each of them having its weight when contributing to the discussion. We appreciate the work by Imre and others using the geotechnical approach as we do appreciate the many numerical studies. However, within the scope of this short communication, we feel it is impossible to discuss and we necessarily limit our scope. Nevertheless, we feel that to embrace the wider community we now more explicitly acknowledge the limitation of our approach including the lack of various processes including the “granular pressure” effects described by Imre et al.:

““To isolate the scale-independent effect of fragmentation we keep both the volume and friction within a narrow range in our models compared to nature. Note, this approach explicitly excludes dynamic weakening mechanisms that are suspected in natural prototypes. Specifically, our models do not include fluids and frictional heating is insignificant such that lubrication mechanisms \citep[e.g.][]{Pudasaini2013,Lucas2014} do not play a role. Granular pressurization \citep[e.g.][]{Imre2010} is also not considered significant in our experiments because of the low energy involved. Other potentially important mechanisms like bedrock erosion \citep[e.g.][]{Hungr2004,Pudasaini2020} are excluded here for simplicity. The experimental design, therefore, means that the observed variation in Heim's ratio is due to fragmentation and dry friction.”

Specific Comments

In section 3.3 the authors apply their experimentally derived data to “a natural data set”. This data set resembles nine rock avalanches reported by Locat et al. (2006). Due to comprehensible reasons the authors derive a data fit to four natural cases. According to the text theses four cases “cover a range of two orders of magnitude (from 2 Â ˚u 10*6 to 90 Â ˚u 10*6 m3)”. Based on these fit authors claim: “The similarity seen between experimental and natural data suggests universality with respect to the empirical constants and that the rock avalanches considered here all have a close to constant effective friction of about 0.15.” “This shows that fragmentation plays a governing role in the runout of rock avalanches and should be included in hazard assessments.” In section 4 the author finally come the conclusion that: “The law is validated against a natural data set proving its universality and predictive power.”

First: A data set of four fits out of nine cases is extremely limited. There are data of much more cases of rock avalanches available. Furthermore, known cases of rock avalanches range from 1 10*6 to 1 10*10 m3, these are 4 orders of magnitude. Adding Martian rock avalanches this range extends to 7 orders of magnitude. Therefore, the data presented within the SC are in fact limited to a very narrow fit giving no justification for the claimed “universality” and “predictive power” of their derived fit. These terms shall be omitted therefore as unproven.

Indeed, volume was not a variable in our model (intentionally) and we do not contribute to the discussion about scale dependency of Heim’s ratio. Instead, we focus here on the about one order of magnitude variability in Heim’s ratio seen for similar-sized (!) avalanches. This reduces both the “universality” of our result (we agree!) but also the natural data available which is a subset of the arguably larger data set if all volumes (and environments) are considered. Note also, we focus on dry slides and need to extract information about the fragmentation from the original reports. This further narrows down the number of examples we can use. We finally decided to rely on a single source of natural cases (i.e. Locat et al., 2006) because these data are harmonized.

From that small data set, we use most (actually 6) out of nine cases for fitting and provide reasoning why the remaining 3 cannot be used. They plot consistent with the individual late-stage processes leading us to discard them above the others. One may try to correct for those effects, however, this would be only qualitative, so we omitted this.

We added a note:

“Note that in all three discarded cases, the late-stage processes tend to increase the expected Heim's ratio and they consistently plot above the trend of the other data in Figure 3b.”

and de-emphasized the universality and use a less provocative terminology, e.g.:

“...shows that variation in the degree of fragmentation can contribute to the large variation in runout of rock avalanches seen in nature.” (in Abstract)

“To study the effects of friction and fragmentation on rock avalanche dynamics, we here analyse analogue models of dynamically fragmenting rock slides of similar size.“ (in Introduction)

“The agreement between these slide deposit lengths and the extrapolation of the experimental trend through Equation~\ref{eq:Heim_3} (Figure~\ref{fig:f03}B) supports the validity {deleted: and predictive power} of our proposed scaling law.” (in application)

“The similarity seen between experimental and natural data suggests <u>some</u> universality concerning the empirical constants.” (in application)

“The scaling law is validated against a natural data set <u>verifying its applicability</u>.” (in Conclusions)

With respect to scale dependency of runout we specify:

“...our results suggest that the variation seen in Heim's ratio for these rock avalanches are not (only) caused by scale-dependent basal friction, but by differing degrees of fragmentation.”

“The scaling law approaches an extreme for which runout is maximized and limited only by basal friction, <u>which itself might be volume-dependent as suggested by earlier studies</u>.“

Second: The fact that the experiments yielded an effective friction of about 0.15 displays an interesting observation, but for this class of rock avalanches this was known since Albert Heim.

We agree the effective friction is close to the basal friction implemented which in turn is similar to natural examples. We specify:

“We use silicate glass as our substrate, on which the basal friction coefficient is ca. 0.15-0.20 \citep{Haug2016} similar to lowermost values found in natural prototypes \citep{Pudasaini2013,Lucas2014}.”

The interesting point for us was, however, that the experiments yield effective frictions higher than the prescribed one which we attribute to fragmentation.

It remains unclear how fragmentation contributes to such a low friction within the experiment, hence how it “plays a governing role in the runout of rock avalanches”, especially since fragmentation has been identified as a major energy sink at the same time. Therefore, while fragmentation truly displays an important role in further research on rock avalanches, and this SC contributes to it, this SC provides no hint at all, how a fragmentation shall be “included in hazard assessments” in practise. This claim shall be omitted.

We feel there is a misunderstanding here. The low friction coefficient (0.15-0.20) is prescribed in the model when using cemented sand sliding on a glass surface. We verified this using friction tests. The observation that we focus on here is not that friction can be so low but rather that apparent friction (Heim’s ratio) is larger than that for most of the fragmentation spectrum. So fragmentation is not meant to lower the apparent friction but to increase it, which is in line with the view of fragmentation as an energy sink.

Technical Corrections ***
None. Interactive comment on Earth Surf. Dynam.